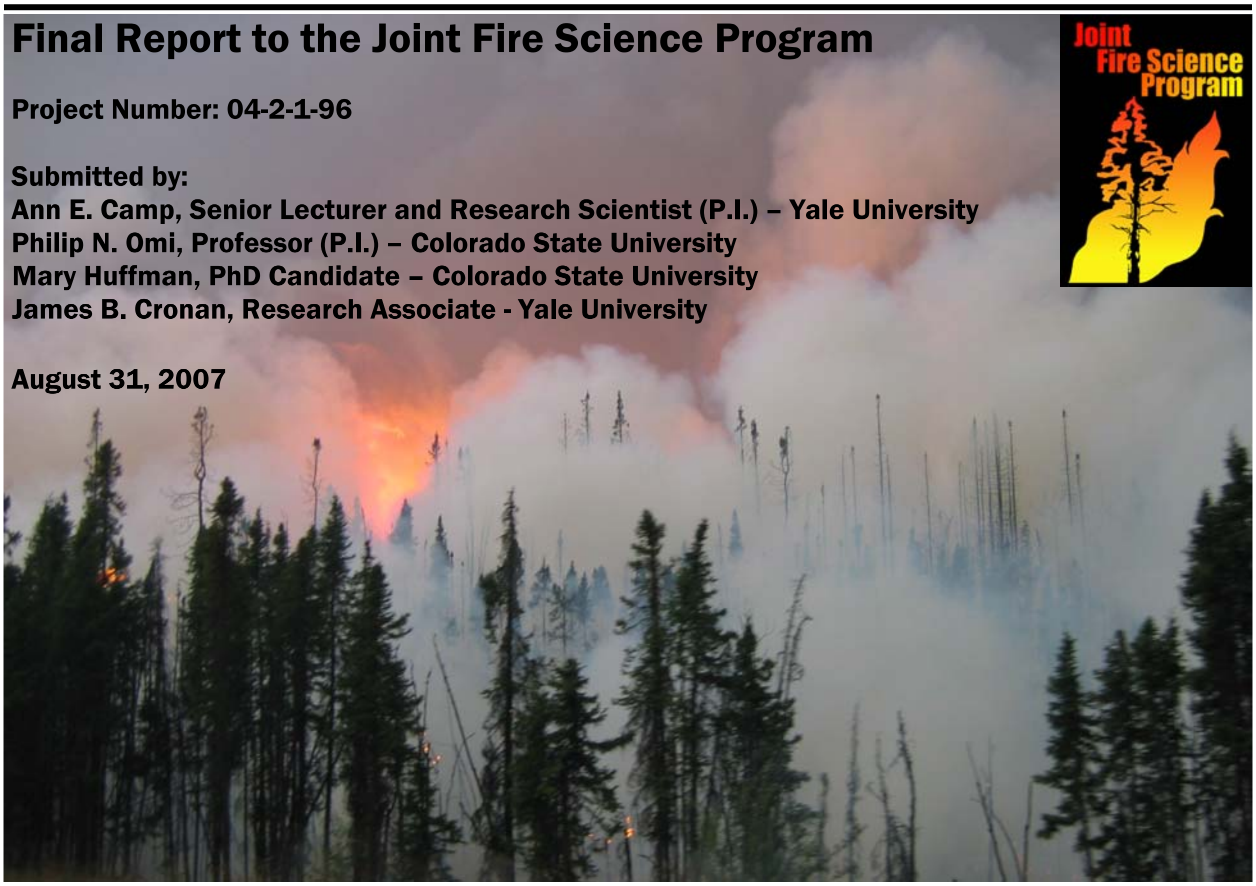
Refinement and Development of Fire Management Decision Support Models Through Field Assessment of Relationships Among Stand Characteristics, Fire Behavior and Burn Severity.

Final Report to the Joint Fire Science Program

Project Number: 04-2-1-96

Submitted by:
Ann E. Camp, Senior Lecturer and Research Scientist (P.I.) – Yale University
Philip N. Omi, Professor (P.I.) – Colorado State University
Mary Huffman, PhD Candidate – Colorado State University
James B. Cronan, Research Associate - Yale University

August 31, 2007



Colorado State University
Warner College of Natural Resources
Western Forest Fire Research Center
Fort Collins, CO 80523

Yale University
School of Forestry & Environmental Studies
205 Prospect Street
New Haven, CT 06511

Table of Contents

Part II: Field-based assessment of fire behavior prediction models in boreal forests of Alaska (Colorado State University)

Report Summary

This report consists of two parts. Part I was conducted by Yale University and investigates the relationship between stand age and fire behavior in black spruce forests of interior Alaska. Part II was conducted by Colorado State University and examines the utility of two fire behavior prediction models, BehavePlus and the Canadian Forest Fire Danger Rating System's (CFFDRS) Fire Behavior Prediction (FBP) System, in the boreal forests of Alaska. Though the subjects each part examines are different, these projects were combined into one JFSP project to eliminate redundant collection of fire behavior and stand data required for each study.

Part I: Relationship between stand age and fire behavior in upland black spruce forests of interior Alaska (Yale University)

To assess the relationship between stand age and fire behavior, fuels were assessed at 21 sites representing a chronosequence of black spruce stands ranging in age from 2 to 227 years. Based on measured fuels data and three standardized weather scenarios representing expected weather during the burn season, fire behavior models were used to predict rate of spread (*ROS*) and fire-line intensity (*FLI*) for each site. Observed fire behavior from 8 sites was used to test the accuracy of predicted *ROS*.

We found several relationships, both positive and negative, between components of the fuel complex and stand age up to about 100 years. Stands aged over 100 years did not exhibit any strong relationships between the fuels and stand age. The most prominent of these relationships is the positive correlation that black spruce canopy bulk density (*CBD*) and pleurocarpous moss loading has with stand age. Both fuel components approximate a sigmoid curve when plotted against age. Measures of *CBD* and pleurocarpous moss loading are low in stands less than 20 years old and then increase steadily before leveling off in stands older than 100 years. Other components of the fuel complex have either a declining relationship with age or have no relationship with age

For all three weather scenarios, measures of fire behavior (i.e. *ROS* and *FLI*) also generated a sigmoid response curve when plotted against stand age; the sigmoid curve begins to crest at about 50 years for both *ROS* and *FLI*. Hierarchical cluster analysis of predicted fire behavior under the three weather scenarios suggests three successional phases in the fuel complex of black spruce forests. We refer to these phases as the pioneer or stand initiation phase, the transition phase and the forested phase. The pioneer phase corresponds to stands less than 20 years old. In this phase predicted fire behavior is nearly zero regardless of weather. The transition phase includes stands between 20 and 45 years old; fire behavior is intermediate and responsive to weather. In the forested phase, corresponding to stands over 45 years old, fire behavior is extreme. Predicted *ROS* and *FLI* are many times higher than in either of the earlier phases, and sensitivity to changes in weather is highest during this phase.

Increasing *CBD* and abundance of pleurocarpous mosses on the forest floor is in large part, responsible for the positive correlation between stand age and fire behavior through the transition phase. Beyond the transition phase, black spruce *CBD* exceeds 0.10 kg m^{-3}, and pleurocarpous mosses cover exceeds 50%. These seem to be threshold conditions, beyond which, there are no relationships between predicted fire behavior and stand age. Additionally, fuel dependent changes in fire behavior in stands that exceed threshold conditions are less important from a fire hazard perspective: *ROS* varies little, and *FLI*, is primarily influenced by weather.

Part II: Field-based assessment of fire behavior prediction models in boreal forests of Alaska (Colorado State University)

Using videography to sample fire behavior on six wildland fires in black spruce forests of Interior Alaska, we found that the flame lengths and rates of spread observed on video differed from predictions by both BehavePlus3 and the Canadian Forest Fire Behavior Prediction System (p-values ranging from 0.0532 to < .0001). Scott and Burgan's fuel model TU04 used in BehavePlus3 predicted surface fire flame lengths and rates of spread with accuracy appropriate for limited use in decision support. However, TU04 and BehavePlus3 failed to adequately predict flame lengths, rates of spread or fire type for active

crown fires. Using fuel moistures gathered in the field, BehavePlus3 under-predicted crown fire flame lengths by an average of 14.5 ± 4.9 ft. This difference in flame lengths overwhelms the threshold of four feet typically used in decision support to distinguish between fires that can be addressed using hand tools and those that require additional resources (Andrews and Rothermel 1982, Albini 1976). In general, BehavePlus3 under-predicted fire type with 86 percent frequency.

Because crown fire behavior is common in the black spruce forest fuel type, and because fire practitioners rely on predictive capabilities for intense fire behavior, we view the utility of the TU04 model used in BehavePlus3 as limited and generally insufficient for decision support. While the Rothermel (1972) model was never intended to predict crown fire behavior, a computer user can operate the crown fire module in BehavePlus3 using the TU04 model. During the course of this study, Joe Scott (pers.com.) informed us that the TU04 model is mathematically derived from Norum's 1982 empirical adaptation of BEHAVE to black spruce fuels. As such, it is not currently designed to provide the active crown fire predictions that are possible to generate in BehavePlus3. To avoid invalid predictions, we respectfully recommend that the authors of BehavePlus3 block the user from connecting the TU04 fuel model with the crown fire module, or at least produce a cautionary on-screen "pop-up" notice to the user.

The C2 fuel model used with the Canadian Forest Fire Behavior Prediction System (CFFBPS) over-predicted flame lengths by an average of 10.7 ± 8.7 ft and rates of spread by an average of 14.3 ± 26.0 ft. Most of the over-prediction occurred in fires that were observed to be of the surface and torching types. CFFBPS matched the observed (video) fire type with 57.14 percent frequency. CFFBPS under-predicted fire type with 19.05 percent frequency and over-predicted fire type with 23.81 percent frequency. The empirically-derived CFFBPS needs to be further calibrated for use in Alaska's black spruce forests; however, we view the structure and function of this model as promising compared to the TU04 model.

Deliverables crosswalk table

Table 1: Deliverables produced through JFSP funding for this project.

Proposed Deliverable	Progress	Remarks
Fire and fuels database	Completed	This database will be submitted upon publication of results in refereed journal.
Flammability curve	Completed	Results presented in this report.
Electronic posting of data and project summaries.	Completed	Project data and summaries are posted on the FIREHouse website: (http://depts.washington.edu/nwfire/).
Presentation	Completed	Presentation of flammability curve. AWFCG Fire Effects Task Group Meeting. Anchorage, AK. September 28, 2006.
Presentation	Completed	Presentation of flammability curve. 2nd Fire Behavior and Fuels Conference. Destin, FL. March 29, 2007.
Refereed paper	In Progress	Present flammability curve in peer reviewed scientific journal.
Government document	In progress	Graphical presentation flammability curve and successional phases of black spruce forests
Dataset of abiotic characteristics surrounding fire events	Completed	Dataset of abiotic conditions submitted with CSU final report in Winter 2006.
Improvements to the CFFDRS C-2 fuel model and NFFL Fuel models TU01-TU05	Completed	Improvements to C-2 and TU04 models provided in CSU final report. Discussion with Alaska Fire Service indicated only TU04 model designed for AK black spruce; other models not considered further.
Electronic posting of data and project summaries	Completed	Fire behavior data posted on CSU website. Interim reports submitted electronically.
Final report and presentations of fuel model assessments and modifications	Completed	Presentation of fuel model assessment to RX310 workshop, emphasizing research methods as requested by Alaska Fire Service, Fall 2006.
Complete dataset from each research plot provided to land managers	Completed	Fire behavior dataset submitted to Alaska Fire Service with CSU final report in Winter 2006.
Value added: make fire videography available for download to researchers managers, trainers	Completed	Created and maintained website for download of videos: 2004-2006.
Value added: develop methodology for using videography to capture fire behavior observations	Completed	Developed and presented three methods to maximize video observations in rapid response wildfire settings.

Part I: Relationship between stand age and fire behavior in upland black spruce forests of interior Alaska (Yale University)

Executive Summary

The fuel complex of the upland black spruce forest type changes over time. Fire behavior models used to investigate these changes suggest that successional shifts in fuels can have a strong influence on fire behavior. To quantify the relationship between stand age and fire behavior, the fuel complex was assessed at 21 sites representing a chronosequence of black spruce stands ranging in age from 2 to 227 years. Custom fuel models developed for each site were incorporated into fire behavior prediction models and used to estimate fire behavior at each site based on three (20^{th}, 55^{th}, and 95^{th} percentile) weather scenarios selected to reflect the spectrum of burn season weather conditions typically observed in interior Alaska. Regression analysis revealed a high degree of direct correlation between predicted and observed rates of spread (*ROS*), indicating the flammability curve presented in this report closely reflects actual *ROS* under these weather conditions. Fire-line intensity (*FLI*) was also predicted but was not correlated with actual values due to the difficulty of obtaining direct measurements.

The fuel complex exhibited several temporal trends during the first 100 years of stand development. Beyond 100 years, no strong relationships between the fuel complex and stand age were observed. The most prominent of these relationships are the positive correlations among black spruce canopy bulk density (*CBD*), pleurocarpous moss loading, and stand age. Both fuel components exhibit a sigmoid curve when plotted against age. Measures of *CBD* and pleurocarpous moss loading are low in stands less than 20 years old, then increase steadily before leveling off in stands aged greater than 100 years. The Pearson's product-moment correlation coefficient indicates that black spruce *CBD* and pleurocarpous moss loading are highly correlated.

Other components of the fuel complex show an opposite relationship with age and are greatest in young stands. These include leaf litter and coarse downed woody debris (DWD). Both are highest in stands aged less than 20 years and decrease to nearly zero in stands aged over 100 years.

For all three weather scenarios, measures of fire behavior (i.e. *ROS* and *FLI*) also generated a sigmoid response curve when plotted against stand age; the sigmoid curve begins to crest at about 50 years for both *ROS* and *FLI*. Hierarchical cluster analysis of predicted fire behavior under the three weather scenarios suggests three successional phases in the fuel complex of black spruce forests. We refer to these phases as the pioneer or stand initiation phase, the transition phase and the forested phase. The pioneer phase corresponds to stands aged less than 20 years. During this phase, predicted fire behavior is nearly zero regardless of weather. The transition phase includes stands aged between 20 and 45 years; fire behavior is intermediate and responsive to weather. During the forested phase, corresponding to stands aged over 45 years, fire behavior is extreme. Predicted *ROS* and *FLI* are many times higher than in either of the earlier phases, and sensitivity to changes in weather is highest during this phase.

Increasing *CBD* and abundance of pleurocarpous mosses on the forest floor is in large part, responsible for the positive correlation between stand age and fire behavior through the transition phase. Beyond the transition phase, black spruce *CBD* exceeds 0.10 kg m^{-3}, and pleurocarpous mosses cover exceeds 50%. These seem to be threshold conditions, beyond which, there are no relationships between predicted fire behavior and stand age.

Chapter 1: Introduction

Overview

This chapter provides justification for research to identify relationships between flammability and stand age in black spruce forests of interior Alaska, reviews relevant background material and explains project objectives. The following sections are included in chapter one:

a) Project Justification
b) The Black Spruce Fuel Type
c) Fire Management in Alaska – reviews history of fire management in Alaska.
d) Fuel Mitigation – explains the importance of fuel breaks in Alaska and how resource management agencies can benefit from information on the relationship between flammability and stand age.
e) Review of Fuel Succession Research – provides context for the black spruce flammability curve research.
f) Objectives – lists the objectives for this research project.

Project Justification

Understanding the complex dynamics between wildland fire behavior and the surrounding environment is integral to the successful management of Alaska's boreal ecosystems. Federal agencies own 65% of the land in the state (Todd and Jewkes 2006) and are mandated by the Federal Wildland Fire Management Policy and Program Review (U. S. Department of the Interior/U. S. Department of Agriculture 1995) to balance protection of life and property through fuel reduction treatments and fire suppression with the often conflicting goal of promoting ecosystem health by restoring the natural process of fire. The Alaska Interagency Wildland Fire Management Plan (Alaska Wildland Fire Coordinating Group 1998) also recognizes the need for suppressing fires that threaten human life and property and the inherent value of fire in regulating natural landscapes. To reconcile these conflicting objectives, land management and fire suppression agencies have refined planning and fire suppression strategies to accommodate fires in some areas while suppressing them in others.

The duality of this management objective, established in Alaska during the 1980's, fostered more sophisticated management strategies relative to historical approaches that mandated rapid and complete suppression of all fires; the increased complexity of decisions stretch from the land management planning level to the fire suppression operations level. Implementing these new management strategies has required greater knowledge of the interactions between fire and the natural landscape in Alaska. This project addresses one of the knowledge gaps identified by an Alaska Fire Service (AFS) draft study plan proposed in 2000 (*Appendix 6*):

> Is there a relationship between flammability and stand age in black spruce (*Picea mariana*) forests of interior Alaska and, if so, when and how do regenerating forests become prone to high intensity forest fires?

Assessing the relationship between fire behavior and forest succession will help fire suppression agencies estimate how fire behavior may change as fire burns across boreal landscapes patterned with large, relatively homogeneous stands in various stages of succession and adjust suppression strategies to focus resources in stands that have the lowest potential flammability. This information will also enable managers to better assess the time utility of fuel breaks created by natural or prescribed fire. Overall, this research will add to the collective knowledge of fire behavior, fuels, and forest succession in Alaska and improve the ability of resource management agencies to meet the goals set by the Alaska Wildland Fire Coordinating Group (AWFCG).

The Black Spruce Fuel Type

This project applies to the black spruce forests (or taiga) of interior Alaska (figure 1-1); the most common and most flammable fuel type for the region. Black spruce forests occupy an estimated 44% of interior Alaska (Viereck et al. 1986), the large sub-arctic area that lies between the Brooks Range to the north and the Alaska Range to the south. Black spruce forests are also prevalent south of the Alaska Range, with extensive forests in the upper Copper River valley, the lower Susitna River valley, and on the Kenai Peninsula.

The vertically and horizontally continuous fuels in the black spruce taiga (Viereck and Schandelmeier 1980) will support high intensity crown fires (Rouse 1976, Van Wagner 1983) (figure 1-2) during periods of warm and dry weather common in summer. The forest floor is carpeted with feathermosses (pleurocarpous mosses), primarily stair-step moss (*Hylocomium splendens*) and red-stemmed feathermoss (*Pleurozium schreberi*). This nearly contiguous mat of vegetation has high loading, low bulk density, and high surface area to volume (*SAV*) ratio (Norum 1982). If dry, the high loading (often over 10 tonnes ha^{-1}) and contiguous cover help to sustain high intensity surface fires and provide a receptive fuel-bed to lightning. Low bulk density permits rapid rates of spread (*ROS*) and increases fire-line intensity (*FLI*). High *SAV* ratio promotes rapid drying of this fuel; feathermoss equilibrates to changes in relative humidity within a matter of minutes. When humidity is low, feathermoss can quickly become a flammable component of the black spruce fuel complex.

Dwarf shrub loading also contributes to *ROS* as well as fire-line intensity (*FLI*). Though loading is much less than pleurocarpous mosses, fine woody twigs and foliage with high wax content are flammable and are easily ignited. The structure of surface and canopy fuels creates a fuel complex with high vertical fuel continuity. Within the surface fuels, dwarf shrubs promote a greater linkage between the surface fuel-bed and canopy fuels (Viereck and Schandelmeier 1980, Van Wagner 1983). Additionally, the structure of canopy fuels has several properties that promote the transition from surface fire to crown fire (Van Wagner 1983). Black spruce trees often have crowns that extend nearly to the ground (Viereck and Schandelmeier 1980). The low canopy base height (*CBH*) and high canopy bulk density (*CBD*) enables surface fires to easily initiate crown fires (Viereck and Schandelmeier 1980, Van Wagner 1983, Bourgeau-Chavez et al. 2000).

Figure 1-1: Typical mature black spruce forest found throughout interior Alaska.

The low nutrient availability induced by permafrost is a limiting factor on growth of black spruce (Viereck and Johnston 1990). As a consequence trees retain living needles for several years to increase photosynthetic return (Hom and Oechel 1983). To protect these needles against herbivory, black spruce accumulates resins, (Bryant and Kuropat 1980) which may increase the flammability of the foliage.

The high flammability of the black spruce fuel complex is exacerbated by summer weather conditions in interior Alaska. Near constant daylight hours reduce the effect of nighttime recovery periods. Thus, the burn period is longer. There are also few natural barriers to fire. In contrast to the rest of the state, interior Alaska has little topographic relief; the landscape consists of gently rolling hills and wide flat river valleys. Additionally, relatively homogenous forests cover large contiguous areas. Consequently, most of the area burned in interior Alaska is consumed by large fires that often burn tens of thousands of hectares (Kasischke et al. 2002, DeWilde and Chapin 2006).

Fire Management in Alaska

Large, high intensity fires burn over a largely un-roaded and inaccessible landscape and poses a difficult challenge to fire management organizations. The situation is made more problematic by the depth of soil organic matter. The moss layer carpeting the forest floor is often over one third of a meter deep, making hand-dug fire-lines (a common strategy employed by firefighters working in inaccessible terrain throughout the rest of the United States) impractical.

Figure 1-2: High intensity crown fires are common in upland black spruce forests.

Prior to 1982, when the Alaska Interagency Fire Management Council (AIFMC) was tasked with drafting policy that promotes natural fire regimes, wildfire policy in Alaska followed what was practiced in the rest of the United States. All fires were considered undesirable, and aggressive action was taken to extinguish fires as quickly as possible given available resources. Large fire size, difficulty establishing fire control lines, and an inaccessible landscape made fire suppression in interior Alaska an expensive undertaking. Costs of fire suppression versus its benefits were compounded by the size of the state, its small population, and the low value of timber resources. Throughout the 1970s, as fire suppression agencies in the state were struggling with the economic hardships of fighting fire, land managers were beginning to realize the ecological benefits of allowing fires to burn (Todd and Jewkes 2006). For both economic and ecological reasons, suppressing all fires in Alaska was not practical. The state of Alaska was forced to rethink its wildland fire policy. This paradigm shift was incorporated into the new fire management plans developed by the AIFMC during the 1980s (Todd and Jewkes 2006).

By 1988, fire management plans for 13 fire management regions within the state were completed. The new policy took an economically and ecologically balanced approach to wildland fire management. Lands are categorized into four fire management options: “limited”, “modified”, “full”, and “critical”. Each option reflects the relative value of the property to which they are assigned. Inhabited areas receive the highest priority for fire suppression and are managed under the “critical” option, meaning all fires are suppressed. Remote, uninhabited areas with no resources sensitive to fires are designated as “limited”. Most of the land in Alaska falls under the “limited” option and fires in these areas are generally allowed to burn, though they are monitored regularly to assess threats to sensitive resources. The other two options reflect the gradient that often exists between cities and remote wilderness and allow for suppression of fires in low value lands near inhabited areas or the suppression of fires in proximity to uninhabited structures (Alaska Wildland Fire Coordinating Group 1998).

The current fire management policy in Alaska has not decreased the importance of fire management agencies in Alaska but rather, re-focused suppression efforts toward the most valuable areas of the state. Between 1990 and 2000 the population of Alaskans living in the wildland-urban interface (WUI), defined as location where developed land meets or intermixes with wildland fuels (U. S. Department of the Interior/U. S. Department of Agriculture 2001), grew at an annual rate of 2.5% from 150,000 to 192,400 people (Alaska Department of Natural Resources 2001), yet the percentage of lands classified as "limited" increased from 47% in 1993 to 66% in 1998 (Todd and Jewkes 2006). These trends may reflect a greater ability of fire suppression agencies to manage wildfires rather than suppressing them.

Fuel Mitigation

Existing fuel breaks around inhabited areas and other valued resources located in vulnerable positions at the front of large high intensity fires can aid in suppression or diversion of forest fires. Three types of fuel-breaks are commonly used in the Alaska black spruce fuel type; windrows, shear-blade cuts, and shaded fuel-breaks. Windrows and shear-blade cuts are created by bulldozers that completely remove the forest overstory; in the former, vegetation is piled in rows while in the latter it is compacted by the bulldozer. Shaded fuel-breaks are created by thinning and removing a significant percentage of the overstory and removing ladder fuels. This presumably mitigates fire behavior by depriving crown fires of a continuous canopy and eliminating the vertical connection between surface and canopy fuels. Windrows and shear-blade fuel breaks are far more destructive to the forest floor than shaded fuel breaks as the insulating layer of organic material is severely disturbed, exposing the underlying permafrost. These methods are ecologically and aesthetically undesirable. Despite these drawbacks, windrows and shear-blade cuts are assumed to effectively mitigate fire behavior by compressing burnable biomass. The efficacy of shaded fuel breaks for reducing fire behavior is not well understood. Predictive modeling suggests they will mitigate crown fire behavior, but also suggests that overall, fire behavior, as measured by *ROS*, *FLI*, and flame length, will increase, primarily due to improved wind penetration into the understory which increases mid-flame windspeeds (Theisen 2003).

Old burn scars are another type of fuel break. Fire managers have long relied on the presence of old burns to mitigate fire behavior and prescribed fires in Alaska often include fuels mitigation as an objective. However, it is not known how long regenerating stands function as effective fuel breaks. No research documents how temporal changes in stand structure and composition relate to increasing flammability. The growing population of Alaska has greatly enlarged the WUI, increasing the need for long term planning and evaluation of fuel hazards. If burn scars can be shown to provide long term fire behavior mitigation, their creation via prescribed fires may be a preferable method of creating buffers around inhabited areas and other sensitive lands. The black spruce forests of Alaska are adapted to fire; using fire to create fuel breaks is less ecologically damaging than windrows or shear-blade cuts and burn scars are likely to provide greater protection over longer timeframes than shaded fuel breaks.

Review of Fuel Succession Research

Few studies have investigated the relationship between stand age and fire behavior. One of the first was conducted in the coniferous forests along the crest of the Cascades in Washington State (Fahnestock 1976). A second study was undertaken in the Douglas-fir forests of Olympic National Park in northwestern Washington State (Agee and Huff 1987). Both concluded that fire behavior in previously burned stands is highest in the decades immediately following fire due to inputs from fire-killed woody vegetation. As this wood decays, fire behavior decreases over time until reaching a low point, then gradually increases as competition-induced tree mortality in the developing stand creates additional inputs of dead and downed woody fuels. Fahnestock (1976) used fuel keys to predict measures of fire behavior including crowning potential, *ROS*, and resistance to control. Agee and Huff (1987) used the BEHAVE program to predict *ROS* and *FLI* of surface fuels. A third study in Yellowstone National Park in northwestern Wyoming concluded that fire behavior would increase with time since fire, peaking at about 400 years (Romme 1982). Romme's conclusion was based on fuel loading, and continuity of the canopy. Though Romme also reported briefly high total loading of fuels in young stands, he reasoned that fire behavior would initially be low, because fine surface and canopy fuels were absent. These studies highlight differences in fuel succession, and hence flammability curves, among different forest types, reinforcing the need for site specific research to determine the relationship between fire behavior and fuels succession

Two studies have examined the relationship between stand age and flammability for forests in northern latitudes (Bessie and Johnson 1995, Schimmel and Granstrom 1997); both conclude that fire behavior is lowest in stands aged < 50 years, and exhibits no relationship with age in stands aged > 50 years. Bessie and Johnson (1995) established 47 sites in sub-alpine conifer forests in central Alberta. Predicted fire behavior indices for 3 stands between 20 and 25 years were significantly lower relative to older stands (aged > 50 years). In boreal Scots pine (*Pinus sylvestris*) forests of Sweden, Schimmel and Grandstrom (1997) modeled fire behavior at 23 sites ranging in age from 1 to 350 years. They reported that pleurocarpous mosses recovered slowly during the first 20 years following fire, rapidly colonized the forest floor during the next 20 to 30 years, and by 50 years, became the dominant forest floor cover. In stands > 50 years, loading and percent cover of pleurocarpous mosses remained steady. Fire modeling of surface fuels revealed that predicted fire behavior had a similar relationship to age as loading and percent cover of pleurocarpous mosses. Schimmel and Granstrom (1997) argued that the pleurocarpous mosses increased predicted fire behavior because they are a readily available quick drying fuel that is increasingly continuous with stand age. Fire behavior modeling was limited to surface fuels because the fire regime of Scots pine forests is typified by surface fires.

Objectives

The four objectives for this study are designed to address the knowledge gap listed in the *Project Justification* section of this chapter.

1. Determine successional phases for fuels in upland black spruce and describe how elements of the fuel complex change over time.
2. Quantify the relationship between fire behavior and stand age.
3. Based on fire behavior predictions, describe the level of significance each fuel component has on fire behavior.
4. Assess the utility of the flammability curve by examining the relationship between predicted and observed fire behavior.

Chapter 2: Methods

Overview

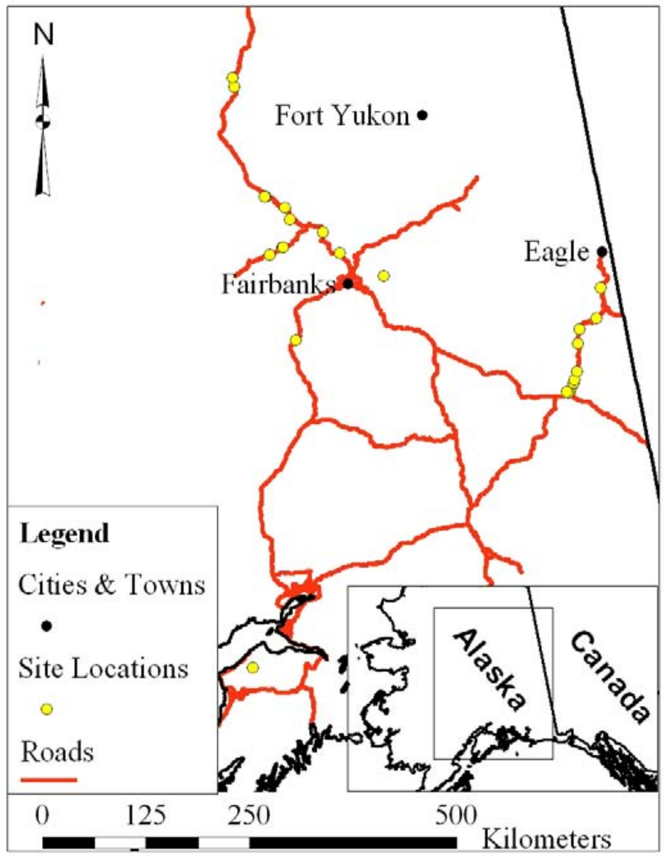
The flammability at 21 sites was modeled by entering fuel properties into a linked fire behavior prediction model for three weather scenarios. Sites represented a chronosequence of upland black spruce forest stands ranging in age from 2 to 227 years. Fuels and age data were collected at each site. Fire behavior modeling and analysis are discussed in *Chapter 3*. Methods for collecting fuels data are discussed in the sections below in the following order:

a) Study Sites – describes general biotic and environmental conditions for the study area.
b) Site Definitions – describes the two types of sites. This is important because sampling strategy at each type of site was different.
c) Fuel inventory – describes how fuels were sampled.
d) Site Selection Criteria – lists criteria used to chose sites.
e) Disturbance History – explains how sites were located.
f) Fire History Data Collection – explains how stand age was determined.

Study Sites

Research sites were established at various locations across Alaska representative of either closed or open black spruce needleleaf forest types (Viereck et al. 1992) in various phases of succession. Site locations are depicted in figure 2-1. Site descriptions below include locations within published ecoregions (Nowacki et al. 2001). Of the 24 original sites (three sites were later removed from analysis; see the *Disturbance History* section of this chapter for more information), 23 sites are classified as intermontane boreal forest. The 24th site is within the Cook Inlet Basin ecoregion on the Kenai Peninsula and classified as Alaska Range transition forest. Within the intermontane boreal forest, 12 sites are in the Yukon Tanana Uplands ecoregion, 10 sites are in the Ray Mountains ecoregion, and one site is in the Tanana-Kuskokwim Lowlands ecoregion. Eight ecoregions within the intermontane boreal forest of Alaska are not represented by this study. Sites were selected subjectively based on accessibility by road and other selection factors explained in the *Site Selection Criteria* section of this chapter.

Figure 2-1: Location of sample sites.



The Ray Mountains and Yukon Tanana uplands are part of the interior Alaska highlands; a broad region of gently sloped mountains between the Tanana and Yukon River valleys. Elevations generally range from 300 to 1050 meters but higher peaks reach 1800 meters (Rieger et al. 1973). Topography of the Tanana-Kuskokwim lowlands ecoregion is fairly flat and the ecoregions is part of a broad alluvial plain that slopes northward from the Alaska Range. The study sites located within interior Alaska are between 150 and 900 meters above sea level. Geology is characterized by bedrock consisting of micaceous schist. During the last glacial period much of the area was unglaciated; the climate was dry and the terrain largely devoid of vegetation. Strong winds moved exposed river sediment into large dunes and as a result, the bedrock near large floodplains is covered in a layer of silty loess. In gently sloped areas, eroding sediments from the mountains has covered the underlying bedrock in a layer of loamy outwash. Soils in interior Alaska are typically loamy Histic Pergelic Cryaquepts, though loamy Aeric Cryaquepts and loamy Histic Cryaquepts are commonly found on sites in low lying terrain (Rieger et al. 1973).

The Kenai Peninsula site, located in the western lowlands region of the peninsula, is underlain by thin beds of lignite and silty and sandy sediments. The area was heavily glaciated during the last glacial period and underlying materials are now buried beneath a layer of glacial outwash which is in turn buried under a mantle of wind deposited loess (Rieger et al. 1962). Soils at this site are loamy Cryaquepts that are found at scattered locations on the west side of the peninsula (Rieger et al. 1973).

With the exception of the Kenai site (which permafrost is absent) permafrost is discontinuous and occurred above the level of the mineral soil at 37% of the sites. The organic mat overlying the mineral soil averaged 330 mm.

All sites except the Kenai Peninsula site have a strong continental climate characterized by large diurnal and seasonal temperature fluctuations, low relative humidity, and low precipitation with about

35% falling as snow (Slaughter and Viereck 1986). In June and early July warm air contributes to the development of thunderstorms that often produce little or no rain. Dry lightning from these storms is a common source of wildfire ignitions. Mean temperature for sites in interior Alaska is -23.4°C in January and 14.6°C in July. The mean annual precipitation is 348 mm. The wettest month is August and the driest month is April (U. S. Department of Commerce 1973).

The site on the Kenai Peninsula is located within a rain shadow that extends northwest of the Kenai Mountains. This site is relatively isolated from maritime influences such that the climate approximates a continental one, yet precipitation is higher and temperatures are warmer than interior Alaska. The Kenai Peninsula has less convective activity during the summertime months and as a result the occurrence of thunderstorms is lower than in the interior. The mean temperature is -11°C in January and 13.4°C in July. Mean annual precipitation is 551 mm; the wettest month is September and the driest month is April (U. S. Department of Commerce 1973).

Site Definitions

Two basic types of sites were established in order to meet objectives outlined for the development of the flammability curve: **fuel inventory sites** and **fire event sites**:

1. **Fuel inventory sites**. These sites were established to collect data needed to develop a flammability curve for the black spruce fuel type. At each site, fuel complex data were collected and used to create custom fuel models. Stand age data, including fire scars were also collected to assess fire history. Figure 2-2 depicts the layout for each plot. Generally, six plots were established at each site, although the number ranged from three to nine. Plots were systematically located within the sampling area. Additional data collected at each plot included plot photos, hemispherical canopy photos, and geographic coordinates.
2. **Fire event sites**. These sites were also established to develop the flammability curve, but also served a second function; the comparison of predicted and observed fire behavior. To accomplish the second function these sites were designed to measure all of the fuels data collected in the fuel inventory sites before being burned. As the site was burning fire behavior and weather data was collected. The combination of fuels and weather data allowed fire behavior to be modeled and then compared with the observed fire behavior data. Figure 2-3 depicts the layout for each plot. The number of plots established at each site varied due to time constraints placed on the fuel inventory by nearby wildland fires. The range of plot numbers was 3 – 9. Plots were systematically located within the sampling area.

Figure 2-2: Fuel inventory site – plot diagram

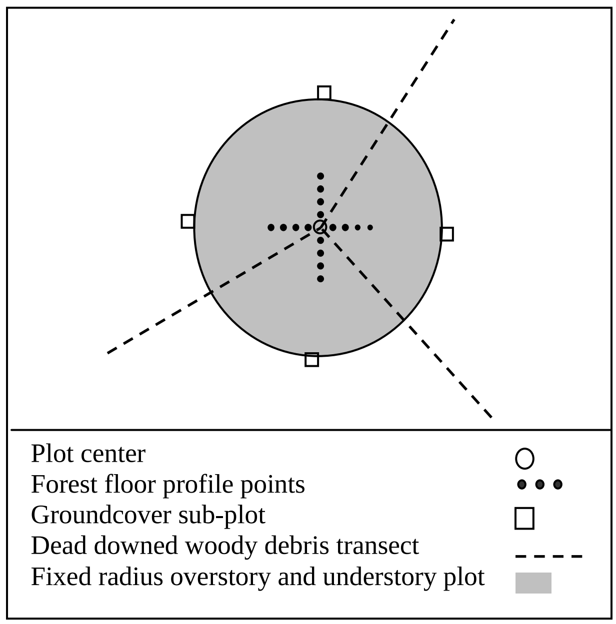
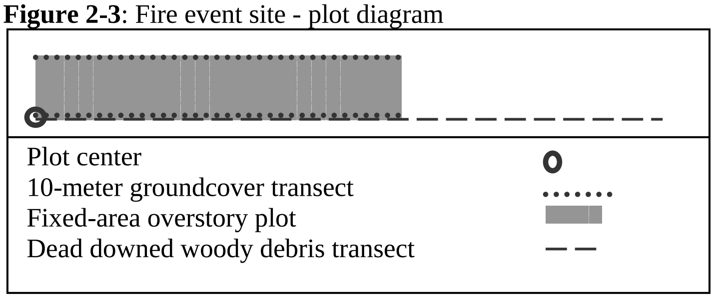


Figure 2-3: Fire event site - plot diagram



Additional data collected at each plot included pre and post fire plot photos, and geographic coordinates.

Fuel Inventory

Vegetation sampling differed slightly between the fuel inventory sites and the fire event sites. Fire event sites were generally established adjacent to active wildfires during periods of low fire activity (late evening through early morning) with the expectation that, as conditions became warmer and drier, fire behavior would intensify and the sampled sites would burn over. Because field crews were working adjacent to actively burning fires that could sometimes cut sampling time short, some measurements collected at fuel inventory sites were omitted. These included seedling counts and sapling counts.

At fire event sites, overstory data were collected from fixed-area rectangular plots and at fuel inventory sites, overstory data were collected from fixed radius circular plots. All standing live and dead trees over 1.37 meters (4.5 feet) tall were included in overstory measurements. Diameter at breast height (DBH) was measured on trees ≥ 3 cm DBH; on trees < 3 cm DBH, diameter was measured at 15cm above the forest floor. The two diameter measurements were collected to satisfy the input requirements for two separate allometric equations intended to predict available canopy biomass (Roussopoulos and Loomis 1979, Singh 1984). Post sampling, a more suitable allometric equation was found for conifers (Stocks 1980) and replaced the two equations originally intended to predict available canopy fuels. Stocks' equation requires DBH as an input. To satisfy this requirement diameters taken at 15 cm above the forest floor were converted to DBH using a regression equation derived by measuring 378 black spruce trees at DBH and 15 cm above the forest floor: $y = 0.7837x – 0.1084$ ($R^2 = 0.98$).

Tree height data were collected using a height pole and measured to the nearest ¼ meter. Height measurements included total height, height to live fuels, and height to dead fuels. "Height to ladder fuels" and "height to live crown" definitions (Ottmar and Vihnanek 1998) were used to assess the vertical heights to dead and live crown, respectively. Additionally, if trees were leaning or had suspended broken tops, separate length data (length of bole, dead crown, and live crown) were collected to account for lean and hanging tops and provide a more accurate assessment of canopy biomass.

CBH was calculated by measuring the average height to the ladder fuels at each site. Height to ladder fuels were used instead of height to live crown because the high concentration of fine dead twigs and arboreal lichens in dead canopies of boreal spruce are known to act as fuel ladders (Van Wagner 1992).

Allometric equations used for black spruce (Stocks 1980) were used to calculate canopy mass for other conifers as well, including white spruce (*Picea glauca)* and tamarack (*Larix laricina)*. Species specific allometric equations were not used for white spruce, and tamarack because existing allometric equations were either not specific to the boreal region, or not able to calculate the mass of fine branch-wood (< 0.64 cm diameter) and foliage, the primary canopy fuel consumed during crown fires (Stocks et al 2004). The Stocks (1980) equation for black spruce is reasonable for white spruce and tamarack, because in forests dominated by black spruce both species have growth forms similar to black spruce. Additionally, only a small percentage of the overall number of trees sampled were tamarack (< 0.1%) or white spruce (3.4%). Species specific allometric equations were used for hardwoods including paper birch (*Betula papyrifera*) (Roussopoulos and Loomis 1979, Singh 1982) and trembling aspen (*Populus tremuloides*) (Roussopoulos and Loomis 1979, Singh 1984). *CBD* was calculated using methods for non-uniform stands (Sando and Wick 1972, Reinhardt and Crookston 2003); this requires calculating the running average across a vertical canopy profile and selecting the canopy increment with the highest value. We made one adjustment to this method; the 3.7 meter running mean based on 0.3 meter canopy increments used by Reinhardt and Crookson (2003) was changed to a 2 meter running mean based on 0.25 meter canopy increments. This adjustment was made to reflect the shorter height of the overstory trees relative to the overstory the Reinhardt and Crookston (2003) protocol is based on. Crown mass of fine fuels < 0.64 cm diameter (W_{ff}), *CBD*, and *CBH* are custom fuel model inputs and are used to calculate crown fire potential, *ROS*, and *FLI*.

Understory data were collected at fuel inventory sites but not at the fire event sites because of the time constraints imposed by collecting data at the front of an active fire. Understory vegetation included seedlings (tree species < 0.5 meters tall) and saplings (tree species 0.5 – 1.37 meters tall). Individuals were counted in fix-radius plots. Species and live/dead status were noted for each individual for seedlings and saplings. Total height was also measured for saplings. These measurements were useful for further characterizing fuel complexes but were not used to assess flammability.

Tall shrubs (defined as shrubs over 0.3 cm in diameter at 15 cm) were tallied in fixed-area plots in both fire event and fire inventory sites. Tallies included live /dead status and species. This information was used to assess the fuel complex but was not used to determine flammability.

At fuel inventory sites, the groundcover layer, including dwarf shrubs (shrubs less than 0.5 meters in height), herbaceous vegetation, and seedlings, were inventoried in four 0.25 meter^2 sub-plots systematically arranged around each plot center. At each sub-plot, ocular estimation was used to estimate percent cover and average depth by species. One of the four sub-plots was randomly selected and destructively sampled to provide a direct biomass estimate. Samples from these sub-plots were sorted by species and time-lag fuel classes; then dried in ovens at 100˚C for 48 hours. Oven dry mass was measured using an electronic scale. At fire event sites, the groundcover layer was characterized by systematically installing two 10 meter transects adjacent to plot center. Absolute cover and depth were measured at 42 points spaced 0.5 meters apart along these transects. Biomass samples were collected along with groundcover point intercept data at two fire event sites. For both site types, we used linear regression analysis to predict fuel loading by species, time-lag and live/dead status from the estimated percent cover or point intercept data. Loading was classified into 4 components that were input into the custom fuel models: live herbaceous, live woody, dead 1-hr and dead 10-hr fuels. The dead fuel fractions from biomass estimates at fire event and fuel inventory sites were combined with the appropriate dead downed woody debris time-lag fuel (described below). Loading data was incorporated into custom fuel models and input into BehavePlus3 to assess flammability.

Dead downed woody debris (DWD) fuel loads were measured using the line intersect method (Van Wagner 1964, Brown 1974, Van Wagner 1976). For fuel inventory sites, three 10 meter transects were established at each plot along randomly selected azimuths radiating from plot centers. Large diameter fuels (i.e. 1000-hour and 100-hour DWD fuels) were measured along the entire length of each transect, 10-hour DWD fuels were measured along the last three meters, and 1-hour DWD fuels were measured along the final meter of each transect. For fire event sites, one 18 meter transect was established at each plot; large diameter DWD fuels were inventoried along the entire transect length, 10-hour DWD fuels were measured along the last 3 meters, and 1-hour DWD fuels were inventoried along the last 2 meters. Specific gravity and mean square diameter for each time-lag class were based on published values (Brown 1974, Nalder et al. 1997, Forest Products Laboratory 1999) (*Appendix 1*, table A1-1). DWD loading is reported for 4 time-lag classes: 1-hr, 10-hr, 100-hr, and 1000-hr. The 1-hr and 10-hr, and 100-hr DWD fuels were included in the custom fuel models. These measurements were subsequently used to evaluate flammability through BehavePlus3. The 1000-hr DWD fuel component was not included in the custom fuel models because the surface fire behavior prediction model does not account for contribution of 1000-hr fuels. The inability of BehavePlus3 to model 1000-hr time-lag dead fuels is discussed further in the *Discussion* section of *Chapter 5*.

Forest floor data for the fire event sites were obtained from the Pacific Wildland Fire Sciences Laboratory (PWFSL). PWFSL had collected the data for a separate consumption study (Ottmar 2003). PWFSL's plots were located among our vegetation plots and represented conditions at the fire event sites. At fuel inventory sites, forest floor data were collected by systematically establishing 16 points (four in each cardinal direction) around the plot center. Each point was spaced 0.5 meter apart. The forest floor profile was measured at each point. For all sites the forest floor profile data and known bulk density values were used to calculate forest floor biomass (*Appendix 1*, table A1-2).

PWFSL and Yale University used the same definitions to delineate layers of the forest floor:

a) Live surface material: the live portion of mosses and lichens.

b) Dead surface material: the dead portion of live mosses and lichens that shows no signs of decomposition. Dead surface material may also include the litter layer (e.g. needle or leaf litter).

c) Duff: partially decomposed organic material.

d) Mineral soil: material is primarily non-organic.

The surface material (live and dead) layer of the forest floor was classified as a 1-hr dead fuel and combined with all other dead 1-hr fuels for the custom fuel models and input into BehavePlus3. Duff material was classified as a 1000-hr fuel and was excluded from the custom fuel model for the same reason as 1000-hr DWD fuels. To increase the accuracy of fire behavior analysis, loading of the forest floor component of the 1-hr dead fuel class was divided into two groups based on *SAV* ratios. This process is described further in the *Model Inputs* section in *Chapter 3*.

Site Selection Criteria

Site selection criteria were instituted to limit the number of conditions affecting forest succession. Fuel inventory and fire event sites were selected based on conformance to the following criteria listed below.

1. Sites are representative of the upland black spruce fuel type. Upland black spruce is characterized by an overstory dominated by black spruce and a forest floor with a high cover of pleurocarpous mosses. Though early seral phases have neither property there are several indicators that can reliably be used to assess future forest composition.
2. Sites have been regenerated from preexisting stands of black spruce destroyed by fire. This selection criterion was included because fire is the primary disturbance affecting black spruce forests (Van Cleve 1986, Johnson 1992) and we wanted to avoid sites where forest development may have been influenced by other disturbances.
3. Minimize slope. Slope and aspect can influence stand composition (Van Cleve et al. 1983). Relatively flat sites were chosen to eliminate possible effects of slope on stand development.
4. Neutral topographic position. Sites were not considered if they were located on steep ridges, or at the bottom of deep valleys. These positions can influence stand composition (Van Cleve et al. 1983).
5. Sites are at low to mid elevations. Black spruce forests near the timberline may have significantly different stand structure relative to black spruce growing at lower elevations (Foote 1983).
6. Avoid sites impacted by anthropogenic disturbance. Human activities in Alaska, especially over the last 100 years have dramatically impacted natural vegetation communities. The most common human disturbance has been surface mining which historically occurred along valley bottoms throughout the interior during the early half of the 20th century.

Disturbance History

The most recent type of stand replacing disturbance to impact each site was determined from two sources of evidence; fire perimeter data from fire management files and physical evidence of past fires. The Bureau of Land Management – AFS maintains digitized historical fire records dating to 1950 for fires > 400 ha known as the large fire database (LFDB). Records from the LFDB as well as archived paper fire files dating back to 1940 were used to locate the general area of sites that have burned since 1940; physical evidence of past fires was used to identify the exact location of stands described in fire records. For sites that burned prior to 1940, only the physical evidence of fire was used to determine disturbance history. Standing fire-killed trees provide the best evidence of past wildfires. Fire-killed trees remain standing for many decades and are found in forests over 100 years old. Fire-killed trees are often numerous and are distinguishable from other dead trees because charred wood is nearly always present and trees have no bark and few if any branches. As stand age increases, so to does the difficulty of determining the past history of disturbance. Forests older than 110 years generally did not contain standing fire-killed trees, making it difficult to determine the history of disturbance. Other indicators used to determine whether or not stands were impacted by fire included fire scars and distinct age cohorts that signal a stand replacing fire. There were no indicators that fire was the most recent stand replacing disturbance at three of the 24 sites considered. However, based on existing knowledge of fire regimes in black spruce forests, it is likely that these sites were regenerated from fires. This assumption is based on short term (Yarie 1981, De Volder 1999, Fastie et al. 2002) and long term (Lynch et al. 2004) data indicating that the primary natural disturbance affecting black spruce forests is fire.

Table 2-1: Site properties.

Site	Stand age (years)	Slope (deg.)	Aspect (deg.)	Elevation (meters)	Evidence of past fire?	Basal area ($m^2 \cdot ha^{-2}$)	Basal area: Black spruce (%)	Basal area: White spruce (%)	Basal area: Deciduous (%)	Basal area: Dead (%)	Pleurocarpous mosses (% cover)
31	2	2	225	491	Yes	11.3	0	0	0	100	0
25	12	1	180	358	Yes	0.8	0	0	5	95	1
29	22	0	-	401	Yes	1.8	1	0	0	98	0
32	34	8	270	458	Yes	0.5	98	0	0	2	1
26	38	1	90	284	Yes	6.1	16	0	28	56	22
27	38	0	-	480	Yes	1.3	0	0	19	81	1
34	39	1	113	716	Yes	4.6	13	0	6	82	35
30	46	0	-	192	Yes	7.2	59	0	38	2	32
2*	57	0	-	137	Yes	16.8	91	2	1	6	74
17	72	0	-	193	Yes	11.1	73	8	0	19	78
28	81	0	-	456	Yes	10.9	95	0	3	2	53
23*	93	0	-	292	No	7.9	87	10	0	3	48
20	97	2	360	435	Yes	13.5	89	0	0	11	56
10	101	1	360	666	Yes	19.3	81	6	8	6	78
22	104	1	203	482	Yes	14.5	98	0	0	2	79
33	104	0	-	363	Yes	19.3	90	0	1	9	91
14	105	5	225	584	Yes	15.9	63	20	4	14	64
9	112	1	293	814	Yes	7.3	95	0	0	5	71
11	114	6	203	664	Yes	27.5	93	4	1	2	91
3	122	15	360	651	No	11.9	79	0	1	15	73
4	139	2	90	744	Yes	9.4	90	0	0	10	88
13*	169	22	270	543	Yes	31.3	8	73	4	20	92
5	184	2	23	860	Yes	22.8	91	0	0	9	82
7	227	5	68	904	No	18	91	3	0	6	94

*Sites excluded from flammability analysis

Three sites were excluded from the flammability curve analysis because they did not represent upland black spruce forests of interior Alaska. Site 2 was on the Kenai Peninsula; although the forest closely resembled black spruce forests north of the Alaska Range, many of the fuel properties were statistical outliers. For its age, the loading of pleurocarpous mosses and *CBD* were high compared to stands located in the interior, probably as a result of the warmer and wetter climate at this site. Site 23, the most northerly site, near the northern limit of trees, south of the Brooks Range, was also removed. Fuel properties at this site were lower than at other sites of similar age. This site was near a sizeable river and may have also experienced flooding as a major form of disturbance. Site 13, located on the Taylor Highway, between Tok and Chicken, Alaska was removed because white spruce was the dominant component of the overstory.

Site characteristics (including stand age, elevation, aspect, slope, stand characteristics, and pleurocarpous moss cover) are listed in table 2-1.

Fire History Data Collection

Fire history data were collected to determine stand age and fire history. Approximately 10 to 25 basal cross sections were collected from trees at each site. The number of samples collected increased with the perceived complexity of age distribution within the stand. At least eight basal cross section samples were taken from trees that appeared to have regenerated since the last stand replacing fire. Additional samples were collected from fire killed snags, remnant trees, (i.e. those trees that appeared to have survived the most recent stand replacing disturbance), and understory trees. Understory trees were not assumed to represent a different age class since they are often the product of layering (Foote 1983). Samples were taken from the general area surrounding, but not within the vegetation plots at each site. Cross sections were collected as close to the root crown as possible. If a cross section was collected above the root crown, the distance between the root crown and the bottom of the sample was measured. Additional sample information included tree species, canopy class position, and bole length.

Basal cross sections were prepared by sanding with increasingly finer grades of sandpaper until all growth rings could be clearly discerned under a dissecting microscope. Rings were then counted from the pith to the outermost ring along one path. The count path was chosen based on the ability to identify all individual rings. This can be particularly difficult for sites in interior Alaska where secondary growth is especially slow. Tree rings, especially toward the outer edge of the tree, often appear to merge together and care must be taken to identify the region of the cross section where rings are distinct. For quality control on initial ring counts, secondary paths were added to 35% of the samples. Few count errors were encountered and were limited to discrepancies of < 5 years.

Each site was searched for fire scarred trees, and if found basal cross sections were collected. Fire scar samples were analyzed using at least two count paths. Fire scar samples were not cross dated but fire dates from each of the count paths were never more than two years apart. If the scar year corresponded to a pulse in regeneration, the scar was assumed to be a fire scar from a stand replacing fire and that date was used to calculate the age of the stand. If there was no regeneration associated with the scar, its cause was deemed to be unknown; many minor or localized disturbances (e.g. frost damage and animal injury) can create tree scars. The assumption that fire scars and a corresponding age cohort indicate the occurrence of a stand replacing fire is supported by information from nine sites where AFS Large Fire Database records matched fire dates derived from tree scars and stand age data. At each of these sites, age class data showed a regeneration response to a known fire event. The same response to fire has been substantiated by other fire history studies conducted in Alaska (De Volder 1999).

By synthesizing stand age information including age class analysis, fire scar data, and known fire dates listed in fire management files, we assigned a stand age to each site. Age class data were used to derive a first approximation of stand age. Age class data can only be used as a general estimate for stand initiation because recruitment following fire occurs over a period of up to several decades in black spruce forests (De Volder 1999, Fastie et al. 2002). To further refine stand age estimates, age class data was matched with LFDB information and/or fire scar data. This technique allowed us to determine the exact year of the fire disturbance for 15 of the 24 sampling sites.

At 9 sites, only age class data were available. To assign a calendar year to the fires that presumably generated these stands a regression equation was developed to predict the relationship between the oldest trees associated with the age class and the fire date. This regression was based on data from the 15 sites that had known fire years and age class data. The relationship is based on an observed pattern where distance, in years, between the measured age of the regeneration and the establishment date increases over time. This is likely because of the increased difficulty of collecting samples from the root collar as the moss layer rises over time.

For each of the 9 sites, the leading edge of the post-fire recruitment was identified as the oldest sample in the cohort separated from the next oldest sample by no more than 5 years. Any sample separated by more than 5 years was considered to be an outlier. A logarithmic regression with an R^2 of 0.81 was selected to predict the fire year for the 9 stands that did not have associated fire scar or management file data. Of the 15 stands used to develop this regression, differences between predicted age and the actual age did not exceed 7 years. This discrepancy is acceptable given that the regression was used to predict stand age for 9 stands, each > 90 years old and variations in age up to 7 years would not have affected the results of this research.

Chapter 3: Fire Behavior Predictions

Overview

Fire behavior was modeled at 21 of the 24 original sites (3 sites were omitted from this analysis; *Chapter 2, Disturbance History*). We used models that are components of BehavePlus3 (Burgan and Rothermel 1984, Andrews et al. 2005), the Fire Behavior Prediction (FBP) System (Van Wagner et al. 1992), and an independent set of passive and active crown fire behavior models (Cruz et al. 2005).

These combined models are hereafter referred to as “the linked model”. The linked model is capable of predicting *ROS* and *FLI* for a continuous range of fuel and weather conditions. The use of Van Wagner’s (1977) crown fire initiation and spread model to join surface and crown fire models is commonly employed and the arrangement is used in both BehavePlus3 (Scott and Reinhardt 2001) and the FBP System (Van Wagner et al. 1992). Byram’s fire-line intensity model, used to predict *FLI* of crown fires is currently a component of the FBP System (Van Wagner et al. 1992).

This chapter explains the reasons for selecting the models used in the linked model. The sections in this chapter review the following subjects:

a) Fire Behavior Prediction Programs – this section looks at two of the most widely used fire behavior prediction programs in Canada and the U. S. that are capable of modeling crown fires and explains why they were not used in this analysis.
b) Linked Model – this section provides an overview of the models used for the flammability curve analysis.
c) Model Inputs – this section reviews how fuel and weather variables were input into the linked model.
d) Additional Analysis – lists analysis methods used to analyze flammability curve.
e) Observed vs. Predicted Fire Behavior Regression – explains how observed fire behavior data were paired with predicted fire behavior data.

Fire Behavior Prediction Programs

Two programs commonly used to predict fire behavior in Canada and the United States, are the Canadian Forest Fire Danger Rating System’s (CFFDRS) FBP System (Van Wagner et al. 1992) and BehavePlus3 (Burgan and Rothermel 1984, Andrews et al. 2005), respectively. Neither program was suitable for developing a flammability curve that includes R_{Total} and F_{Total}. Determining the flammability curve for black spruce forests required a series of fire behavior prediction models that could represent the changing fuel complex across all successional phases leading up to mature forests. This required models able to differentiate the relative contributions of surface and canopy fuels and the consequent range of fire behaviors that occur between smoldering surface fires and fast moving crown fires.

Of these fire behavior prediction programs, BehavePlus3 came closest to meeting the modeling requirements for developing a flammability curve for a continuous range of fuels. Both, the surface fire prediction model (Rothermel 1972, Burgan and Rothermel 1984) and crown fire initiation and spread model (Van Wagner 1977) within BehavePlus3 accept fuel property inputs that encompass the range of fuels measured at each site. This permitted modeling of surface fire behavior and determination of fire type (i.e. surface fire, passive crown fire, or active crown fire). BehavePlus3 program was not used to develop the flammability curve because the crown fire behavior modeling component (Rothermel 1991) is not the most accurate model available to predict crown fire behavior in boreal forests. The model was not used for the following three reasons:

1. Rothermel’s crown fire behavior model is based on a regression with eight observations from various coniferous forests, mostly in the western United States. In contrast, Cruz’s crown fire behavior model (used in this analysis) is based on observations from 37 sites representing fuel types in the boreal forests of Canada including the black spruce type.
2. Cruz et al (2005) found that Rothermel’s crown fire behavior model under-predicted *ROS* for crown fires in boreal forests.
3. Wind speed is the only input for Rothermel’s crown fire model, whereas model inputs for Cruz’s crown fire behavior model include *CBD*, which has been shown to have a significant correlation with active crown fire behavior in boreal forests (Cruz et al 2005).

The FBP System (Van Wagner et al. 1992) relies on empirical relationships developed by measuring fire behavior over a gradient of weather conditions within a given fuel type. The fuel types used to develop the relationships modeled by the FBP System are representative of fuel types in Alaska and the models within the program are able to predict fire behavior for the full range of surface and crown fires that typically occur in Alaska. Unfortunately, in the FBP System, there is no way to adjust fuel properties on a continuous scale; only weather inputs can be changed in this manner. Fuel properties can only be changed by switching fuel models. This constrains the system's flexibility to measure differences in fuels among sites and, as we needed such flexibility for our analysis, the FBP System was considered inappropriate for use in developing the flammability curve.

Appendix 5 contains a detailed review of the fire prediction models that were used in the linked model.

Linked Model

The linked model combines the surface fire behavior component of BehavePlus3 with Cruz's crown fire model and a fire-line intensity model (Byram 1959) through the crown fire initiation and spread model (Van Wagner 1977). Fire type was determined by evaluating predicted fire behavior against threshold values calculated through the crown fire initiation and spread model. Based on assigned fire type, the appropriate models were then used to predict total *ROS* (R_{Total}) and total *FLI* (F_{Total}). R_{Total} and F_{Total} represent the *ROS* and *FLI*, respectively, if both surface fuels and canopy fuels are included in fire behavior modeling. For each site and weather scenario, the fire behavior models were arranged in a five tier cascade that is outlined below:

1. BehavePlus3 surface fire behavior model. The surface fuel parameters, fuel moisture, weather conditions, and terrain features were entered into BehavePlus3. BehavePlus3 predicts surface *ROS* ($R_{Surface}$) and surface *FLI* ($F_{Surface}$).
2. Van Wagner's crown fire initiation criteria. The crown fire initiation criteria rely on *CBH* and foliar moisture content (*FMC*) to calculate the critical surface fire-line intensity (I_O). The I_O is the minimum $F_{Surface}$ required to initiate crowning. The $F_{Surface}$ predicted in step one was compared with the I_O. If predicted $F_{Surface} < I_O$, no crown fire activity was expected and the fire type was classified as a surface fire. For surface fires:
$$R_{Total} = R_{Surface} \qquad \& \qquad F_{Total} = F_{Surface}$$
If predicted $R_{Surface} > I_O$ then some level of crown fire behavior could be expected. In cases where $R_{Surface} > I_O$, R_{Total} and F_{Total} are determined in the subsequent steps.
3. Cruz's crown fire model (active crown fire component). The next step is counterintuitive. Rather than moving to the passive crown fire component, which would logically be next, the active crown fire component of Cruz's crown fire model (*Appendix 5*, eq. 5-9) was used to predict active crown fire *ROS* ($CROS_A$) based on *CBD*, *FMC*, and weather conditions. The portion of *FLI* contributed by the canopy during an active crown fire (F_{Active}) was also calculated during this step (eqs. 3-1 through 3-3) using Byram's *FLI* equation (*Appendix 5*, eq. 5-5).
4. Van Wagner's crown fire spread criteria. The crown fire spread criteria uses *CBD* to determine the minimum observed or predicted $CROS_A$ that is required to sustain an active crown fire, this is called the critical *ROS* (R_O). If $CROS_A > R_O$, the fire is moving fast enough through the canopy to sustain an active crown fire, and is classified as an active crown fire.
For active crown fires:
$$R_{Total} = CROS_A \qquad \& \qquad F_{Total} = F_{Active} + F_{Surface}$$
If $CROS_A < R_O$, the fire is not moving fast enough through the canopy to sustain an active crown fire. In this case $F_{Surface}$ is compared to I_O to determine if the fire is a surface fire or a passive crown fire.
5. Cruz's crown fire model (passive crown fire component). When $F_{Surface} > I_O$ and $CROS_A < R_O$ the fire is classified as a passive crown fire. In this case, the passive crown fire component of Cruz's crown fire model is used to calculate passive crown fire *ROS* ($CROS_P$). The contribution of canopy fuels to *FLI* during a passive crown fire ($F_{Passive}$) was also calculated during this step (eqs. 3-4 through 3-6) using Byram's *FLI* equation (*Appendix 5*, eq. 5-5).
For passive crown fires:
$$R_{Total} = CROS_P \qquad \& \qquad F_{Total} = F_{Passive} + F_{Surface}$$

Five measures of fire behavior ($R_{Surface}$, $F_{Surface}$, R_{Total}, F_{Total}, and fire type) were predicted at each site under the three weather scenarios. The R_{Total} predictions from the linked model were compared with observed fire behavior at eight locations accompanied by on-site weather measurements. The purpose of this analysis was to determine how well the linked model can simulate actual fire behavior. Figure 3-1 depicts the linked model and will aid in understanding how each model is applied.

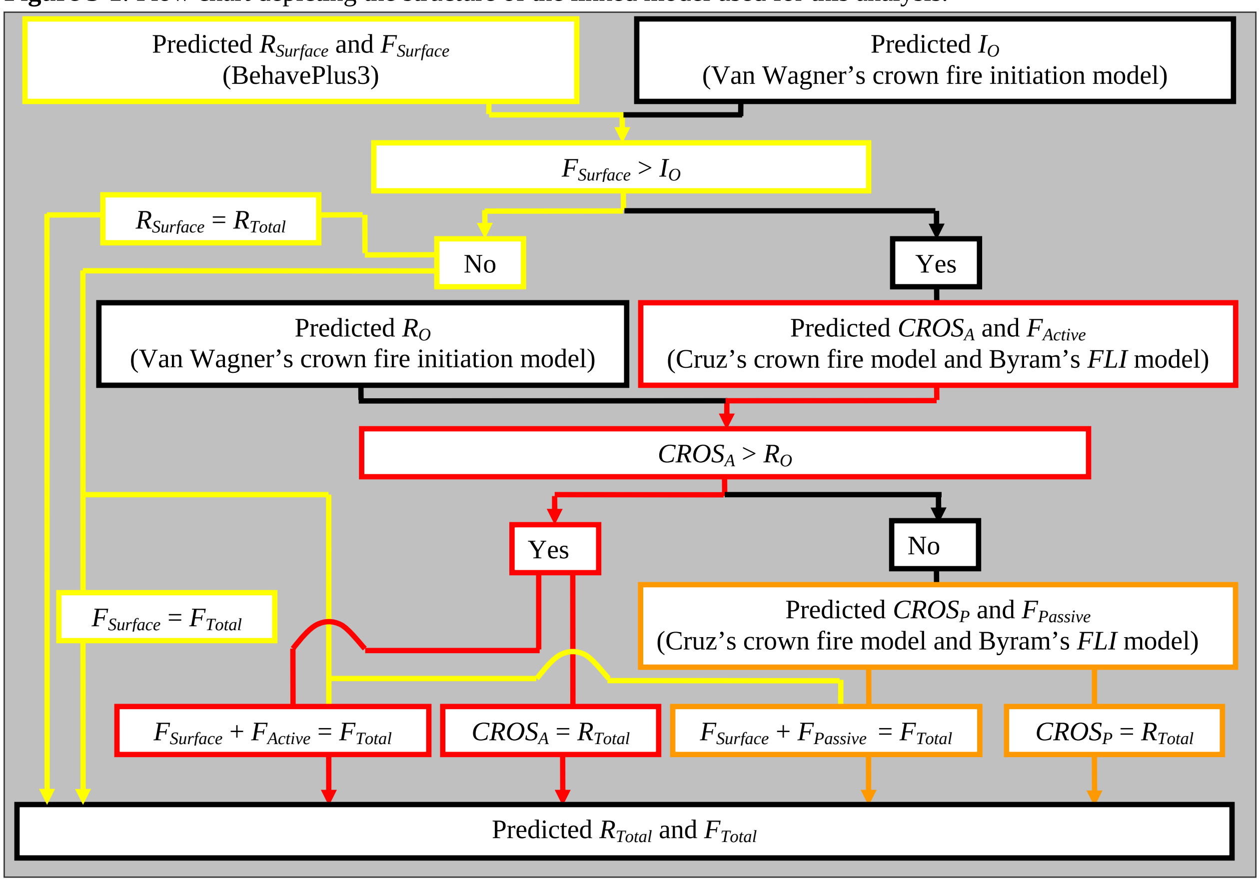
Table 3-1: Measures of fire behavior used to assess flammability.

Fire Behavior	Term	Models Used	Definition
Surface *ROS* Surface *FLI*	$R_{Surface}$ $F_{Surface}$	• BehavePlus3	*ROS* and *FLI* are based only on surface fuels. The purpose of these measurements is to show how temporal changes in surface fuels influence fire behavior. This is a hypothetical situation and does not represent actual fire behavior.
Total *ROS* Total *FLI*	R_{Total} F_{Total}	• BehavePlus3 • Cruz's crown fire model • Byram's fire-line intensity model	*ROS* and *FLI* are calculated for all fire types and model output that corresponds with fire type is selected to represent total fire behavior. This is an estimate of actual fire conditions. All fuels are incorporated into fire behavior modeling.
Fire Type	No Term	• Van Wagner's crown fire initiation and spread model.	Determines whether fire will be one of three types: surface fire, passive crown fire, or active crown fire.

Model Inputs

Data used to create the custom fuel models were derived from a combination of field data and known variables. In general, extrinsic fuel properties were calculated from field data and intrinsic properties (i.e. *SAV* ratio and heat content) were based on published values (*Appendix 1*, table A1-3). In addition to fuel

Figure 3-1: Flow chart depicting the structure of the linked model used for this analysis.



properties provided by the custom fuel models, the linked model requires weather data. Site flammability was modeled using three weather scenarios. The weather scenarios represent the range of conditions most likely to occur in interior Alaska during the burning season. The upper end of fire behavior is represented by 95th percentile weather conditions (K. Howard, personal communication, January 16, 2007). Moderate fire behavior is represented by 55th percentile weather conditions and marginal fire behavior is represented by 20th percentile weather conditions (*Appendix 2*, table A2-1). These weather scenarios will be referred to throughout this report as extreme, moderate, and marginal, respectively.

Weather data were pooled from 32 Remote Automatic Weather Stations (RAWS) in interior Alaska located in representative fuel types. RAWS data were acquired from a National Interagency Fire Center (NIFC) online database (National Information Systems Group 2007). Percentile weather conditions were calculated using Fire Family Plus (U. S. Department of Agriculture 2002). The burning season was defined as May 15 through August 1 (S. Alden, personal communication, January 10, 2007) and data from each site represented up to 38 burning seasons from 1965 to 2002.

The 1-hr dead fuel moisture was calculated using percentile weather as inputs into the Fine Dead Fuel Moisture Tool in BehavePlus3. Fuel moisture for 10-hr and 100-hr fuels was calculated by adding 1 and 2 percent, respectively to the 1-hr fuel moisture (Rothermel 1983). The 10-meter windspeed was assumed to be the same as the 20-foot windspeeds reported by the RAWS stations and mid-flame windspeed was calculated based on the 0.21 wind adjustment factor reported for the open canopy black spruce fuel type in Alaska (Norum 1983).

The BehavePlus3 surface fire component treats each fuel model as a fuel-bed with homogeneous properties. This is generally an oversimplification of actual fuel properties. Fuels are often arranged in distinct vertical layers, and on the horizontal plane, can occur as patchy mosaics of fuels whose properties cause them to burn differently. For instance, patches of sphagnum moss, leaf litter and feathermoss can all occur within the same forest, yet each burns differently. Similarly, surface fuels can also occur in distinct vertical layers. The 1-hr forest floor fuels have different properties than the 1-hr groundcover layer made up of herbs and low growing shrubs. To account for this complexity, adjustments were made to create fuel models that reflected actual distributions of fuels at each site.

To account for the horizontal discontinuity of fuels, the two dimensional expected spread feature in BehavePlus3 was used. This feature models fire behavior for two surface fuel models that exist as a mottled pattern. The 1-hr forest floor fuels were divided into two classes (table 3-2) based on published *SAV* ratios (*Appendix 1*, table A1-3). Forest floor fuels with lower *SAV* ratios burn at a slower *ROS* relative to fuels with higher *SAV* ratios. Additionally, fuels in black spruce forests with lower *SAV* ratios generally burn at lower *FLI*s because depth is often shallow (and consequently loading is lower) relative to fuels with higher *SAV* ratios.

Table 3-2: 1-hr forest floor fuel categories.

Litter	Feathermoss
Leaf lichen	Pleurocarpous mosses (feathermoss)
Acrocarpous mosses (pioneer mosses)	Reindeer lichen
Liverworts	
Needle litter	
Leaf litter	

The feathermoss category is for fuels with high *SAV* ratios including pleurocarpous mosses and reindeer lichens. Though both are live fuels, they lack a vascular system for transporting water. Thus, their moisture content rapidly equilibrates with that of the surrounding air. Reindeer lichens were sporadically encountered at our sites, thus feathermoss category almost exclusively represents pleurocarpous mosses. The litter category is for forest floor fuels with lower *SAV* ratios. In contrast to fuels in the feathermoss category, litter takes longer to equilibrate to the ambient relative humidity. Fuels in this category include leaf lichen, liverworts, acrocarpous mosses, needle litter and leaf litter. Litter fuels are not dominated by one forest floor type, though leaf lichen, acrocarpous mosses, and leaf litter are the most common.

Although the two-dimensional expected spread feature provides a more accurate measure of $R_{Surface}$, the predicted $F_{Surface}$ can be less accurate because BehavePlus3 uses the higher of the two values produced by the fuel models. Thus, if one fuel model occupies 1% of the landscape but the predicted $F_{Surface}$ three times higher than the second fuel model, BehavePlus3 will report the higher $F_{Surface}$ despite its minimal representation on the landscape. This feature of BehavePlus3 potentially misrepresents actual $F_{Surface}$; to avoid this error, predicted $F_{Surface}$ is calculated by taking a weighted average of $F_{Surface}$ for each fuel model based on its relative cover on the landscape.

To account for the affect of distinct vertical layers within the surface fuel-bed on fire behavior, fuel-bed depths were calculated by adding the depth of the 1-hr forest floor fuels to the depth of the groundcover fuels. This contrasts with similar studies (Schimmel and Granstrom 1997) where fuel-bed depth was equal to the weighted average of each surface component based on loading. This method was initially used to calculate fuel-bed depth but fire predicted surface fire behavior was near zero, even under dry and windy conditions. This was clearly incorrect and attributed to the unique properties of the feathermoss surface fuel category discussed below.

In BehavePlus3, predicted *ROS* and *FLI* are positively correlated with 1-hr fuel loading up to a threshold bulk density. Loading reaches this threshold bulk density at lower values when fuel-bed depth is lower. In black spruce forests a large fraction of 1-hr dead fuel loading is contributed by the forest floor. The forest floor is also shallow relative to traditional fuel-beds modeled in BehavePlus3 such as shrub and grass fuel types. Calculating fuel-bed depth using the weighted average of the surface fuel components resulted in high bulk densities that were insensitive to changes in loading. This produces unreasonably low predicted *ROS* and *FLI* for sites, especially later seral phases where the forest floor is the most prominent component of the surface fuels. Adding fuel-bed depths from different fuel layers (i.e. groundcover layer and forest floor layer) produced lower surface fuel bulk densities relative to averaging the same fuel-bed depths (a more common practice). As a result fire behavior was more sensitive to changes in surface fuel loads. The higher sensitivity to fuel load yielded more reasonable measures of fire behavior. This situation is discussed further in the *Discussion* section of *Chapter 5*.

To calculate I_O, *CBH* was determined from field data and *FMC* was held constant at 100% (J. H. Scott, personal communication, September 29, 2006). Van Wagner's crown fire initiation and spread model was adjusted slightly for this analysis. Minimum I_O was changed from 0 kW m^{-1} to 80 kW m^{-1}. This produced the greatest amount of agreement between predicted and observed fire type and is similar to changes made to the crown fire initiation model in similar studies (Bessie and Johnson 1995). Both I_O and Cruz's crown fire behavior model require *CBH* as an input.

Calculating *FLI* for crown fires required Byram's (1959) *FLI* model (*Appendix 5*, eq. 5-5). This requires three inputs: heat of combustion (*H*), mass of fuel consumed (*W*) and *ROS*. *H* is an extrinsic fuel property provided in *Appendix 1*, table A1-3, and *ROS* is predicted by Cruz's crown fire model. The mass of canopy fuels available for consumption is represented by *Wc*, and is calculated based on the fire type. Reported fraction of consumption for fine fuels (<1.0 cm in diameter) during active crown fires in the boreal forest is about 90% (Stocks et al. 2004). To calculate *Wc* for canopy fuels consumed during an active crown fire (Wc_A), W_{ff} was multiplied by the fraction consumed (0.90).

[3-1] $$Wc_A = W_{ff} * 0.90$$

FLI contributed by canopy fuels during an active crown fire was then calculated using Byram's *FLI* equation:

[3-2] $$F_{Active} = 300 * H * CROS_A * Wc_A$$

Where $F_{Acxtive}$ is the *FLI* contributed by canopy fuels during an active crown fire. F_{Total} was then calculated by adding the F_{Active} to the $F_{Surface}$ predicted by BehavePlus3.

[3-3] $$F_{Total} = F_{Active} + F_{Surface}$$

For passive crown fires, calculating *Wc* was slightly more complicated because anywhere between 10 and 90% (Van Wagner et al. 1992) of the canopy may be involved in flaming consumption during a passive crown fire. To evaluate the portion of the crown involved in flaming combustion the criterion for active crowning (*CAC)* (*Appendix 5*, eq. 5-10) was used as a proxy for crown consumption. *CAC* represents the gradient crown involvement in canopy fires as indicated by a number between 0 and 1. *CAC* was scaled to a value between 0.10 and 0.90 and used as a coefficient to determine available canopy fuels for passive crown fire as illustrated in the equation below.

[3-4] $$W_{Passive} = (W_{ff} * 0.90) * (CAC * 0.8 + 0.1)$$

Where $W_{Passive}$ equals the fuel consumed during a passive crown fire. As with active crown fires, the *FLI* contributed by canopy fuels during a passive crown fire was then calculated using Byram's *FLI* equation:

[3-5] $$F_{Passive} = 300 * H * CROS_P * W_{Passive}$$

Where $F_{Passive}$ is the *FLI* contributed by canopy fuels during a passive crown fire. F_{Total} was then calculated by adding the $F_{Passive}$ to the $F_{Surface}$ predicted by BehavePlus3.

[3-6] $$F_{Total} = F_{Passive} + F_{Surface}$$

F_{Total} is presented in logarithmic scale throughout this report. The reason for this conversion is related to the range of *FLI* that is practical from a fire suppression viewpoint. Limit of control guidelines for fire suppression activities based on *FLI* run between 190 – 1800 kW m^{-1} (Deeming et al. 1977). *FLI* for high intensity crown fires modeled for this project ranged between 10,000 – 30,000 kW m^{-1}. Though this range is dramatic it is relatively unimportant from a control standpoint since fires with FLI values over 1800 kW m^{-1} are nearly impossible to contain. By converting *FLI* to a logarithmic scale more importance was placed on patterns in the lower range of *FLI* that span the limits of control.

To standardize the effects of terrain, slope was kept constant at zero for all model runs. Custom fuel models for each site are presented in *Appendix 3*.

Additional Analysis

Hierarchical cluster analysis using the complete agglomeration method was used to determine successional phases of the fuel complex based on predicted R_{Total} and F_{Total} from each of the three weather scenarios. Groups were delineated from the tree diagram until age was no longer a factor in determining groups. F_{Total} was changed to a log scale to reflect the decreasing importance of variance among sites at high values and inputs were evaluated based on the standardized Euclidean distance.

Surface fuels play a key role in initiating and sustaining crown fires. To understand how surface fuels impact fire behavior, the canopy fuels were removed from fire behavior modeling to illustrate the relationship between surface fuels and stand age. Multiple regression analyses were then conducted to determine the relative influence of surface fuel properties on the predicted $R_{Surface}$ and $F_{Surface}$. The predictor variables did not include all inputs to the surface fuel model to avoid over-parameterization of the model. Fuel model parameters were selected based on the amount of variability among sites. For example, *SAV* ratios for each fuel category were excluded because they varied little between sites and did not have a large impact on predicted fire behavior. Fuel variables selected for input included loading for all surface fuels, fuel-bed depth, and percent cover of feathermoss fuels.

Observed vs. Predicted Fire Behavior Regression

Predictions derived from the linked model were compared to observed fire behavior data collected at fire event sites by Colorado State University (CSU) to determine how well the flammability curve reflects actual fire behavior conditions. Observations were included only if they represented a unique custom fuel model (i.e. site). If multiple fire behavior observations were represented by one fuel model, a single observation was randomly selected. For each observation, onsite weather conditions and the corresponding fuel model were input into the linked model. Predicted R_{Total} was compared with observed R_{Total} using linear regression analysis. The regression analysis included eight observations.

Chapter 4: Results

Overview

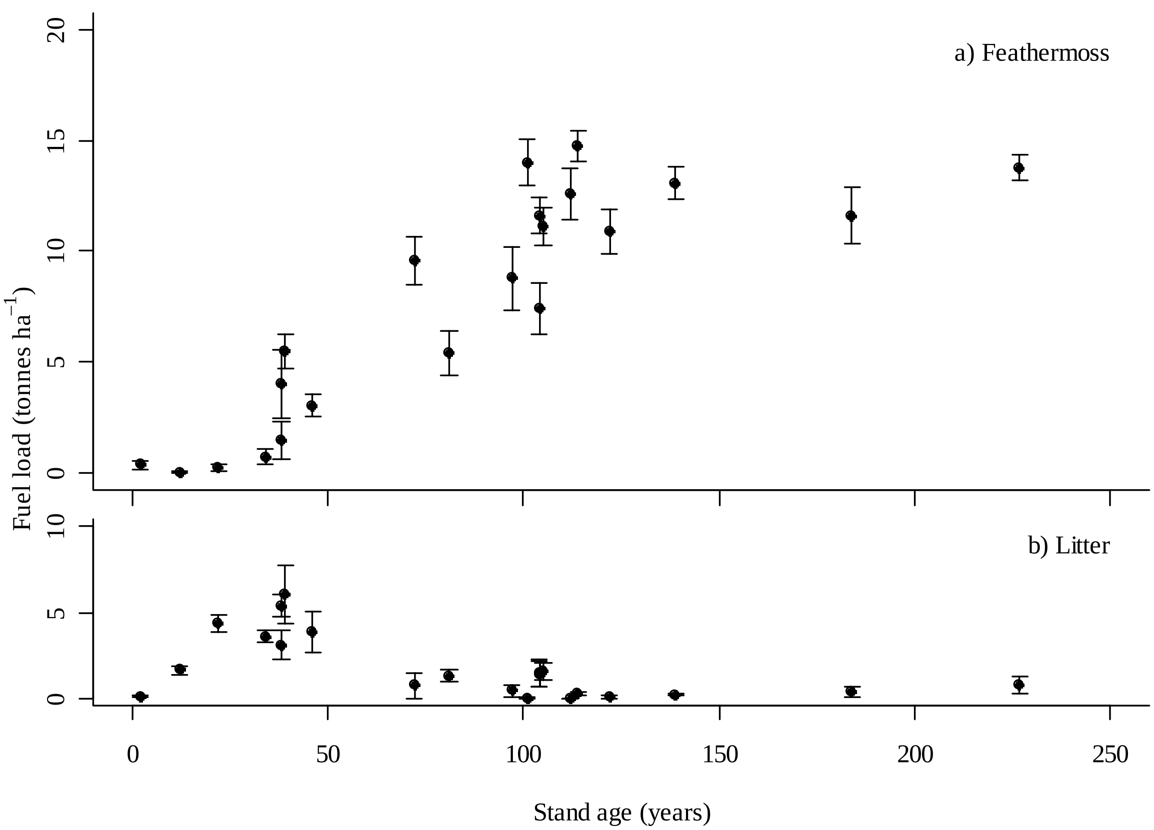
This section presents the results of the analysis used to designate a flammability curve for black spruce forests. This chapter is divided into two main sections:

a) Fuel Properties – presents results for trends in fuel properties that were measured.
b) Flammability – presents predicted measures of fire behavior that represent the relative flammability of each stand and analysis.

Fuel Properties

Loading for both categories of 1-hr forest floor fuels showed a clear relationship with time since fire (figure 4-1). Litter was the greatest contributor to forest floor loading during early succession and was slowly replaced by feathermoss as the stand progressed towards later phases of succession. Loading of these two fuel classes appeared to be mutually exclusive; litter ceded loading to feathermoss over time.

Figure 4-1: Average forest floor 1-hr fuel load in relation to stand age. The feathermoss category primarily is pleurocarpous mosses, but also includes reindeer lichen. The litter fuel category includes leaf litter, leaf lichen, needle litter, and pioneer mosses. Error bars represent ± one standard error.

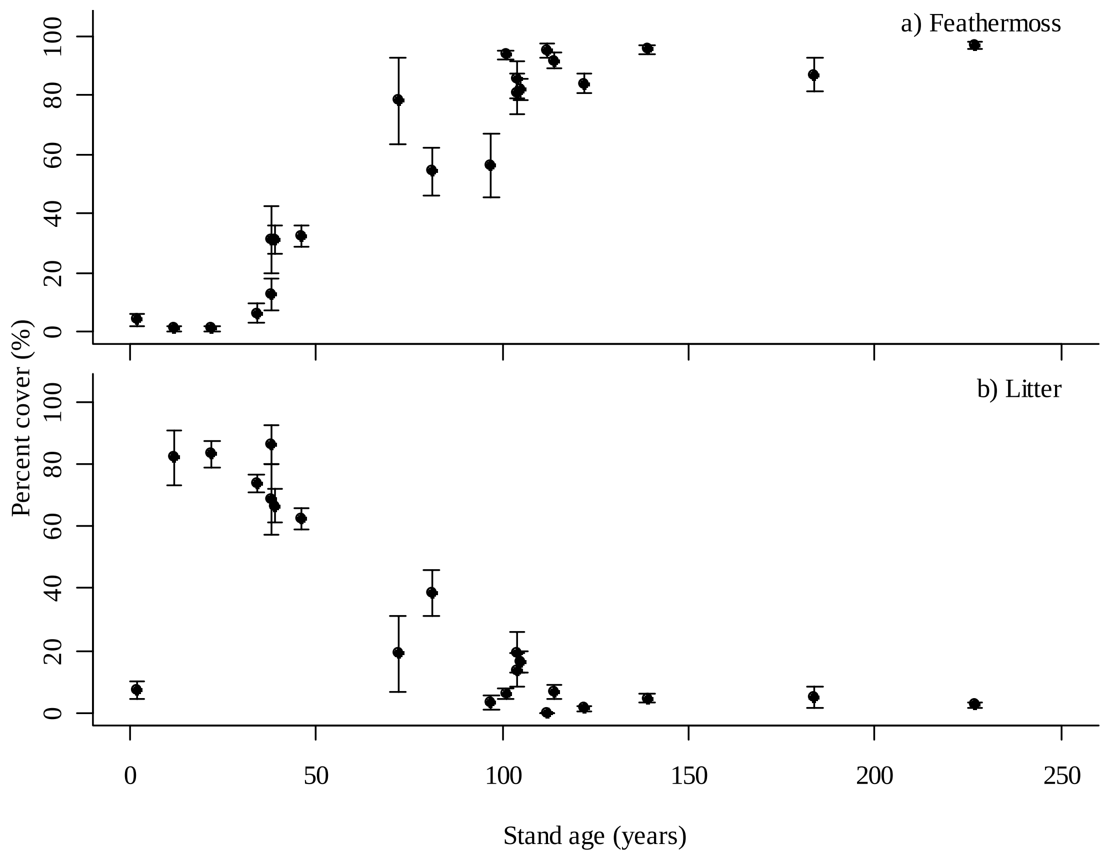


Feathermoss loading was < 1 tonne ha^{-1} at sites less than 25 years old. From age 25 through age 110, loading of feathermoss increased steadily before reaching a plateau of about 13 tonnes ha^{-1}. At sites older than 110 years, feathermoss loading remained steady at a range of between 10 – 14 tonnes ha^{-1}.

In contrast, loading of litter peaked earlier and decreased with age. Immediately following fire, litter loading rose rapidly and peaked at about 6 tonnes ha^{-1} within 40 years. During this period the majority of litter loading was contributed by leaf fall from dwarf shrubs (e.g. Labrador tea (*Ledum groenlandicum*), bog blueberry (*Vaccinium uliginosum*) and lowbush cranberry (*Vaccinium vitis-idaea*)), deciduous shrubs and trees (e.g. paper birch, willow (*Salix* sp.), green alder (*Alnus crispa*)), and pioneer mosses. Litter loading steadily decreased in stands between 40 and 100 years, the same period that feathermoss loading increased most rapidly. At sites > 100 years, fuels in the litter category were dominated by spruce needle litter and loading ranged from 0 – 2 tonnes ha^{-1}.

The sphagnum moss forest floor type is the only type excluded from the flammability analysis. While it would have been placed in the feathermoss fuel category due to its high *SAV* ratio, it was omitted because it holds moisture well and rarely burns, even during hot and dry weather conditions (Viereck 1980). No strong relationship existed between sphagnum moss accumulation and stand age, but it did not occur in stands aged < 80 years. Sphagnum moss presence appeared to be more closely associated with aspect in older stands. Of the six sites were sphagnum moss is present, five were north facing. The range of sphagnum moss loading in the surface material layer was 0 – 14 tonnes ha^{-1}.

Figure 4-2: Average percent cover of feathermoss and litter fuels relative to stand age. Error bars represent ± one standard error.

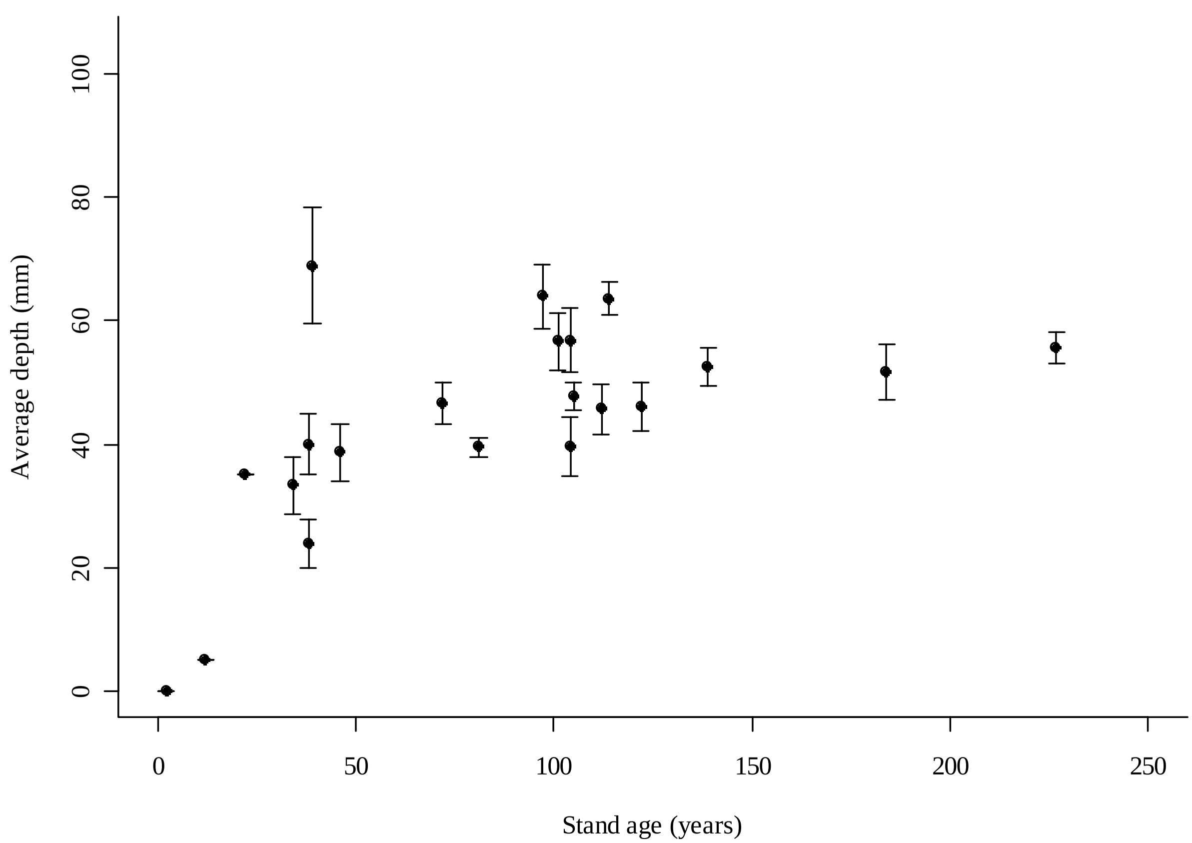


There is no correlation between duff loading and stand age (data not shown). Loading is very high relative to any other component of the fuel complex and ranged from 76 – 284 tonnes ha^{-1}, though the range for most sites was narrower; 60% of the sites had duff loadings between 170 – 215 tonnes ha^{-1}. Variations in duff loading may be a function of aspect, slope, and possibly burn severity. The five sites with duff loading less than 170 tonnes ha^{-1} are the only ones with south to west facing aspects and slopes > 5%. This suggests steeper slopes with drier aspects have lower duff loading than other locations. The four sites with duff loading > 215 tonnes ha^{-1} do not appear to have any unique site characteristics; the sites are relatively flat (slope < 2%) and aspect ranges widely. Fire severity may have impacted duff loading at two early seral sites with similar terrain and located within close proximity. One site was burned by an early season low severity fire and the other was burned by a late season fire that showed signs of high severity (e.g. few root sprouts from shrubs, few standing fire-killed trees, and high cover of herbaceous cover). Duff loading at the low severity site was 206 tonnes ha^{-1} and duff loading at the high severity site was 175 tonnes ha^{-1} indicating that higher severity fires consume more duff material.

With the exception of the site measured within the first few years after fire (the forest floor was dominated by charred duff and mineral soil), percent cover of feathermoss and litter fuels had an inverse relationship (figure 4-2). This relationship was closely associated with stand age. Feathermoss fuels increased and litter fuels decreased until stand age reached about 100 years.

As with the feathermoss loading, percent cover remained low (less than 5%) in stands less than 25 years old, increased in stands between 25 and 100 years old, and subsequently leveled off to between 80 and 100% cover in stands > 100 years. Variance of feathermoss percent cover within stands between 25 and 100 years was high. This was due to the heterogeneity of the forest floor in developing stands of black spruce. Pleurocarpous mosses existed in patches surrounded by litter fuels such as leaf litter, pioneer mosses, and leaf lichen.

Figure 4-3: Fuel-bed depth of feathermoss relative to stand age. Error bars represent ± one standard error.

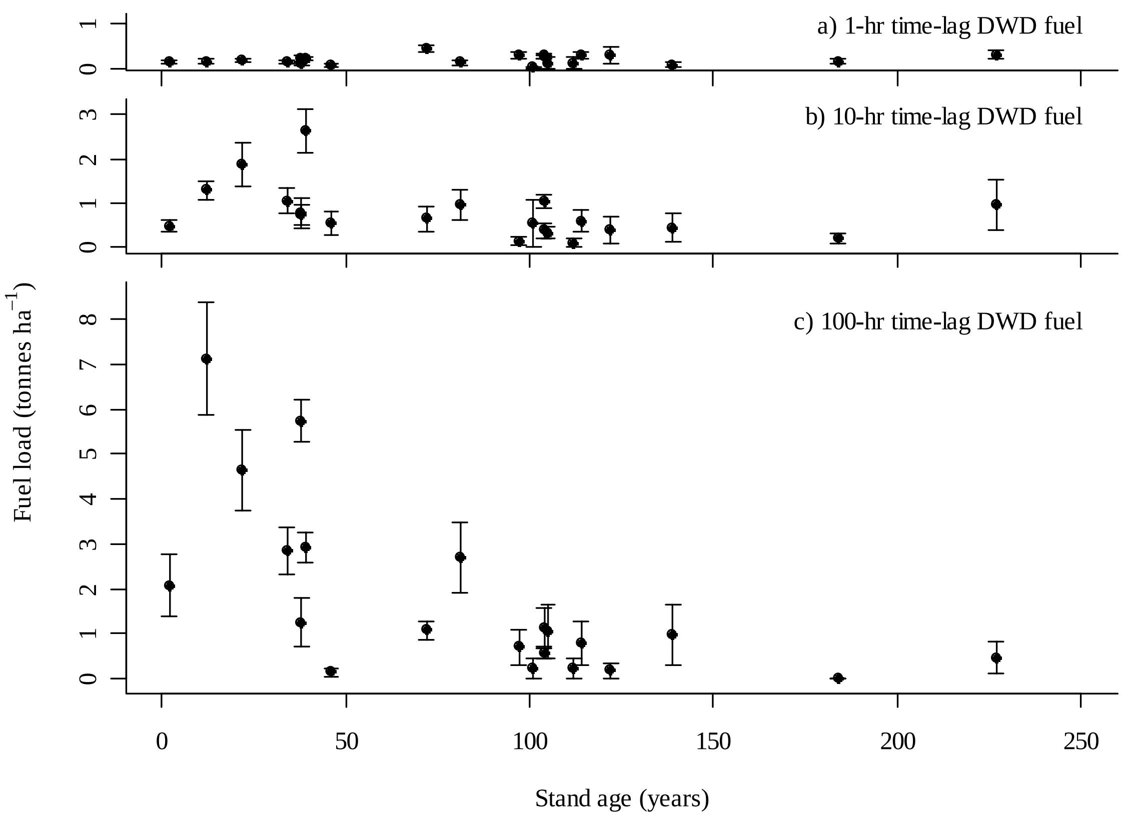


Relative to feathermoss, litter fuels colonize sites rapidly. Within 12 years following fire, litter fuels cover > 80% of the forest floor. This was not surprising given that pioneer mosses and shrubs re-colonize burned areas quickly after a fire. A steady decline followed the surge in coverage of litter fuels as these fuels were replaced by the pleurocarpous mosses. Litter fuels maintained a minimum percent cover (< 20%) in stands aged > 100 years, primarily as pockets of spruce litter beneath dense groups of black spruce trees.

The relationship between average depth of feathermoss and stand age is slightly different from percent cover (figure 4-3). Percent cover had a sigmoid relationship with age while the depth and stand age relationship more closely resembles a negative exponential curve (figure 4-3). The average depth begins to rise immediately, and from 0 to 90 years following fire average depth of feathermoss increased steadily to between 40 and 65 mm. At sites over 90 years old the average depth remained steady and averaged 53 mm among all sites.

Compared with forest floor fuel attributes, the relationship between stand age and DWD fuel loading is weaker with higher variance among sites (figure 4-4). The 1-hr DWD fuels, which can have a large impact on $R_{Surface}$, had no relationship with age and fuel loads were minimal (< 1 tonnes ha^{-1}). There was no evidence of a post-fire spike in 1-hr DWD fuel loading that occurred as a result of fire-killed trees. The 10-hr and 100-hr DWD fuel loads were negatively correlated with age, suggesting that fire-killed trees contribute to coarse DWD fuel loads following fire. For 10-hr DWD fuels, loads decreased over time until stand age reached about 50 years. Similarly, 100-hr DWD fuel loads decreased over time but did not plateau until stand age was about 100 years.

Figure 4-4: DWD fuel loading relative to stand age. Error bars represent ± one standard error.



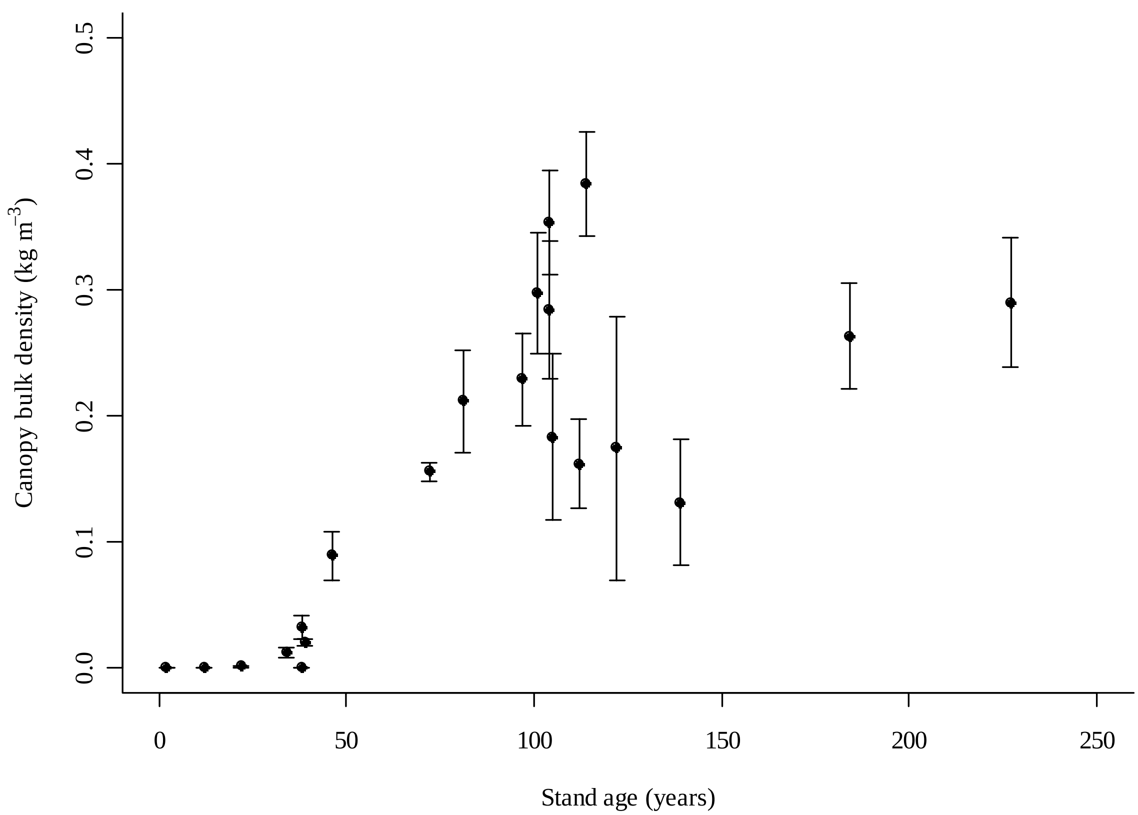
The 10-hr DWD fuel load was initially as high as 2 tonnes ha^{-1}; in stands aged > 50 years, loading remained < 1 tonne ha^{-1}. The highest 100-hr DWD fuel load was about 7 tonnes ha^{-1}; in stands aged > 100, loading was steady at < 1 tonne ha^{-1}.

The 1000-hr DWD fuels (data not shown) exhibited no relationship with stand age. For this category of fuel, loading ranged from 0 – 9 tonnes ha^{-1}; though a majority of the sites (63%) had fuel loads < 1 tonne ha^{-1}. The 1000-hour DWD fuel loading is likely to be, at least in part, a function of stand productivity. Overstory trees in many stands often do not attain diameters large enough to be classified as

1000-hour fuels. Thus if a stand is not productive enough to grow trees > 7.62 cm in diameter, the 1000-hour time-lag class will never exist.

Loading of groundcover fuels, including herbs and live woody plants, was weakly correlated with age due to high variance among sites (data not shown). Live woody shrub loading was initially low and loading was < 1 tonne ha^{-1} in stands aged < 20 years. Loading was highest (2 – 4 tonnes ha^{-1}) in stands between 20 and 75 years and slightly lower (< 3 tonnes ha^{-1}) in stands > 75 years. This measure of woody shrubs only includes dwarf shrubs < 0.5 meters in height, large shrubs (i.e. willow and alder) are not included. In younger stands, tall shrubs potentially contribute significantly to live woody plant loadings. Were tall shrubs included, the relationship between live woody plant loading and age would likely be similar to that for 10-hr and 100-hr DWD fuels, with live woody fuel loading initially high, but decreasing as black spruce became dominant and shrubs senesced. Live herbaceous fuel loading was < 1 tonne ha^{-1} in stands < 50 years and was approximately 1 tonne ha^{-1} in stands > 50 years. Overall there was a weak positive correlation between age and live herbaceous fuel load.

Figure 4-5: *CBD* relative to stand age. Error bars represent ± one standard error.



The softwood *CBD* had a relationship with age that was similar to feathermoss loading and percent cover (figure 4-5). The Pearson's product-moment correlation between *CBD* of softwoods and average loading of feathermoss was 0.835 with a p value < 0.0001, indicating that pleurocarpous mosses and softwood *CBD* are highly correlated. Stands aged < 35 years had softwood *CBD* < 0.01 kg m^{-3}. Softwood *CBD* then increased for a period of about 50 years, from near zero in stands < 40 years to over 0.15 kg m^{-3} in stands between 80 and 90 years. In stands aged > 90 years, softwood *CBD* appeared to have a slight positive relationship with age but variance among sites was high. The variance in *CBD* among sites older than 90 years likely reflects differences in site characteristics.

In addition to softwood *CBD*, the *CBD* of hardwood trees and dead trees were also measured. In both cases these values were negligible and bore no relationship with stand age. The highest value for hardwood *CBD* was 0.05 kg m^{-3}, and the highest value for *CBD* of dead trees was 0.01 kg m^{-3}. Although successional trajectories of black spruce forests may include an intermediate hardwood phase (Foote 1983), we did not encounter this phase at any of the sites, adding to the preponderance of recent data indicating the relay floristic model of succession is far less prevalent than has been assumed. The *CBD* of dead trees remained low because the agent of mortality for most black spruce is stand replacing fire which consumes most of the fine fuels.

There was a low positive correlation between *CBH* and age (data not shown). *CBH* is delineated by two age brackets. In stands aged < 80 years, *CBH* was < 0.2 meters and in stands aged > 80 years, *CBH* was generally > 0.2 meters. The average *CBH* for stand age < 80 years was 0.03 meters with a range of 0 – 0.09 meters and for stand age > 80 years, the mean *CBH* was 0.39 meters and the range was 0.08 – 0.73 meters. Within each of these age classes *CBH* is quite variable and unrelated to age.

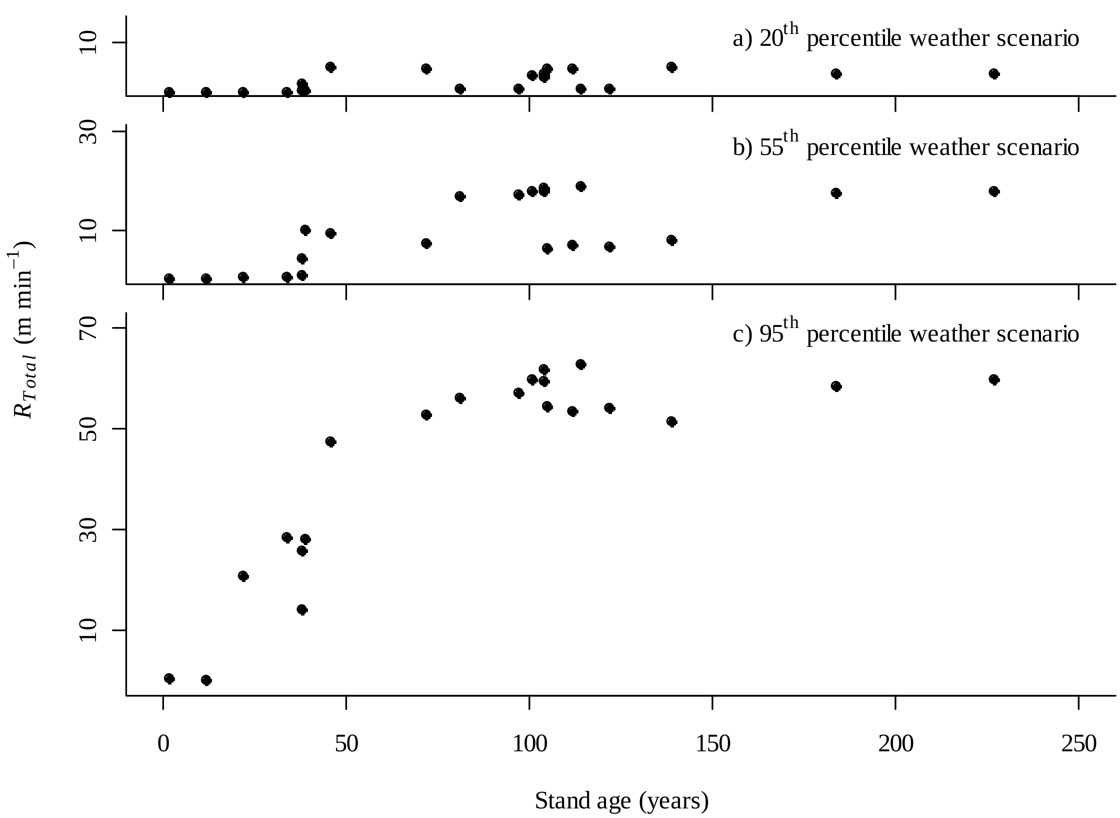
W_{ff} exhibited a similar relationship to age as *CBD* (data not shown). W_{ff} for stand age < 34 years ranged from 0.07 – 0.33 tonnes ha^{-1}; for stand age between 34 – 50 years, W_{ff} ranged from 0.24 – 4.08 tonnes ha^{-1}; and for stand age > 50 years W_{ff} ranged from 6.40 – 19.6 tonnes ha^{-1}. There is a moderate positive correlation between W_{ff} and age for all stands aged > 50 years.

Fire Behavior

Output from the linked model demonstrated a clear relationship between stand age and flammability as measured through R_{Total} (figure 4-6) and F_{Total} (figure 4-7). As fire weather conditions worsened, the shape of the response curve was increasingly sigmoid for R_{Total}, and increasingly resembled a negative exponential model for F_{Total}.

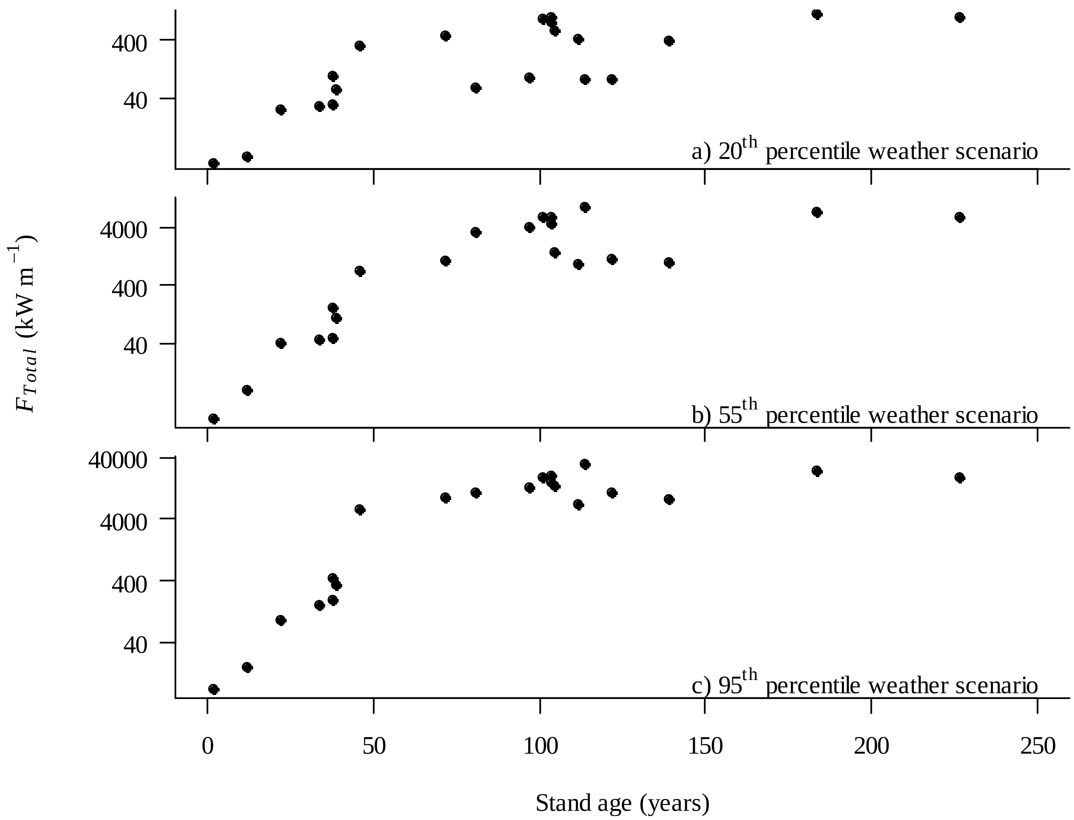
The direct relationship between stand age and F_{Total} was not initially as strong relative to R_{Total}, however, when F_{Total} was converted to log scale to reduce variance among older stands the degree of correlation between stand age and F_{Total} improved (figure 4-7).

Figure 4-6: Predicted R_{Total} relative to stand age for 20th (marginal), 55th (moderate), and 95th (extreme) percentile weather scenarios.



Cluster analysis based on predicted fire behavior outputs for each of the three weather scenarios suggests three distinct groups of fire behavior based on age (figure 4-8). The first group of sites was < 20 years old. R_{Total} and F_{Total} for these sites was nearly zero under all weather scenarios. The second group of sites had stand ages between 20 and 45 years. Predicted R_{Total} and F_{Total} varied more widely, but in general, were greater than the first group (younger) and less than the third group (older). A third group (on the left side of the dendrogram) includes sites spanning a large range of ages (46 - 227 years). Predicted R_{Total} and F_{Total} were distinctly higher than either of the two earlier groups, crown fire activity was possible under any weather scenario, and this was the only age group where active crown fires were predicted.

Figure 4-7: Predicted F_{Total} relative to stand age for 20^{th} (marginal), 55^{th} (moderate), and 95^{th} (extreme) percentile weather.



For stands aged < 20 years: Under the marginal weather scenario the average predicted R_{Total} was 0.1 m min^{-1} and the range was 0.1 – 0.1 m min^{-1}. The average predicted F_{Total} was 4 kW m^{-1} and the range was 3 – 4 kW m^{-1}. Fire behavior was nearly unchanged for these stands under the moderate weather scenario. The average predicted R_{Total} remained 0.1 m min^{-1} with a range of 0.1 – 0.1 m min^{-1}. The average predicted F_{Total} was 4 kW m^{-1} and the range was 2 – 6 kW m^{-1}. For the extreme fire weather scenario predicted fire behavior was slightly higher. The average predicted R_{Total} was 0.4 m min^{-1} with a range of 0.3 – 0.4 m min^{-1}. The average predicted F_{Total} was 12 kW m^{-1} and the range was 7 – 16 kW m^{-1}. For all sites and weather scenarios, fires in this phase were classified as surface fires.

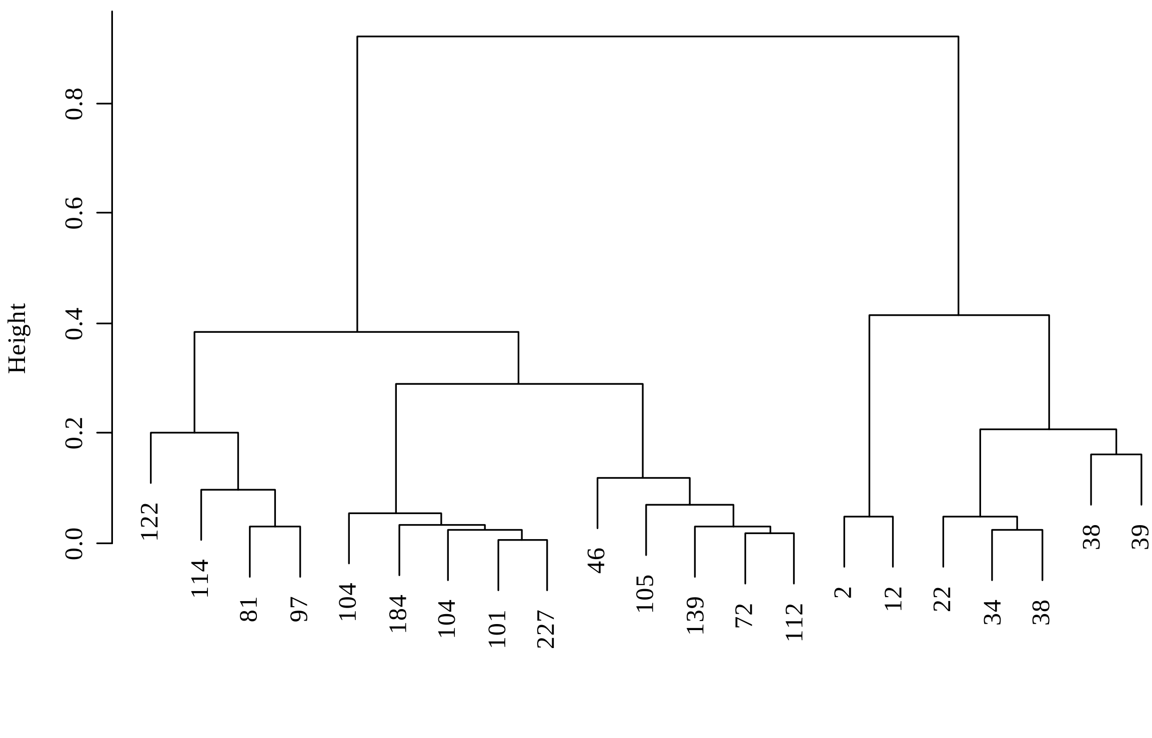
Predicted fire behavior for the mid-successional group (20 - 45 years) was intermediate between the early and late successional groups for each weather scenario. Under the marginal weather scenario the average predicted R_{Total} was 0.6 m min^{-1} and the range was 0.2 – 1.9 m min^{-1}. The average predicted F_{Total} was 47 kW m^{-1} and the range was 25 – 94 kW m^{-1}. Fire behavior was noticeably higher for these stands under the moderate weather scenario. The average predicted R_{Total} was 3.1 m min^{-1} with a range of 0.3 – 9.9 m min^{-1}. The average predicted F_{Total} was 81 kW m^{-1} and the range was 39 – 163 kW m^{-1}.

Extreme fire weather conditions produced a sharp spike in predicted fire behavior, especially R_{Total}. The average predicted R_{Total} was 23.5 m min^{-1} with a range of 14.2 – 28.5 m min^{-1}. The average predicted F_{Total} was 240 kW m^{-1} and the range was 91 – 430 kW m^{-1}. Most of the fires predicted for the marginal weather scenario were surface fires (80%) and the rest were passive crown fires (20%). As weather deteriorated surface fires were replaced by passive crown fires. Under the moderate weather scenario the number of predicted surface fires dropped to 60% and the predicted passive crown fires increased to 40%. Under the extreme weather scenario 100% of predicted fires were passive crown fires. No active crown fires were predicted for the mid-successional group under any of the weather scenarios.

Table 4-1: Average predicted R_{Total} and F_{Total} (± one standard error) for each fuel succession category and weather scenario.

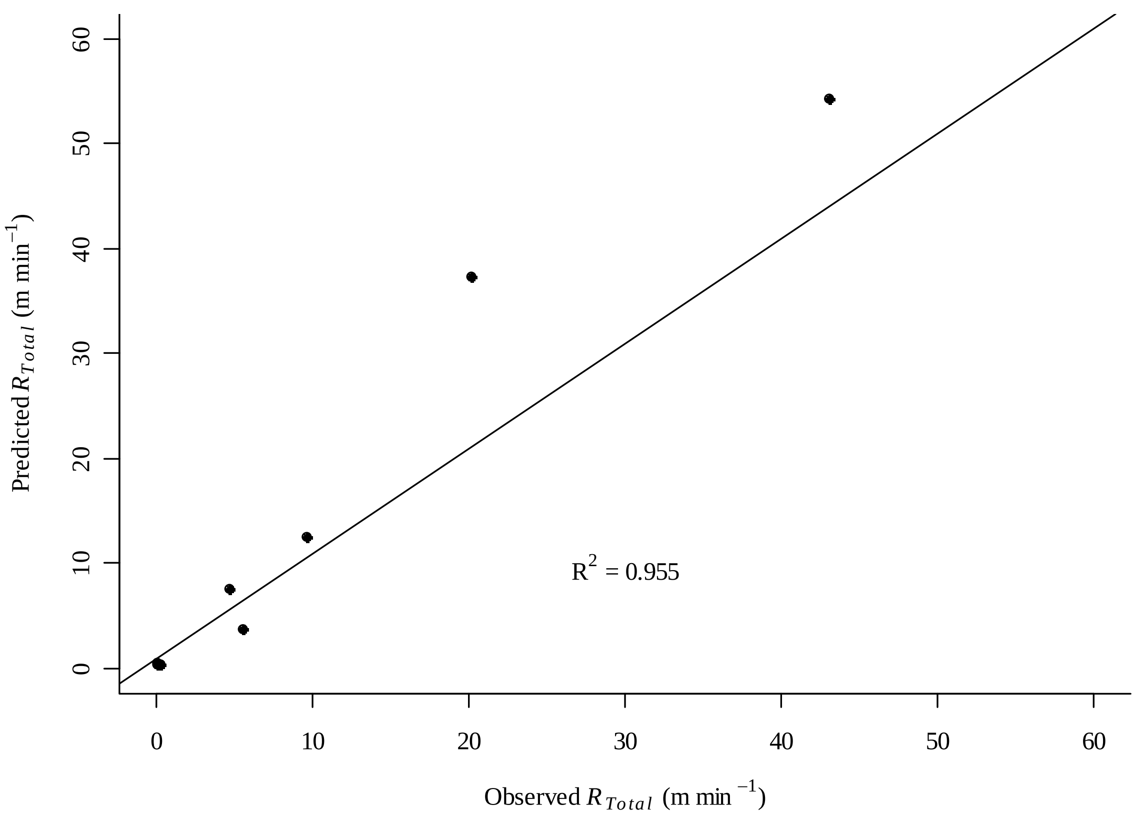
Percentile Weather	R_{Total} (m min^{-1})			F_{Total} (kW m^{-1})		
	Stand Age: < 20 years	Stand Age: 20-45 years	Stand Age: > 45 years	Stand Age: < 20 years	Stand Age: 20-45 years	Stand Age: > 45 years
20th	0.1 ± 0	0.6 ± 0.3	3 ± 0.5	4 ± 1	47 ± 13	482 ± 105
55th	0.1 ± 0	3.1 ± 1.9	13.9 ± 1.4	4 ± 2	81 ± 24	3891 ± 696
95th	0.4 ± 0.1	23.5 ± 2.7	56.4 ± 1.1	12 ± 4	240 ± 62	15,027 ± 1739

Figure 4-8: Cluster analysis diagram based on predicted fire behavior from all weather scenarios.



For stands aged > 45 years predicted R_{Total} and F_{Total} diverged widely as a function of weather. Within this age bracket, F_{Total}, and to some extent R_{Total}, had variance among sites that was quite high within each of the weather scenarios. Under the marginal weather scenario, the average predicted R_{Total} was 3 m min^{-1} and the range was 0.7 – 5.3 m min^{-1}. The average predicted F_{Total} was 482 kW m^{-1} and the range was 58 – 1090 kW m^{-1}. Unlike earlier age brackets, predicted fire behavior under the moderate weather scenario had much higher predicted fire behavior than under the marginal weather scenario. For the moderate weather scenario average predicted R_{Total} was 13.9 m min^{-1} with a range of 6 – 18.7 m min^{-1}. The average predicted F_{Total} was 3891 kW m^{-1} and the range was 687 – 8923 kW m^{-1}. Extreme fire weather conditions produced an even stronger increase in predicted fire behavior. The average predicted R_{Total} was 56.4 m min^{-1} with a range of 47.5 – 62.7 m min^{-1}. The average predicted F_{Total} was 15,027 kW m^{-1} and the range was 5504 – 29,886 kW m^{-1}. Fire type was divided between surface fires (36%) and passive crown fires (64%) under marginal weather conditions. Active crown fires become more prominent as weather conditions worsened. Under the moderate weather scenario only 36% of the sites supported passive crown fires and 64% of the sites supported active crown fires. Under the extreme weather scenario 100% of all predicted fires were active crown fires. Average values for each category (table 4-1) and boxplots (figures 5-5 and 5-6) demonstrate the impact of stand age and weather conditions on predicted fire behavior.

Figure 4-9: Observed R_{Total} vs. predicted R_{Total}. The line represents a slope of one. Reported R^2 is for the best fit regression line (not shown): y = 1.3341x + 0.5207.



Results for the pairwise comparison of predicted and observed R_{Total} showed a high degree of correlation (figure 4-9). The eight comparisons between predicted and observed behavior had an R^2 value of 0.955. The slope for the linear model is close to one (1.3341) and the y-intercept is near zero (0.5207). While the linked model slightly over-predicts R_{Total}, in general the slope, y intercept, and R^2 values indicate that the model does a good job at predicting actual R_{Total}. This assessment is based on a relatively small number of observations (n=8) and cannot be considered a conclusive evaluation of the effectiveness of the linked model. Comparisons included 1 custom fuel model from the intermediate aged stands (20-45 years old) and 7 custom fuel models from the mature stands (aged over 45 years old).

Fire behavior modeling for only surface fuels using BehavePlus3 depicted similar relationships to stand age (figures 4-10 and 4-11).

In stands < 20 years, predicted $R_{Surface}$ and $F_{Surface}$ were identical to the output from the linked model since all fires were predicted to be surface fires.

As with total fire behavior, predicted surface fire behavior for the mid-successional group (20 - 45 years) was intermediate between the early and late successional groups for each weather scenario.

Figure 4-10: Predicted $R_{Surface}$ relative to stand age for 20th (marginal), 55th (moderate), and 95th (extreme) percentile weather.

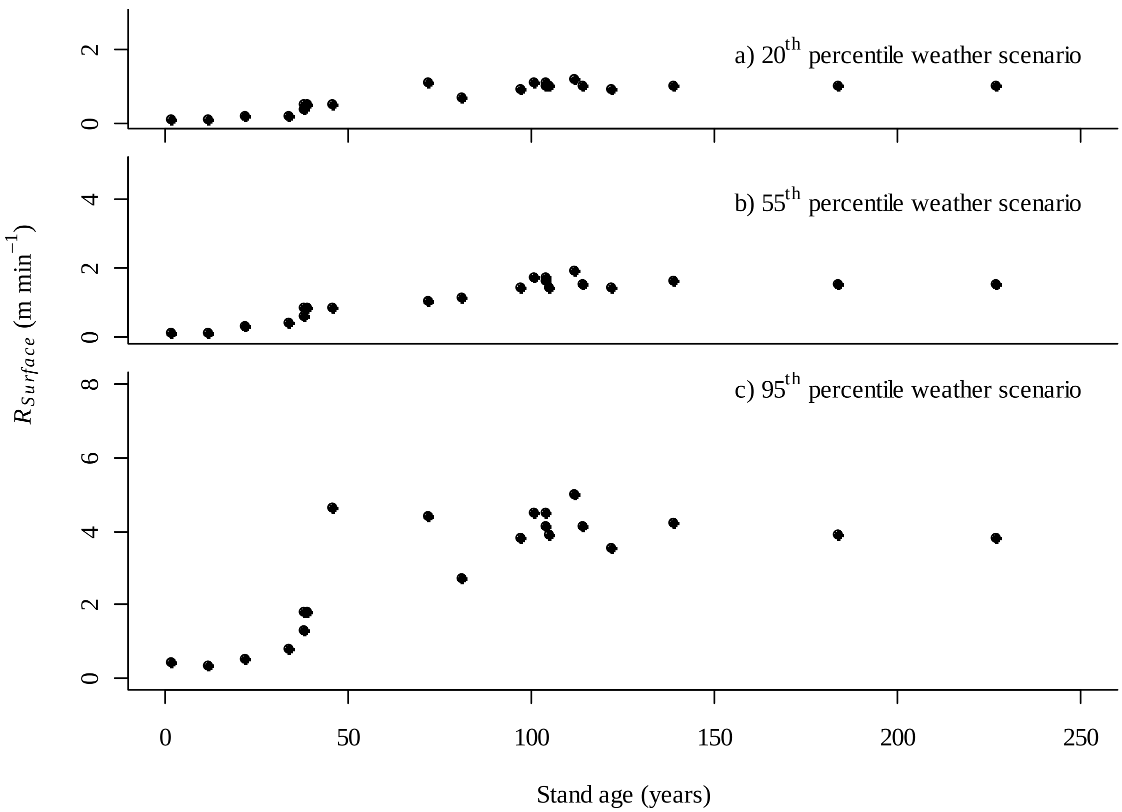
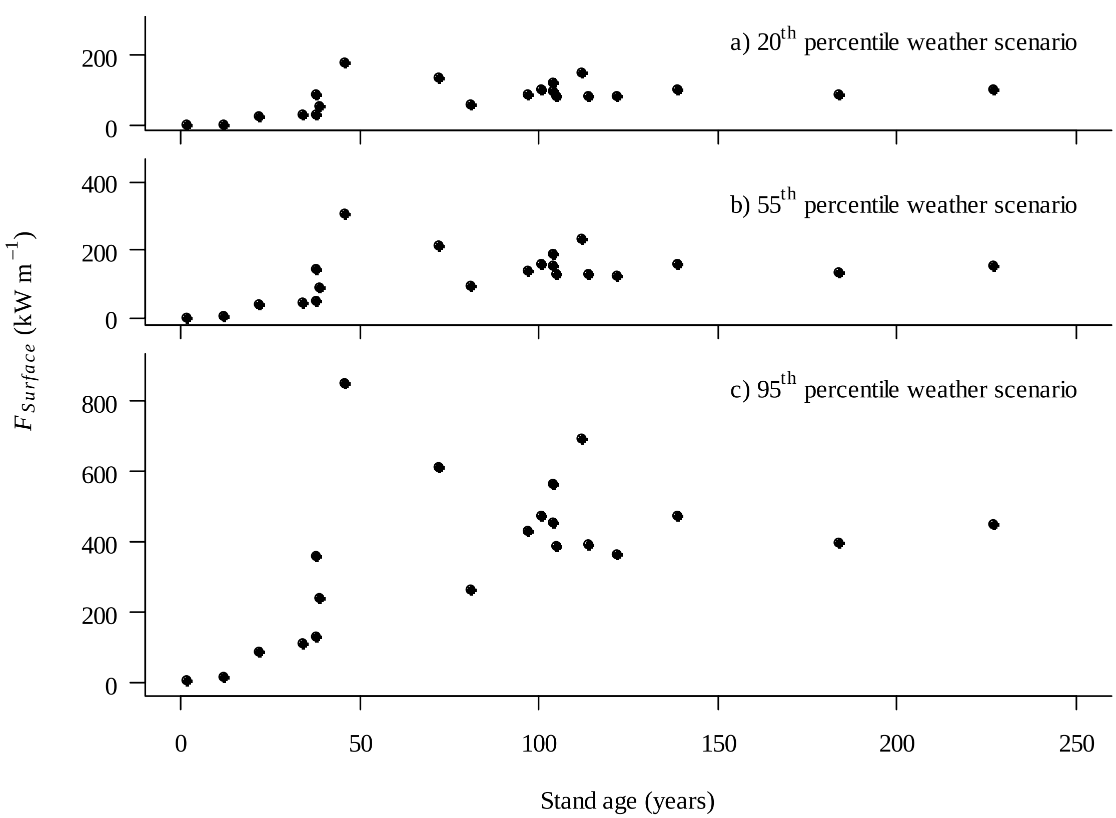


Figure 4-11: Predicted $F_{Surface}$ relative to stand age for 20th (marginal), 55th (moderate), and 95th (extreme) percentile weather.



Under the marginal weather scenario the average predicted $R_{Surface}$ was 0.4 m min^{-1} and the range was 0.2 – 0.5 m min^{-1}. The average predicted $F_{Surface}$ was 45 kW m^{-1} and the range was 25 – 85 kW m^{-1}. For the moderate weather scenario, the average predicted $R_{Surface}$ was 0.6 m min^{-1} and the range was 0.3 – 0.8 m min^{-1}. The average predicted $F_{Surface}$ was 72 kW m^{-1} and the range was 39 – 142 kW m^{-1}. Extreme fire weather conditions produced a slight increase in predicted surface fire behavior. The average predicted $R_{Surface}$ was 1.2 m min^{-1} with a range of 0.5 – 1.8 m min^{-1}. The average predicted $F_{Surface}$ was 186 kW m^{-1} and the range was 90 – 360 kW m^{-1}.

For stands > 45 years, the increase of predicted $R_{Surface}$ and $F_{Surface}$ as a function of weather was modest relative to total predicted fire behavior. Under the marginal weather scenario the average predicted $R_{Surface}$ was 1 m min^{-1} and the range was 0.5 – 1.2 m min^{-1}. The average predicted $F_{Surface}$ was 99 kW m^{-1} and the range was 58 – 176 kW m^{-1}. For the moderate fire weather scenario the average predicted $R_{Surface}$ was 1.4 m min^{-1} with a range of 0.7 – 1.9 m min^{-1}. The average predicted $F_{Surface}$ was 155 kW m^{-1} and the range was 92 – 304 kW m^{-1}. For the extreme fire weather scenario the average predicted $R_{Surface}$ was 4 m min^{-1} with a range of 2.7 – 5 m min^{-1}. The average predicted $F_{Surface}$ was 462 kW m^{-1} and the range was 262 –849 kW m^{-1}.

Multiple regression analysis of extrinsic surface fuel properties and $R_{Surface}$ indicated that 3 of 7 inputs were significantly related to predicted $R_{Surface}$ and (table 4-2). The most highly correlated were fuel-bed depth and percent cover of feathermoss ($p < 0.001$). Live woody fuel loading had a moderately significant negative relationship with predicted $R_{Surface}$ ($p < 0.01$). Note, that the feathermoss loading used in multiple regression analysis is different from that reported in figure 4-2 because the former was not adjusted for percent cover (i.e. loading in table 4-2 assumes 100% coverage of feathermoss). Feathermoss fuel loading is reported based on 100% coverage to reflect requirements of BehavePlus3 model inputs which were used as parameters for the multiple regression analysis.

Table 4-2: Multiple regression analysis of selected extrinsic surface fuel properties and $R_{Surface}$.

Fuel Input	Estimate	Standard Error	t value	p value
Intercept	-2.01674	0.62903	-3.206	0.00689
Feathermoss percent cover	3.32438	0.39278	8.464	1.20e-06
Fuel-bed depth	21.39888	2.88439	7.419	5.06e-06
Live herbaceous fuel loading	0.15097	0.41239	0.366	0.72036
Live woody fuel loading	-0.22740	0.10461	-2.174	0.04879
Feathermoss loading	0.02791	0.02121	1.315	0.21107
10-hr dead fuel loading	0.15268	0.19300	0.791	0.44309
100-hr dead fuel loading	-0.04281	0.06642	-0.644	0.53050

Residual standard error: 0.3097 on 13 degrees of freedom
Multiple R-Squared: 0.9755, Adjusted R-squared: 0.9624
F-statistic: 74.09 on 7 and 13 DF, p-value: 1.849e-09

Multiple regression analysis of extrinsic fuel properties and $F_{Surface}$ indicated that similar surface fuel properties were responsible for changes in $F_{Surface}$, but at different levels of significance. The

Table 4-3: Multiple regression analysis of selected extrinsic surface fuel properties and $F_{Surface}$..

Fuel Input	Estimate	Standard Error	t value	p value
Intercept	-566.055	146.952	-3.852	0.00200
Feathermoss fuel percent cover	315.618	91.761	3.440	0.00440
Fuel-bed depth	4647.591	673.847	6.897	1.09e-05
Live herbaceous fuel loading	10.289	96.343	0.107	0.91658
Live woody fuel loading	-7.797	24.440	-0.319	0.75476
Feathermoss fuel loading	5.173	4.956	1.044	0.31556
10-hr dead fuel loading	44.028	45.089	0.976	0.34665
100-hr dead fuel loading	-5.521	15.518	-0.356	0.72771

Residual standard error: 72.35 on 13 degrees of freedom
Multiple R-Squared: 0.9288, Adjusted R-squared: 0.8905
F-statistic: 24.23 on 7 and 13 DF, p-value: 1.730e-06

predicted $F_{Surface}$ was most sensitive to changes in fuel-bed depth which was highly significant ($p < 0.001$). Percent cover of feathermoss was moderately significant ($p < 0.01$). No other surface fuel properties had a significant influence on $F_{Surface}$, perhaps most surprising was the absence of feathermoss loading. Loading for this fuel type was up to 14 tonnes ha^{-1} and varied widely across all sites. Despite the small diameter and quick drying time of this fuel it was not weighed heavily by BehavePlus3 as a determinate of $F_{Surface}$. Though feathermoss loading was positively correlated with $F_{Surface}$, the correlation was weak ($p = 0.465$).

Chapter 5: Discussion & Conclusions

Overview

This section synthesizes results and draws conclusions with respect to how new information gained from this research applies to resource management agencies in Alaska. There are two sections in this chapter:

a) Discussion – proposes fuel succession categories, explains trends in flammability, discusses how assumptions of fire behavior models impact the flammability curve, and reviews differences in fire behavior analysis techniques between this report and the companion CSU report.
b) Conclusions – summarizes knowledge gained from this research and explains pertinence of results.

Discussion

The flammability curves represented by R_{Total} (figure 4-6), F_{Total} (figure 4-7), $R_{Surface}$ (figure 4-10), and $F_{Surface}$ (figure 4-11) depict a clear and consistent relationship between stand age and fire behavior. This relationship exists for all weather scenarios. Linear regression analysis of paired observed and predicted fire behavior data indicated that the linked model produced reliable estimates of fire behavior. Hierarchical cluster analysis of the flammability curves suggested three phases of fuel succession in upland black spruce forests in interior Alaska. Each phase has differences fire behavior and unique dynamics among fuels, weather, and fire behavior. These phases, described below, are the pioneer phase (0-20 years), the transition phase (20-45 years) and the forested phase (> 45 years).

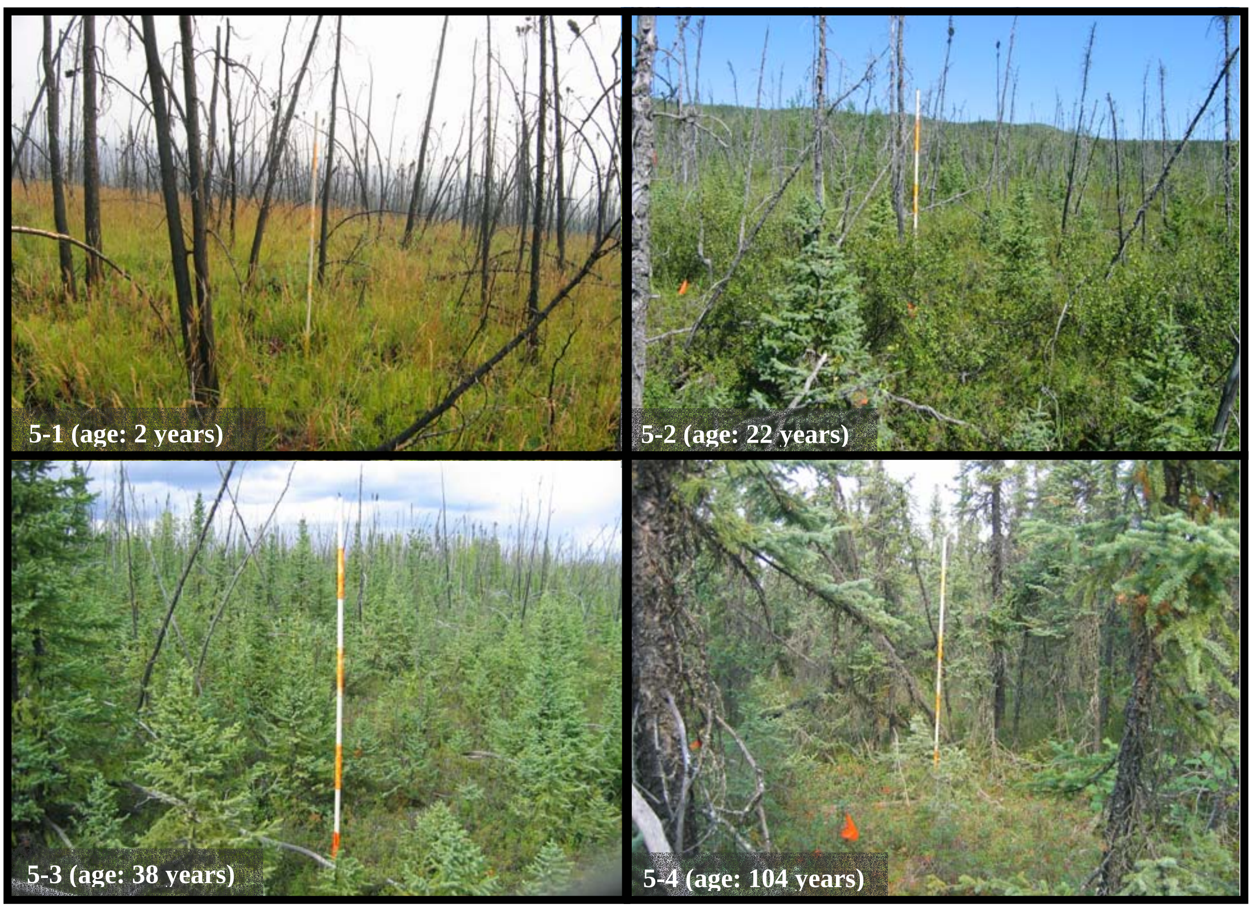
The first phase (pioneer phase) begins immediately after a stand replacing fire and continues for approximately 20 years. This phase corresponds to the early stand initiation phase (Oliver and Larson 1996). The pioneer phase is characterized by standing fire killed trees, an extensive cover of herbaceous plants and grasses, aggressive colonization by acrocarpous mosses, and light accumulations of leaf litter on the forest floor. DWD loading can be especially high during this phase if rates of tree fall are high. Sites in this phase have the lowest predicted fire behavior. The R_{Total} and F_{Total} are near zero for all weather scenarios; all predicted fires are smoldering surface fires.

The second phase (transition phase) includes young regenerating stands aged between 20 and 45 years. This phase corresponds to the later phases of Oliver and Larson's (1996) stand initiation phase. Forest composition is increasingly dominated by black spruce saplings and small trees; consequently *CBD* registers above zero and begins to steadily climb. In the groundcover layer, dwarf shrubs replace herbs as the dominant fraction. Loading of forest floor fuels increases dramatically, and initially dominant litter fuels are supplanted by feathermoss. DWD fuel loading begins to decline during this phase. Predicted fire behavior is only slightly higher than the pioneer phase under marginal and moderate fire weather conditions; however, under the extreme weather scenario, predicted fire behavior is markedly higher.

The third phase of fuel development (forested phase) applies to all stands > 45 years. This phase is characterized by a dense canopy of nearly pure black spruce and a deep layer of pleurocarpous mosses. The groundcover remains dominated by dwarf shrubs unless canopy cover is high, in which case the groundcover may nearly disappear. DWD and litter fuels are nearly absent. Measures of predicted fire behavior are dramatically higher relative to the previous phase for all weather scenarios, and especially so as weather severity increases. The variance of fuel characteristics among sites is high but unrelated to stand age. Despite this variance, *ROS* reaches a state of equilibrium for each weather scenario and *FLI* varies widely but is considerably higher than upper limits of control. Predicted fire behavior varies widely with weather. Fires are predicted to burn as rapidly moving active crown fires under the extreme weather scenario, a mixture of passive and active crown fires in the moderate weather scenario, and as a mixture of slow moving surface and passive crown fires (i.e. occasional torching) during the marginal weather scenario.

In general, our results agree with other research pertaining to succession and fire behavior in boreal forests. During the pioneer phase, the forest floor was initially devoid of fine fuels, and dominated by charred duff. In the youngest stand we sampled (2 years), the fraction of the forest floor categorized as charred duff (81%) was similar to observations recorded by Foote (1983) in stands < 5 years (76%). The only fine fuels (in the forest floor layer) recorded at this site were acrocarpous mosses and liverworts (7% cover) including *Marchantia polymorpha*, *Polytrichum* sp. and *Ceratodon purpereus*; this was expected given that other research indicates these species are aggressive pioneers of recently burned black spruce forests (Viereck 1973, Viereck and Dyrness 1979, Viereck and Schandelmeier 1980, Foote 1983, Schimmel and Granstrom 1997). During the course of the pioneer phase, acrocarpous mosses and leaf litter were pervasive forest floor types. High acrocarpous moss cover (52%) and hardwood leaf litter cover (29%) at a 12 year old site attest to the relative dominance of these forest floor types. This trend was also noted by Viereck (1973) and Foote (1983). Despite high cover during the pioneer phase, litter layer depth was shallow, and loading was relatively low (< 2 tonnes ha^{-1}).

Figures 5-1 – 5-4: Phases of fuel succession in upland black spruce. Figure 5-1 depicts regenerating black spruce in the pioneer phase; figures 5-2 and 5-3 show the variation in canopy development during the transition phase; and figure 5-4 provides an example of a stand during the forested phase. Height poles are 2 meters.



The establishment and rapid expansion of pleurocarpous mosses recorded during the transition phase has also been observed by Foote (1983), and Schimmel and Granstrom (1997). Expansion of feathermoss continued well into the forested phase before reaching plateau with an average cover of 89% for stands over 100 years, (figure 4-2). Similar values for feathermoss cover were also reported by Schimmel and Granstrom (1997) for the Scots pine boreal forest type in Sweden. This agreement suggests that feathermoss succession following forest fires may be similar throughout the boreal forest biome, at least in North America and Europe. Dominance of pleurocarpous mosses in mature black spruce forests of Alaska has also been reported by others (Viereck and Schandelmeier 1980, Foote 1983).

Coarse DWD loading was highest in the pioneer and transition phases and lowest during the forested phase (figure 4-4). A pulse of coarse DWD during the first 50 years following fire has been observed across a wide range of coniferous forest types (Fahnestock 1976, Romme 1982, Agee and Huff 1987, Schimmel and Granstrom 1997). Reported trends for coarse DWD loading diverge for late successional stands. Fahnestock (1976) and Romme (1982) both report a resurgence of coarse DWD loading in mature stands. In contrast, this study and results reported by Schimmel and Granstrom (1997) indicate that after an initial peak, coarse DWD loading equilibrates at < 2 tonnes ha^{-1} and stays steady into late successional stands. The divergence between trends is likely due to differences in the disturbance frequency among study areas. Boreal forests in northern Sweden (Zackrisson 1977, Engelmark 1984, Bradshaw and Zackrisson 1990) and interior Alaska (Yarie 1981, Fastie et al. 2002) are affected by disturbance frequently enough to limit maximum stand ages to 350 years and 250 years, respectively. The maximum stand age sampled by Schimmel and Granstrom (1997) did not exceed 350 years and the maximum stand age sampled in this study did not exceed 250 years. In contrast, the sub-alpine forests studied by Fahnestock (1976) and Romme (1982) appear to have a much longer disturbance free period and the maximum stand age approached 600 years. Thus, senescence of overstory trees and consequent buildup of coarse DWD is more likely in sub-alpine forests than in relatively short-lived boreal forests.

Variance of coarse DWD loading during the early seral phases (i.e. pioneer and transition phases) was high among sites (figure 4-4). This variability may be related to fire severity. In black spruce forests, the rate at which trees fall after fires is likely a function of burn depth. Black spruce forests of interior Alaska are frequently underlain by permafrost; as a consequence rooting depth is shallow and restricted to the organic mat (Van Cleve et al. 1983). High severity fires that burn down to mineral soil eliminate the supporting substrate for fire-killed trees and they can fall relatively rapidly. This organic mat is not entirely consumed by low severity fires and the root systems of fire-killed trees remain anchored permitting trees to stand for longer periods of time. Given this information it is plausible that pulses of coarse DWD input following fire may be higher and occur more rapidly if fire severity is high.

Fuel succession studies reported no trends between 1-hr DWD fuel load and stand age (Fahnestock 1976, Schimmel and Granstrom 1997); the results of this study also show no relationship between loading of 1-hr DWD and age. Loading was also low (< 1 tonne ha^{-1}) and contributions to the fine fuel loading of surface fuels were inconsequential.

Our findings relating to the groundcover layer were similar to those reported by Schimmel and Granstrom (1997) who reported that herbaceous plant loading was < 1 tonne ha^{-1} and remained steady with age. Although we noted a slight positive trend, our fuel load values were similar. The maximum live herbaceous fuel load at our sites was just over 1 tonne ha^{-1}. For dwarf shrubs, Schimmel and Granstrom (1997) reported the lowest fuel loads in stands sampled during the first two decades after fire. Loading was increased in older stands and averaged 2 tonnes ha^{-1}. Trends for this study were slightly different. Loading was also lowest during the first two decades after fire. This was followed by a spike and loading was between 2 – 4 tonnes ha^{-1}. In stands < 75 years loading subsided and the average was 2 tonnes ha^{-1}. The spike in dwarf shrub loading that we observed may be related to differences in post-fire stand structure. Forest fires in Scots pine forests of Sweden do not result in complete overstory mortality; fires in Alaskan black spruce generally do. This difference in mortality would likely increase the amount of sunlight received by the groundcover layer in Alaska and promote more vigorous growth of dwarf shrubs followed by senescence and a decrease in loading as the overstory became re-established.

Black spruce overstory development results reported in this study are different from results reported by other studies of succession in Alaska (Foote 1983, Viereck et al. 1986). Tree density data was not reported in *Results* section. Briefly, the relationship between tree density and stand age was similar to the relationship between *CBD* and stand age. Mean tree density was nearly zero during most of the pioneer phase, increased to 1719 stems ha^{-1} during the transition phase, and to 6670 stems ha^{-1} during the forested phase. During the forested phase, tree density varied widely, from 1625 to 14,142 stems ha^{-1}, and, as with *CBD*, appeared to be a function of site specific environmental conditions, or, as recently reported, related to pre-fire stand density (Johnstone and Kasischke 2005). Mean tree density during the forested phase was three times higher than tree density reported by Foote (1983) and Viereck et al (1986). Foote (1983) and Viereck et al (1986) also reported that stand density reached a maximum of between 3000 and 6000 stems ha^{-1} between 30 and 60 years, before falling to lower densities in older stands. In contrast, we recorded maximum stand densities at sites aged > 50 years and did not observe a decline in older stands. The difference in stem density is possibly due to varying definitions. We defined stems as all tree species > 1.37 meters (DBH). Definitions from authors referenced above were unclear.

Fire behavior was largely influenced by three fuel variables; *CBD*, W_{ff}, and feathermoss cover. *CBD* was the most important determinant of R_{Total} because it represents the horizontal contiguity of canopy fuels which in turn determines fire type. Each increase in fire type increases the effect fuels and weather have on R_{Total} (Alexander and Lanoville 1989). *CBD* is also an important determinant of F_{Total}. As with R_{Total}, increasing fire type induces large marginal increases in F_{Total}. This is because formulas used to calculate F_{Total} for each successive fire type make increasingly larger percentages of fine fuels available for consumption.

Table 5-1: Fire type, as a percentage of sites, for the three fuel succession categories and three weather scenarios.

Fuel Succession Phase	Weather Scenario and Fire Type ('Passive' and 'Active' refer to crown fires)								
	Marginal (20th Percentile)			Moderate (55th Percentile)			Extreme (95th Percentile)		
	Surface	Passive	Active	Surface	Passive	Active	Surface	Passive	Active
Pioneer	100	0	0	100	0	0	100	0	0
Transition	80	20	0	60	40	0	0	100	0
Forested	36	64	0	0	36	64	0	0	100

CBD is indirectly correlated with crown fire initiation. Normally I_O is determined by variations in *CBH* but in this study *CBH* did not exceed 1 m. The consistently low values of *CBH* essentially permitted crown fire initiation if the overstory was present and if *CBD* exceeded 0, crown fire initiation was possible.

CBD is directly correlated with the transition from passive to active crown fire type. *CBD* is the only variable in the R_O formula (*Appendix 5*, eq. 5-8) and the only fuel-based variable in the $CROS_A$ formula (*Appendix 5*, eq. 5-9). *CBD* is inversely correlated with R_O and positively correlated with $CROS_A$. R_O and $CROS_A$ are the only variables used to calculate *CAC* (*Appendix 5*, eq. 5-10), a ratio used to assess crown fire type. Assuming a crown fire is initiated, the crown fire is classified as active if *CAC* > 1 and passive if *CAC* is ≤ 1. Based on this scenario, *CBD* has a compounding positive affect on *CAC* because R_O is the denominator and $CROS_A$ is the numerator. Essentially this means that small increases in *CBD* can cause fire type to transition from passive to active.

The influences of *CBD* on fire type extend the influence of *CBD* to R_{Total} and F_{Total}. This influence is apparent in the designation of successional phases. Stands with little or no overstory (*CBD* ~ 0 kg m^{-3}) produced only surface fires and thus R_{Total} and F_{Total} were always relatively low. Stands with a *CBD* > ~0, but < 0.1 kg m^{-3}, the proposed minimum threshold for supporting active crown fires (Agee 1996), supported passive crown fires but did not support active crown fires. R_{Total} and F_{Total} were higher relative to stands with no overstory, but less than if active crown fires occurred. Stands with a *CBD* ≥ 0.1 kg m^{-3} were able to support active crown fires. As a consequence R_{Total} and F_{Total} values were the highest reported. The fire behavior values were inputs for the hierarchical cluster analysis which consequently delineated fuel succession phases based on *CBD* brackets. *CBD* values were: ~ 0 kg m^{-3} at all sites in the pioneer phase, ~0 – 0.1 kg m^{-3} for all sites in the transition phase, and ≥ 0.1 kg m^{-3} for all sites in the forested phase.

The influence of *CBD* on R_{Total} is compounded further by the positive correlations between *CBD* and $CROS_A$, and between *CBD* and $CROS_P$.

W_{ff} only influenced F_{Total}, but is primarily responsible for the negative exponential shape of the F_{Total} curve. Though W_{ff} was near zero (average: 0.2 tonnes ha^{-1}) during the pioneer phase, $F_{Surface} > I_O$, and prevented W_{ff} from contributing to F_{Total}. During the transition phase, W_{ff} rose slightly (average: 0.6 tonnes ha^{-1}), passive crown fires made W_{ff} available for consumption, and W_{ff} began to contribute to F_{Total}. However the contribution of W_{ff} to F_{Total} was minor during the transition phase. Under the extreme weather scenario, when all predicted fires in the transition phase were passive, W_{ff} contributed 21.2% to F_{Total}. In contrast, under the same weather conditions, W_{ff} contributed 95.3% to F_{Total} in the forested phase. Rising forest floor loads were primarily responsible for increased F_{Total} from the pioneer phase to the transition phase and W_{ff} was primarily responsible for increases F_{Total} from the transition to the forested phase (table 5-2). The average loading of W_{ff} during the forested phase was 10.1 tonnes ha^{-1} and rivaled loading of the surface material layer of the forest floor. As shown in the example above, the large increase in W_{ff} had a dramatic impact on F_{Total} if weather permitted crown fire activity.

Table 5-2: Relative contributions of surface fuels and W_{ff} to F_{Total} for the three fuel succession categories and three weather scenarios.

Fuel Succession Phase	Percent contribution to F_{Total}					
	Marginal (20^{th} Percentile)		Moderate (55^{th} Percentile)		Extreme (95^{th} Percentile)	
	Surface Fuels	W_{ff}	Surface Fuels	W_{ff}	Surface Fuels	W_{ff}
Pioneer	100	0	100	0	100	0
Transition	98.1	1.9	93.4	6.6	78.8	21.2
Forested	57.2	42.8	11.3	88.7	4.7	95.3

W_{ff} was also largely responsible for the weak positive linear correlation between stand age and F_{Total} during the forested phase. This relationship, which was not statistically significant, is not seen in figure 4-7 because F_{Total} is displayed on a log scale and values reported for the forested stage are compressed. If F_{Total} was displayed on a normal scale for any of the weather scenarios the linear relationship with age during the forested phase would be apparent. R^2 for the relationship between F_{Total} and stand age during the forested stage for each weather scenario ranged from 0.1 – 0.20 and the p values were not significant ($p \approx 0.1$).

Feathermoss cover was also an important determinant of R_{Total} and F_{Total}. During the pioneer phase, the forest floor fuel load was near zero and horizontally discontinuous. This produced measures of fire behavior near zero. The development of feathermoss in tandem with canopy establishment during the transition and forested phase produced increased measures of surface fire behavior. The higher measures of $F_{Surface}$ exceeded I_O and crown fires initiated with the emergence of a canopy. This resulted in a large difference in fire behavior between the pioneer phase and the transition phase. Though fuel-bed depth was a significant determinant of $F_{Surface}$ (table 4-3) it did not change with age and had no impact on temporal changes in fire behavior.

As explained above, canopy fuels (expressed as *CBD* and W_{ff}) largely determine the relationship between fire behavior and fuel succession in black spruce forests. It is not surprising that the sigmoidal response curve of R_{Total} (figure 4-6) and F_{Total} (figure 4-7) resemble the temporal response curves of *CBD* (figure 4-5) and W_{ff}. Surface fire behavior is strongly related to total fire behavior because growth of feathermoss, the primary fuel impacting surface fire behavior, is highly correlated with *CBD*. Previous research has shown that these mosses are dependent on the overstory for shade (Tamm 1964), providing some explanation for why these two fuel properties develop in unison.

The impact of canopy development on fire behavior has been noted in other fuel succession studies, but that impact differs by forest type. On the Olympic Peninsula in Washington, crown closure is associated with low predicted fire behavior. In these forests, canopy closure causes the base of the live crown to recede upwards and the dead branches self-prune. Following crown closure in these forests, the

CBH was 20 meters above the surface fuels and the canopy was not deemed to be susceptible to ignition from surface fires (Agee and Huff 1987). In sub-alpine forests of northwestern Wyoming, high *CBH* was also presented as a reason for low susceptibility of young forests (with high *CBD*) to crown fires (Romme 1982). Romme (1982) argued that crown fire risk does not become high until forests age > 400 years. Only then do low *CBH* and a continuous surface fuel-bed of fine fuels coincide with high *CBD*. These three conditions are present in black spruce stands as early as 45 years after establishment (the beginning of the forested phase). In the sub-alpine forests of Alberta, predicted fire behavior had only a minor relationship with fuels and that relationship did not change with age in stands > 25 years (Bessie and Johnson 1995). Bessie and Johnson report that flammability in the three youngest stands (aged 20 to 25 years) was significantly less than flammability of stands > 25 years old, 25 years was also the reported age of crown closure for their study area. This change in flammability may be a result of the canopy achieving the minimum threshold *CBD* for active crown fire spread. If so, the same pattern of increasing fire behavior below a minimum threshold for active crown fire is achieved exists in black spruce forests of interior Alaska as well. Black spruce forests in interior Alaska achieve this threshold by age 45. The 20 year difference in threshold age between stands in Alberta and Alaska is reasonable given that the colder climate in Alaska may slow forest development.

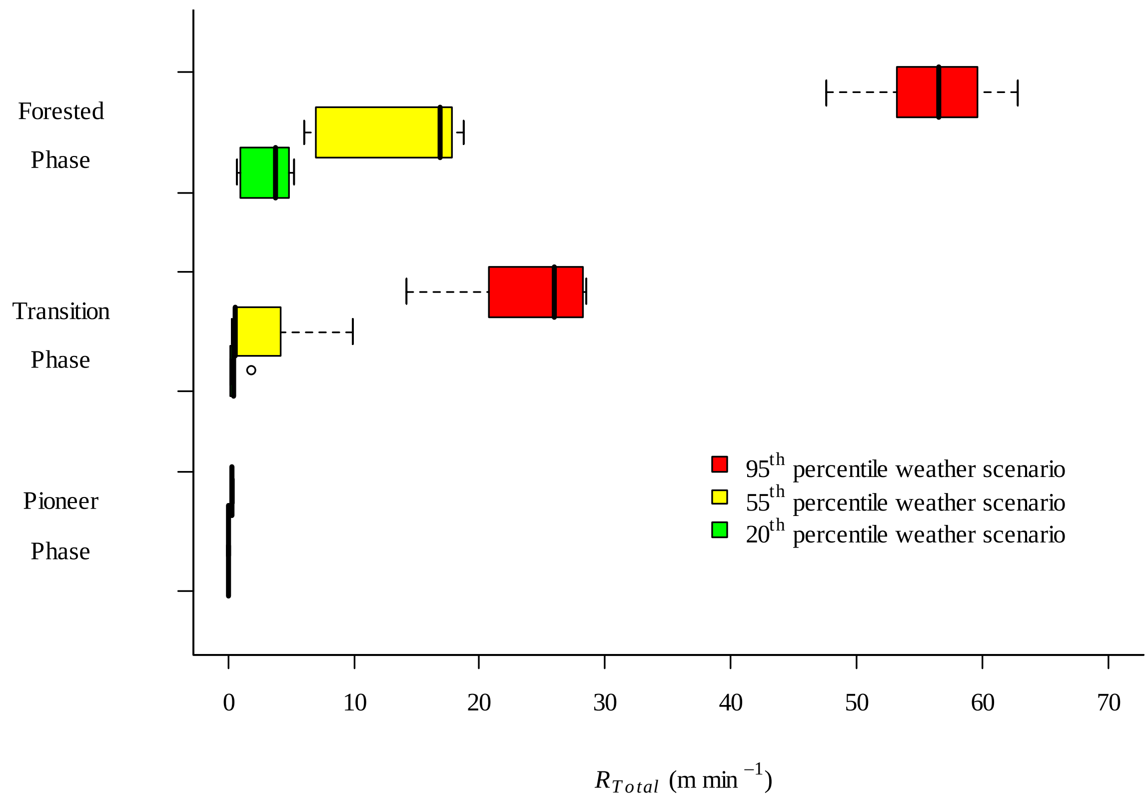
Fire behavior is impacted by the properties of feathermoss which support surface fires with high *ROS* and *FLI*. The high *SAV* ratio of feathermoss lowers the effective heating number, a variable in Rothermel's (1972) surface spread equation (*Appendix 5*, eq. 5-1), thereby increasing *ROS*. The high *SAV* ratio also means that feathermoss moisture content can adjust to the ambient humidity within a matter of minutes. Feathermoss also attains high fuel loads that range from 10 to 14 tonnes ha^{-1} during the forested phase. The high loading of rapidly drying fuels exists as a nearly continuous mat capable of supporting high intensity surface fires. The fuels that feathermoss replaces, primarily hardwood litter and acrocarpous mosses, have the opposite qualities. These early seral fuels have a lower (intermediate) *SAV* ratio and loading (generally < 5 tonnes ha^{-1}) and consequently do not burn well (Schimmel and Granstrom 1997).

Multiple regression analysis of surface fire behavior predicted by BehavePlus3 shows that cover of feathermoss and fuel-bed depth are the primary determinants of surface fire behavior. Schimmel and Granstrom (1997) also concluded that the change in forest floor from litter fuels to feathermoss fuels drove changes in fire behavior over a successional gradient. Feathermoss development in the boreal forests of Sweden (Schimmel and Granstrom 1997) was nearly identical to feathermoss development observed in this study (figures 4-1a and 4-2a). Consequently the phases of fuel succession (0-20 years, 20-45 years, and > 45 years) proposed by Schimmel and Granstrom (1997) and the associated fire behavior (lowest, intermediate, and highest, respectively) are identical to the fuel succession categories and associated fire behavior presented in this report. The main difference between the two studies is that predicted fire behavior measures for the two later fuel succession phases in Alaska were many times higher than in Sweden; a function of the intense crown fire behavior supported by black spruce forests which develops in unison with feathermoss. Crown fires are relatively rare in the Scots pine forests of Sweden and only surface fuels influence temporal changes in fire behavior.

While other fuels also change with age, their relative impacts on predicted fire behavior were low and almost completely overwhelmed by the combined effect of black spruce and feathermoss on fire behavior. Despite the relatively large quantities of blowdown that follow crown fires, accumulations of coarse DWD fuels in our study were still well below reported loadings for the light slash model (Anderson 1982) and loading was not high enough to cause a significant increase in *FLI*. Coarse DWD also reduces *ROS* by increasing the heat sink component of the Rothermel (1972) surface spread model. Components of the groundcover layer (live herbaceous and live woody loading) lacked changes with age on a scale large enough to affect predicted fire behavior.

Conclusions from other research on the relationships between flammability and stand age in boreal forests of North America were not supported by the results of this study. Van Wagner (1984) concluded that flammability of boreal forests reaches a zenith after two or three decades of growth and then declines once the overstory becomes established. The suggested reason for this proposed pattern is, as the forests age, the elevated canopy and dense organic mat are increasingly unable to support high intensity crown fire while high surface fuel loads and dense regenerating canopy in younger stands are more conducive to high intensity crown fires. While this pattern may be true for some boreal forests, such as those common across Canada, the opposite pattern exists for black spruce stands in Alaska. In mature forests, the organic mat contributes significantly to fuels consumed in the flaming front. Additionally, the canopy remains low (maximum *CBH* is only 1-2 meters from the surface), and fuel ladders are extensive; both properties support easy transition from surface to crown fires. Results reported by Yarie (1981) suggest that flammability of Alaskan black spruce may actually decline slightly with age; however results of this research show that flammability initially increases rapidly and then

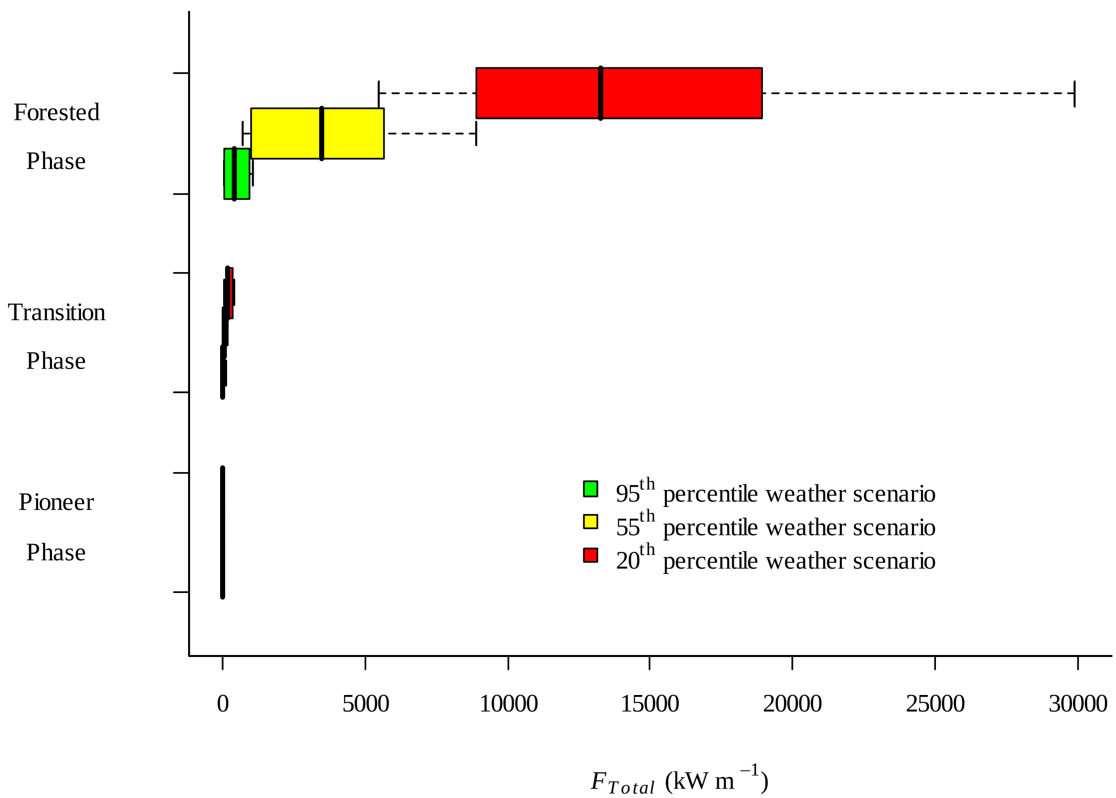
Figure 5-5: Boxplots showing R_{Total} relative to fuel succession phase and weather. The dark line represents the median, the boxed area represents the first and third quartile and the whiskers represent the minimum and maximum values.



remains flat. There are two reasons results of Yarie (1981) analysis may suggest declining flammability for black spruce. The low sample size in his study (3-5 samples per site) may underestimate stand age (De Volder 1999) and Yarie's (1981) analysis did not include stands in the 0-20 year age bracket, the period when black spruce may have the highest resistance to fire. A greater number of samples and and the ability (Yarie excluded the 0-20 year age bracket due to possible affects of fire suppression) to include the 0-20 year age bracket may have shifted the stand age distribution enough in Yarie's study to more closely resemble the Weibull distribution rather than the negative exponential distribution. If this was the case, the Weibull distribution would then have likely generated a shape parameter value > 1, suggesting that fire behavior increases with stand age. In contrast, De Volder's (1999) analysis of stand distribution in black spruce on the Kenai Peninsula resembled the Weibull distribution and lead to the conclusion that flammability increased with stand age. Though, due to the nature of these fire history studies it is not possible to attribute these changes in flammability to temporal changes in the fuel complex.

The analysis of observed versus predicted values of fire behavior indicated that the linked model did a good job predicting fire behavior in black spruce forests. However this comparison does not cover the range of predicted fire behavior for the pioneer and transition phases. Cruz's (2005) crown fire model calculated *ROS* for several passive and active crown fires that were well correlated with our observed values. Predicted *ROS* for crown fires in this study also fell within the range of observed *ROS* for several other fire behavior studies (Alexander and Lanoville 1989, Stocks et al. 2004) that were used to develop Cruz's crown fire model. Since seven out of eight fires were observed burning in sites in the forested phase over a wide range of weather conditions, we believe the linked model reasonably predicts R_{Total} in mature black spruce forest. Data from two sites suggest that the active crown fire component of Cruz's crown fire model slightly over-predict *ROS* during extreme fire weather (figure 4-9). The ability of the linked model to accurately predict R_{Total} for fuels in the pioneer and transition phase is largely untested for any weather conditions.

Figure 5-6: Boxplots showing F_{Total} relative to fuel succession phase and weather. The dark line represents the median, the boxed area represents the first and third quartile and the whiskers represent the minimum and maximum values.



Based on published values, F_{Total} in boreal forests ranges from 1100 – 8200 kW m^{-1} during passive crown fires and F_{Total} ranges from 4800 – 100,000 kW m^{-1} during active crown fires (Alexander and Lanoville 1989, Ryan 2002). Predicted F_{Total} for this study was lower than the published values during passive crown fires. The average predicted F_{Total} for passive crown fires was 591 kW m^{-1} and ranged from 91 – 1105 kW m^{-1}. Predicted F_{Total} for active crown fires was closer to the published values, but at the low end of the range. The averaged predicted F_{Total} was 11,293 kW m^{-1} and ranged from 3144 – 29,886 kW m^{-1}. This indicates that the linked model may under predict F_{Total}, especially during passive crown fires.

Predicted fire type has a basis in reality similar to predicted *ROS* because it was compared with video footage of the same eight paired fire observations used to assess predicted *ROS*. Van Wagner's

(1977) crown fire initiation and spread model tended to over-predicted fire type; this was anticipated because Van Wagner specified the model was intended for a fuel complex with a distinct gap separating surface and canopy fuels. In Alaskan black spruce forests, canopy fuels are often intertwined with surface fuels. This problem was mitigated by assigning a minimum I_O to Van Wagner's model. Without a minimum I_O, Van Wagner's model would predict crowning even when $F_{Surface}$ = 0. With a minimum I_O set to 80 kW m^{-1}, Van Wagner's model correctly predicted fire type for 94% of the observed fire events. Thus, it appears the linked model has the ability to predict fire type for a wide range of weather conditions in mature black spruce forests, but its ability to accurately predict fire type during the pioneer and transition phase is yet to be assessed.

It was not possible to compare surface fire behavior predictions to actual fire behavior values because of the pervasive influence of canopy fuels in black spruce forests. Given the high loading of forest floor material, BehavePlus3 appeared to under-predict $F_{Surface}$, especially during the forested phase when forest floor loading was highest. There are two reasons BehavePlus3 may under-estimate $F_{Surface}$. Both reasons have to do with the use of reaction intensity (I_R) to calculate $F_{Surface}$ (*Appendix 5*, eqs. 5-2 and 5-3) instead of Byram's *FLI* model (*Appendix 5*, eq. 5-5). Relative to estimates produced by Byram's *FLI* model, I_R produces proportionally lower estimates of $F_{Surface}$ as fuel-bed density increases (Catchpole et al. 1993). By adding rather than averaging the fuel-beds (*Chapter 3, Model Inputs*), surface fuel bulk density was inflated enough to overcome the threshold bulk density explained in the *Model Inputs* section of *Chapter 3* and generate a response from changing forest floor loads. Even so, the predicted $F_{Surface}$ may still underestimate $F_{Surface}$. The second reason is that the declining accuracy of BehavePlus3's ability to estimate $F_{Surface}$ as bulk density increases means that coarse dead fuels (i.e. the duff layer) cannot be incorporated into the surface fuel model. The inability of BehavePlus3 to incorporate duff material may decrease estimates of $F_{Surface}$ by a factor of two or three (Rothermel 1993) and has been noted by several other authors who have used BehavePlus3 to model fire behavior in boreal forests (Bessie and Johnson 1995, Hely et al. 2001, Cruz et al. 2004).

It is unlikely that this limitation of BehavePlus3 contributed to an inaccurate assessment of fuel succession categories because the $F_{Surface}$ and $R_{Surface}$ were overwhelmed by crown fire activity when forest floor loading was high. Even if actual fire behavior from forest floor fuels was high enough to rival measures produced by the overstory there would be little affect on the flammability curve because the forest floor develops in tandem with the overstory. Additionally, the low *CBH* of the canopy initiates crown fires even when $F_{Surface}$ is low; thus it is unlikely that underestimates of $F_{Surface}$ would cause any crown fires to be incorrectly categorized as surface fires. Predicted $F_{Surface}$ described in the *Results* section of this chapter might contribute to an underestimate of F_{Total} if a large fraction of the duff layer (a potentially large source of available fuel) is consumed. This has important implications for resource managers trying to assess potential *FLI* using BehavePlus3 for surface fuels in Alaska where there is a thick organic mat but no overstory involvement (i.e. shaded fuel breaks).

This study highlights the dynamic between weather, fuels and fire behavior. Earlier work in boreal forests (Bessie and Johnson 1995) suggested that fire behavior was driven by changes in weather and largely overwhelmed the impacts that successional changes of the fuel complex would have on fire behavior. Our results show that this claim cannot be entirely extended to black spruce forests in interior Alaska (figure 5-5 and 5-6) and that successional changes in the fuel complex strongly influence fire behavior, regardless of weather.

In large part, Bessie and Johnson's analysis was limited to forests aged > 25 years with a developed canopy (i.e. forests with a closed canopy). Had we also limited our study sites to forests with a mature canopy (i.e. stands aged > 45 years where trees have reached their maximum height and *CBD* > 0.1 kg m^{-2}) we would also have concluded that there is no significant relationship between fire behavior and stand age. Thus, for stands > 45 years, our results concur with Bessie and Johnson's (1995) conclusion that fire behavior is limited by weather not fuels. Similarly, work by Cruz et al (2005) show that the *CBD* influence on *ROS* for active crown fires is secondary to weather variables (windspeed and fine fuel moisture, a function of relative humidity) and Ryan (2002) argues that wind is the single most important driver of crown fire behavior. This body of knowledge strongly supports the hypothesis that in mature stands of coniferous boreal forests, fire behavior is largely a function of weather. But our research importantly notes that during early-mid stages of development, fire behavior is a function of available fuels. Our conclusions are supported by Bessie and Johnson (1995) when they include the three youngest stands (all aged < 25 years) in their analysis. In addition to this study, Schimmel and Granstrom (1997) also note fire behavior can be limited by successional patterns in the fuel complex rather than weather.

Fire behavior was most limited by fuels during the pioneer phase when F_{Total} and R_{Total} were close to zero, even under extreme weather conditions. Since fuels were the limiting factor, fire behavior was insensitive to changes in weather (figures 5-5 and 5-6). During the transition phase, predicted fire behavior was more sensitive to weather. R_{Total} was most sensitive to changes in weather because the newly formed continuous fine fuel-bed removed fuels as a limiting factor on $R_{Surface}$ (figure 5-5) F_{Total} was more sensitive to changes in weather relative to the pioneer stage but since W_{ff} and *CBD* were very low, fuels were still a limiting factor for F_{Total} (figure 5-6). During the forested phase, predicted fire behavior was extremely sensitive to weather with large differences in predicted fire behavior observed for each of the weather scenarios. R_{Total} was insensitive to changes in fuels while F_{Total} was still sensitive to changes in W_{ff}. (figures 5-5 and 5-6). Additional responses of predicted fire behavior to successional changes in fuels and weather are presented in tables 4-1 and 5-1.

Some of the methods used to analyze fire behavior in this section of the report are fundamentally different from the companion section produced by Colorado State University (CSU) and concurrently submitted under Joint Fire Science Program project no. 04-2-1-96. As a result, fire behavior predictions and conclusions about fire behavior may not be comparable.

The most prominent difference between the two research components is the number of observations used to compare observed and predicted fire behavior. These comparisons are derived from the same datasets: CSU used 42 fire behavior observations to evaluate the efficacy of the BehavePlus3 and FBP System programs and this report used eight observations to evaluate the efficacy of the linked fire behavior model. There are two reasons we eliminated 34 observations from CSU's fire behavior dataset. First, we concluded that many of the observations in the CSU dataset were correlated. At several sites, multiple fire behavior observations were collected at the same point, during the same time period, and under the same measured weather conditions. These observations tended to be surface fires and their duplication skewed the fire behavior distribution towards low intensity fires. Including this large number of low intensity fires may have overwhelmed the relative influence of intermediate and high intensity fires in our regression analysis. To avoid this, we randomly selected single points from different sites, producing an even distribution of observed fire behavior. Additional observations were removed such that custom fuel models were represented only once.

Another difference between the two threads of research was the use of wind reduction factors. The CSU report used a wind reduction factor of 0.11, as proposed by Norum (1982) for closed canopy black spruce forests. The majority of the sites selected for our analysis had an open canopy and thus more suited to Norum's wind reduction factor of 0.22 for open canopy black spruce stands. Had we used the lower wind reduction factor for this analysis, we would have reduced estimated mid-flame wind speeds by half. This reduction in wind speed would significantly underestimate crown fire behavior by reducing predicted $F_{Surface}$. The lower wind reduction coefficient used by CSU had little effect on their results because only the surface component of BehavePlus3 was used to predict fire behavior, with mid-flame wind speeds measured directly at each site.

The CSU and Yale researchers also used different techniques to estimate wind. CSU relied on a combination of on-site wind measurements and wind measurements from nearby RAWS stations and lag time between wind and fire behavior measurements averaged 60 minutes. Yale University determined windspeed directly from the fire videos, visually estimating 10-meter windspeed by applying the Beaufort wind scale. We believe this produced more reliable wind estimates during the fire because fire behavior responds rapidly to changes in windspeed (Albini 1982, Taylor et al. 2004).

Two potentially significant components of the fuel complex were omitted from our analysis because of difficulty incorporating them into the custom fuel models; the duff layer and the tall shrub/sapling layer. The potential impacts of excluding the duff layer have already been discussed earlier in this section. The tall shrub layer and saplings were especially prominent in the later end of the pioneer phase and early part of the transition phase, but also occurred at sites in the forested phase. The dominance of tall shrubs during early succession in interior Alaska has been previously noted (Foote 1983). These fuels, especially black spruce saplings, could be a potentially significant source of flammable fuel. If included in the fuel models these fuels could increase F_{Total} and R_{Total} at sites without canopies and act as fuel ladders at sites with an overstory. Cruz's crown fire model which was often invoked to model passive crown fires during the transition phase may do a good job of representing the effect of this class of fuels on R_{Total}, but comparisons of observed and predicted values at the pioneer and transition phases are needed to verify this assumption. The fraction of these fuels that burn during fires is unknown, but it is nearly certain that F_{Total} is underestimated, especially during the transition phase when these fuels are abundant and a sufficient fuel-bed of fine dead fuels exists to ignite them.

This analysis also does not directly address different pathways of succession and their influence of the flammability curve. Site selection factors were used to minimize the large influence of slope and aspect on forest development (Viereck 1973), but one variation that was difficult to standardize was disturbance history. Research has shown that fire severity (Viereck and Dyrness 1979, Foote 1983, Lieffers et al. 1993, Arseneault 2001, Johnstone and Kasischke 2005) and pre-fire stand composition (Johnstone and Kasischke 2005) can affect successional trajectories in black spruce. Therefore, this study must be taken as a general overview of successional trends. The large range in *CBD* reported for stands in the forested phase is probably related to the severity of the fire that initiated the stand and the pre-fire stand composition.

Fire severity may have strong impacts on forest development trajectories that could strongly influence successional patterns of flammability. Johnstone and Kasischke (2005) conclude that high severity fires may produce a deciduous phase that precedes pure stands of mature black spruce. Studies that investigate the susceptibility of burning for deciduous and coniferous stands in boreal forests show that a deciduous phase would likely delay high intensity fire behavior (Bergeron 1991, Hely et al. 2001). We did not observe such a deciduous phase at any of the sites, possibly indicating that many stands in our study regenerated following low severity fires. One of the stands in the pioneer phase (12 years) established following a late season high severity fire. The impact of this high severity fire was evident because of the prevalence of deciduous tree seedlings and saplings and the absence of dwarf shrubs and grasses that typically occur following low severity fires (Viereck and Dyrness 1979, Boucher 2003). Over time this site may produce a stand of deciduous trees with an understory of black spruce.

We also noticed that the observed patterns of flammability seemed to wane at the southern extreme of black spruce forests in Alaska. One site on the Kenai Peninsula was removed from analysis because *CBD*, W_{ff}, and forest floor loading were exceptionally high, indicating that the stand was more productive than stands north of the Alaska Range. We suspect that the durations of the pioneer and transition phases may be shorter in black spruce stands in the Matanuska-Susitna Valley and on the Kenai Peninsula where the climate is relatively mild.

The widespread agreement of this study with other chronosequence studies in boreal forests (Foote 1983, Viereck et al. 1986, Schimmel and Granstrom 1997) suggests that concerns regarding the utility of studies that substitute space for time (Johnstone et al. 2004) are unfounded unless site specific trends are desired.

Conclusion

The results of the flammability curve analysis address the knowledge gap stated by Alaska Fire Service concerning the relationship between stand age and flammability (*Chapter 1*, *Project Justification* section). The two are indeed linked, although the relationship ends relatively quickly; fire behavior is relatively uniform in stands > 45 years. The positive relationship between fire behavior and stand age for stands aged < 45 years strongly suggests that young stands (< 20 years) can act as reliable fuel breaks even under extreme weather conditions. This relationship also indicates that developmental changes in the forest floor and canopy are the primary drivers of fire behavior for stands < 45 years. The concurrent regeneration of black spruce and feathermoss increases flammability until threshold conditions are reached at crown closure (approximately 45 years). Thereafter weather conditions overwhelm differences in the fuel complex.

The importance of this research to resource managers is that burned over stands of black spruce can reliably serve as fuel breaks for at least 20 years. Thereafter, these burned over stands will vary as to their efficacy in mitigating fire behavior for another 20 to 30 years, with increasing F_{Total} and R_{Total} expected, especially as weather conditions become more severe. Fire behavior for stands within the forested phase (> 45 years) is primarily a function of weather, thus fire management organizations should focus on weather conditions rather than subsequent changes in fuels when assessing fire hazard in mature stands of black spruce.

Based on fire behavior predictions, Theisen (2003) concluded that shaded fuel-breaks reduce some measures of fire behavior while exacerbating others. With respect to the ability of shaded fuel breaks to mitigate fire behavior, we believe that stands burned by stand replacing fires are much more effective toward preventing wildfires from burning in the wildland urban interface. While we did not explore the respective costs of using prescribed fire versus creating shaded fuel breaks, we suggest that prescribed fire may be a viable and effective alternative.

Climate change is altering the vegetative landscape and disturbance regimes in Alaska. Annual area burned in boreal forests of North America has grown (Kasischke et al. 1999), the length of the burning season appears to be increasing (Wotton and Flannigan 1993), and potentially, so may the incidence of weather supporting high severity fires. Over time, these trends will increase the percentage of black spruce stands in early successional phases; based on observations by Johnstone and Kasischke (2005), the increase in high intensity fires could extend the deciduous phase of regenerating black spruce. Over time, the combined effect of an increasing areal extent of early seral black spruce forests and the slower development to a closed canopy black spruce overstory would decrease the contiguity of mature black spruce forests and ultimately serve as a negative feedback, reducing fire size and frequency (Rupp et al. 2002). Fire frequency may decrease as the area of fuel types receptive to ignition by lightning decreases; fire size may decrease because extent of uninterrupted high hazard fuel types would shrink. Thus, while a warming climate may initially increase the incidence of large, high intensity fires, the fire regime may change and fire intensity decrease as deciduous stands cover a larger fraction of the landscape. This conclusion is supported by long term historic assessments of fire, climate, and forest communities in Alaska as warmer drier periods resulted in a greater percentage of deciduous forests and less active fire regimes (Lynch et al. 2002).

A still unfilled gap in knowledge about fire regimes and forest development in Alaska is an evaluation of the effects of fire severity on future forest development and thus on fuels succession and fire behavior. Increased sampling, use of fire management records and fire scar analysis can all be used to provide information on fire seasonality, often a reasonable proxy for fire severity. We also suggest that future research on the relationship between fire severity and seasonality would be extremely valuable towards evaluating the efficacy of seasonality as a proxy for burn severity. In the absence of such information, this research provides a useful tool for resource managers to assess general fire hazard in black spruce forests and understand how changes in the fuel complex influence fire behavior.

Acknowledgements

We would like to thank Alaska Fire Service, the National Park Service, the US Fish & Wildlife Service, the Pacific Wildland Fire Sciences Laboratory, and Colorado State University for their support of this project. Specifically, Randi Jandt, 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. Glenn Juday (University of Alaska Fairbanks) provided help with the development of the field sampling protocol. Erin Shanely, David Click and Jennifer Mitchell all put in long hours to collect field data. Roger Ottmar, Bob Vihnanek, David Wright, and Mary Huffman all generously provided data that was used in this analysis.

Financial support for this project was provided through a grant from the Joint Fire Science Program under project number 04-2-1-96.

References

Agee, J. K. 1996. The influence of forest structure on fire behavior. *In* Proceedings of the 17th Annual Forest Vegetation Management Conference, January 16-18, 1996, Redding, CA. pp. 52-67.

Agee, J. K., and M. H. Huff. 1987. Fuel succession in a western hemlock/Douglas-fir forest. Canadian Journal of Forest Research 17:697-704.

Alaska Department of Natural Resources. 2001. State of Alaska FY2003 Governor's Operating Budget. Fire Suppression BRU/Component Summary; 8 p.

Alaska Wildland Fire Coordinating Group. 1998. Alaska Interagency Wildland Fire Management Plan. 61 p.

Albini, F. A. 1982. Response of Free-Burning Fires to Non-Steady Wind. Combustion Science and Technology 29:225-241.

Alexander, M. E., and R. A. Lanoville. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. Forestry Canada, Northern Forestry Center, & Northwest Territories Provincial Government, Dept. of Renewable Resources, Territorial Forest Fire Center

Anderson, H. E. 1969. Heat transfer and fire spread. USDA Forest Service Res. Pap. INT-69.

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. USDA Forest Service Gen. Tech. Rep. INT-122.

Andrews, P. L. 1986. BEHAVE : fire behavior prediction and fuel modeling system : BURN subsystem, part 1. USDA Forest Service Gen. Tech. Rep. INT-194.

Andrews, P. L., C. D. Bevins, and R. C. Seli. 2005. BehavePlus fire modeling system, version 3.0: user's guide. USDA Forest Service Gen. Tech. Rep. RMRS-106.

Arseneault, D. 2001. Impact of fire behavior on postfire forest development in a homogeneous boreal landscape. Canadian Journal of Forest Research 31:1367-1374.

Bergeron, Y. 1991. The Influence of Island and Mainland Lakeshore Landscapes on Boreal Forest-Fire Regimes. Ecology 72:1980-1992.

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.

Boucher, T. V. 2003. Vegetation response to prescribed fire in the Kenai Mountains, Alaska. USDA Forest Service Res. Pap. PNW-554.

Bourgeau-Chavez, L. L., M. E. Alexander, B. J. Stocks, and E. S. Kasischke. 2000. Fire, Climate Change, and Carbon Cycling in the Boreal Forest, in E. S. Kasischke and B. J. Stocks (eds), Distribution of forest ecosystems and the role of fire in the North American boreal region, Springer-Verlag, New York, pp. 111-132.

Bradshaw, R. H. W., and O. Zackrisson. 1990. A 2-Thousand-Year History of a Northern Swedish Boreal Forest Stand. Journal of Vegetation Science 1:519-528.

Brown, J. K. 1974. Handbook for inventorying downed woody material. U. S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station Gen. Tech. Rep. INT-16.

Bryant, J. P., and P. J. Kuropat. 1980. Selection of Winter Forage by Sub-Arctic Browsing Vertebrates - the Role of Plant Chemistry. Annual Review of Ecology and Systematics 11:261-285.

Burgan, R. E., and R. C. Rothermel. 1984. BEHAVE : fire behavior prediction and fuel modeling system : FUEL subsystem. USDA Forest Service Gen. Tech. Rep. INT-167.

Byram, G. M. 1959. Forest fire: control and use. 2nd edition, Combustion of forest fuels, McGraw-Hill, New York, NY, pp. 61-89.

Catchpole, E. A., W. R. Catchpole, and R. C. Rothermel. 1993. Fire Behavior Experiments in Mixed Fuel Complexes. International Journal of Wildland Fire 3:45-57.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. Forest Science 50:640-658.

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.

De Volder, A. 1999. Fire and climate history of lowland black spruce forests, Kenai National Wildlife Refuge, Alaska. M.S. Thesis. Northern Arizona University, Flagstaff, AZ. 127 p.

Deeming, J. E., R. E. Burgan, and J. D. Cohen. 1977. The national fire danger rating system--1978. USDA Forest Service Gen. Tech. Rep. INT-39.

DeWilde, L., and F. S. Chapin. 2006. Human impacts on the fire regime of interior Alaska: Interactions among fuels, ignition sources, and fire suppression. Ecosystems 9:1342-1353.

Engelmark, O. 1984. Forest Fires in the Muddus-National-Park (Northern Sweden) during the Past 600 Years. Canadian Journal of Botany-Revue Canadienne De Botanique 62:893-898.

Fahnestock, G. R. 1976. Fire, fuels and flora as factors in wilderness management: the Pasyten case. *In* Proceedings of the Tall Timbers Fire Ecology Conference 15, October 16-17, 1974, Portland, OR. *Edited by* E. V. Komarek. Tall Timbers Research Station, Tallahassee, FL. pp. 33-70.

Fastie, C. L., A. H. Lloyd, and P. Doak. 2002. Fire history and postfire forest development in an upland watershed of interior Alaska. Journal of Geophysical Research-Atmospheres 108:6·1-6·13.

Foote, M. J. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. Res. Pap. PNW-307.

Forest Products Laboratory. 1999. Wood handbook: wood as an engineering material. USDA Forest Service Gen. Tech. Rep. FPL-113.

Frandsen, W. H. 1971. Fire Spread through Porous Fuels from Conservation of Energy. Combustion and Flame 16:9-16.

Hely, C., M. Flannigan, Y. Bergeron, and D. McRae. 2001. Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems. Canadian Journal of Forest Research 31:430-441.

Hom, J. L., and W. C. Oechel. 1983. The Photosynthetic Capacity, Nutrient Content, and Nutrient Use Efficiency of Different Needle Age-Classes of Black Spruce (Picea-Mariana) Found in Interior Alaska. Canadian Journal of Forest Research 13:834-839.

Johnson, E. A. 1992. Fire and vegetation dynamics : studies from the North American boreal forest. Cambridge University Press, Cambridge.

Johnstone, J. F., F. S. Chapin III, J. Foote, S. Kemmett, K. Price, and L. Viereck. 2004. Decadal observations of tree regeneration following fire in boreal forests. Canadian Journal of Forest Research 34:267-273.

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-Revue Canadienne De Recherche Forestiere 35:2151-2163.

Kasischke, E. S., K. Bergen, R. Fennimore, F. Sotelo, G. Stephens, A. Janetos, and H. H. Shugart. 1999. Satellite imagery gives a clear picture of Russia's boreal forest fires'. EOS - Transactions of the American Geophysical Union 80:141-147.

Kasischke, E. S., D. Williams, and D. Barry. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. International Journal of Wildland Fire 11:131-144.

Lieffers, V. I., S. E. Macdonald, and E. H. Hogg. 1993. Ecology of and Control Strategies for Calamagrostis-Canadensis in Boreal Forest Sites. Canadian Journal of Forest Research 23:2070-2077.

Lynch, J. A., J. S. Clark, N. H. Bigelow, M. E. Edwards, and B. P. Finney. 2002. Geographic and temporal variations in fire history in boreal ecosystems of Alaska. Journal of Geophysical Research-Atmospheres 107:8152.

Lynch, J. A., J. L. Hollis, and F. S. Hu. 2004. Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. Journal of Ecology 92:477-489.

Nalder, I. A., R. W. Wein, M. E. Alexander, and W. J. d. Groot. 1997. Physical properties of dead and downed round-wood fuels in the boreal forests of Alberta and Northwest Territories. Canadian Journal of Forest Research 27:1513-1517.

National Information Systems Group. National Fire and Aviation Management web applications - fire and weather data: Alaska. 10-Jan-2007. National Interagency Fire Center: Boise, ID. 11-Jan-2007. <http://famweb.nwcg.gov>

Norum, R. A. 1982. Predicting wildfire behavior in black spruce forests in Alaska. U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station Res. Note PNW-401.

Norum, R. A. 1983. Wind adjustment factors for predicting fire behavior in three fuel types in Alaska. U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station Res. Pap. PNW-309.

Nowacki, G. J., P. Spencer, T. Brock, M. Fleming, and T. Jorgenson. 2001. Ecoregions of Alaska and neighboring territories. U.S. Geological Survey Miscellaneous Investigations Series 1 Map.

Oliver, C. D., and B. C. Larson. 1996. Forest stand dynamics. Wiley

Ottmar, R. Forest Floor Consumption and Smoke Characterization in Boreal Forested Fuelbed Types of Alaska. Joint Fire Science Program: Boise, ID. May, 15, 2007.

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. National Wildfire Coordinating Group, National Interagency Fire Center PMS-831.

Reinhardt, E. D., and N. L. Crookston. 2003. The fire and fuels extension to the forest vegetation simulator. USDA Forest Service Gen. Tech. Rep. GTR-116.

Rieger, S., G. W. Allen, A. D. Backer, E. G. Link, and B. B. Lovell. 1962. Soil Survey of Kenai-Kasilof Area, Alaska. USDA Soil Conservation Service. Series 1958, No: 2.

Rieger, S., D. B. Schoephorster, and C. E. Furbush. 1973. Exploratory soil survey of Alaska. U. S. Department of Agriculture, Soil Conservation Service

Romme, W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecological Monographs 52:199-221.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Res. Pap. INT-115.

Rothermel, R. C. 1983. How to predict the spread and intensity of forest and range fires. USDA Forest Service Gen. Tech. Rep. INT-143.

Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA Forest Service Res. Pap. INT-438.

Rothermel, R. C. 1993. Some fire behavior modelling concepts for fire management systems. *In* Proceedings of the 20th National Conference on Fire and Forest Meteorology, Jekyll Island, GA. pp. 71-81.

Rouse, W. R. 1976. Microclimate changes accompany burning in subarctic lichen woodland. Arctic & Alpine Research 8:357-376.

Roussopoulos, P. J., and R. M. Loomis. 1979. Weights and dimensional properties of shrubs and small trees of the Great Lakes conifer forest. USDA Forest Service Res. Pap. NC-178.

Rupp, T. S., A. M. Starfield, F. S. Chapin_III, and P. Duffy. 2002. Modeling the impact of black spruce on the fire regime of Alaskan boreal forest. Climate Change 55:213-233.

Ryan, K. C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36:13-39.

Sando, R. W., and C. H. Wick. 1972. A method of evaluating crown fuels in forest stands. USDA Forest Service Res. Pap. NC-84.

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

Scott, J. H., and E. D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service Res. Pap. RMRS-29.

Singh, T. 1982. Biomass equations for ten major tree species of the prairie provinces. Environment Canada, Canadian Forestry Service Info. Rep. NOR-X-242.
Singh, T. 1984. Biomass equations for six major tree species of the Northwest Territories. Environment Canada, Canadian Forestry Service Info. Rep. NOR-X-257.
Slaughter, C. W., and L. A. Viereck. 1986. Forest Ecosystems in the Alaskan Taiga, in K. Van Cleve, F. S. Chapin III, P. W. Flanagan, L. A. Viereck, and C. T. Dyrness (eds), Climate characteristics of the taiga in interior Alaska, Springer-Verlag, New York, pp. 9-21.
Stocks, B. J. 1980. Black Spruce Crown Fuel Weights in Northern Ontario. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 10:498-501.
Stocks, B. J., M. E. Alexander, B. M. Wotton, C. N. Stefner, 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.
Tamm, C. O. 1964. Growth of Hylocomium splendens in relation to tree canopy. Bryologist 67:423-426.
Taylor, S. W., B. M. Wotton, M. E. Alexander, and G. N. Dalrymple. 2004. Variation in wind and crown fire behaviour in a northern jack pine – black spruce forest. Canadian Journal of Forest Research 34:1561-1576.
Theisen, S. 2003. An analysis of shaded fuel breaks on fire behavior. USDI BLM - Alaska Fire Service Technical Fire Management 17.
Todd, S. K., and H. A. Jewkes. 2006. Wildland Fire in Alaska: A history of organized fire suppression and management in the last frontier. University of Alaska Fairbanks Agricultural and Forestry Experiment Station Bulletin No. 114.
U. S. Department of Agriculture, F. S. 2002. Fire Family Plus Users Guide, version 3.0.
U. S. Department of Commerce. 1973. Monthly averages of temperature and precipitation for state climate divisions 1941-1970. National Climate Center Climatology of the United States No. 85 (by state).
U. S. Department of the Interior/U. S. Department of Agriculture. 1995. Federal Wildland Fire Management Policy and Program Review. Final Report. Boise, ID: National Interagency Fire Center; 45 p.
U. S. Department of the Interior/U. S. Department of Agriculture. 2001. Urban wildland interface communities within the vicinity of federal lands that are at high risk from wildfire. Federal Register 66: 751-777.
Van Cleve, K. 1986. Forest ecosystems in the Alaskan taiga : a synthesis of structure and function. Springer-Verlag Ecological studies ; v. 57.
Van Cleve, K., C. T. Dyrness, L. A. Viereck, J. Fox, F. S. C. III, and W. Oechel. 1983. Taiga ecosystems in interior Alaska Bioscience 33:39-44.
Van Wagner, C. E. 1964. The line intersect method in forest fuel sampling. Forest Science 10:267-276.
Van Wagner, C. E. 1968. Fire behavior mechanisms in a red pine plantation: field and laboratory evidence. Canadian Dept. of Forestry and Rural Development Dept. Pub. No. 1229.
Van Wagner, C. E. 1976. Diameter measurement in the line intersect method. Forest Science 22:230-232.
Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7:23-24.
Van Wagner, C. E. 1983. The Role of Fire in Northern Circumpolar Ecosystems, in R. W. Wein and D. A. MacLean (eds), Fire behavior in northern conifer forests and shrublands, John Wiley & Sons Ltd., New York, pp. 65-80.
Van Wagner, C. E., B. J. Stocks, B. D. Lawson, M. E. Alexander, T. J. Lynham, and R. S. McAlpine. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Canadian Forest Service Info. Rep. ST-X-3.
Viereck, L. A. 1973. Wildfire in the taiga of Alaska. Quaternary Research 3:465-495.
Viereck, L. A., and C. T. Dyrness. 1979. Ecological effects of the Wickersham Dome fire near Fairbanks, Alaska. USDA Forest Service, Gen. Tech. Rep. PNW-90.

Viereck, L. A., C. T. Dyrness, A. R. Batten, and K. J. Wenzlick. 1992. The Alaska vegetation classification. USDA Forest Service Gen. Tech. Rep. PNW-286.
Viereck, L. A., and W. F. Johnston. 1990. Silvics of North America, Volume 1. Conifers, in R. M. Burns and B. H. Honkala (eds), Picea mariana (Mill.) B.S.P. Black Spruce, USDA Forest Service, Washington, D. C., pp. 227-237.
Viereck, L. A., and L. A. Schandelmeier. 1980. Effects of fire in Alaska and adjacent Canada - a literature review. USDI BLM Alaska State Office BLM-Alaska Tech. Rep. 6.
Viereck, L. A., K. Van Cleve, and C. T. Dyrness. 1986. Forest Ecosystems in the Alaskan Taiga, in K. Van Cleve, F. S. Chapin III, P. W. Flanagan, L. A. Viereck, and C. T. Dyrness (eds), Forest ecosystem distribution in the taiga environment, Springer-Verlag, New York, pp. 22-43.
Wotton, B. M., and M. D. Flannigan. 1993. Length of the Fire Season in a Changing Climate. Forestry Chronicle 69:187-192.
Yarie, J. 1981. Forest fire cycles and life tables: a case study from interior Alaska. Canadian Journal of Forest Research 11:554-562.
Zackrisson, O. 1977. Influence of Forest Fires on North Swedish Boreal Forest. Oikos 29:22-32.

Appendix 1: Fuel Properties

Table A1-1: Fuel properties used to calculate loads for DWD fuels.

Fuel Type	Specific Gravity* (tonnes m^{-3})	Mean Quadratic Diameter* (cm^2)
1-hour dead downed woody debris	0.518[b]	0.0787[a]
10-hour dead downed woody debris	0.59[b]	1.961[a]
100-hour dead downed woody debris	0.482[b]	18.516[a]
1000- hour rotten dead downed woody debris (general)	0.3[a]	---
1000-hour sound dead downed woody debris (general)	0.4[a]	---
1000-hour sound dead downed woody debris (paper birch)	0.55[c]	---
1000-hour sound dead downed woody debris (white spruce)	0.4[c]	---
1000-hour sound dead downed woody debris (black spruce)	0.46[c]	---
1000-hour sound dead downed woody debris (trembling aspen)	0.38[c]	---

*Sources: a: Brown 1974; b: Nalder et al 1997; c: Forest Products Laboratory 1999.

Table A1-2: Bulk density values.

Forest Floor Type	Forest Floor Layer	Bulk Density* (tonnes mm^{-1} $hectare^{-1}$)
Pleurocarpous Mosses	Surface Material	0.25[a]
	Duff	1.34[a]
Acrocarpous Mosses	Surface Material	0.25[a]
	Duff	1.34[a]
Sphagnum Moss	Surface Material	0.364[a]
	Duff	0.682[a]
Dwarf Shrub Litter	Surface Material	0.375[b]
	Duff	1.34[a]
Hardwood Litter	Surface Material	0.233[a]
	Duff	1.09[a]
Spruce Litter	Surface Material	0.375[b]
	Duff	1.34[a]
Lichens	Surface Material	0.41[a]
	Duff	1.34[a]
Wood Rot	Surface Material	1.34[a]
	Duff	1.34[a]

*Sources: a: Ottmar 2003; b: Brown 1981

Table A1-3: Intrinsic fuel properties.

Fuel component	*SAV* ratio* (m^{-1})	Heat content* ($kJ\ kg^{-1}$)
Forest floor: 1-hr feathermoss surface material	12,733[c, d]	18,600[c]
Forest floor: 1-hr litter surface material	5062[a, c]	18,600[c]
Woody debris: 1-hr	1247[e]	18,600[c]
Woody debris: 10-hr	295[e]	18,700[b]
Woody debris: 100-hr	98[e]	18,700[b]
Live herbaceous	9795[c]	18,450[c]
Live woody	5509[c]	21,800[c]

*Sources: a: Brown 1970; b: Albini 1976; c: Sylvester and Wein 1981; d: Norum 1982; e: Brown and Bevins 1986.

Appendix 2: Percentile Weather Conditions

Table A2-1: Percentile weather conditions and associated fuel moisture values.

Percentile weather	Dry Bulb Temperature (°C)	Relative Humidity (%)	Windspeed (km hr^{-1})	1-hr dead fuel moisture (%)	10-hour dead fuel moisture (%)	100-hr dead fuel moisture (%)
95	26	29	18	4	5	6
55	18	46	10	8	9	10
20	13	62	5	9	10	11

Appendix 3: Custom Fuel Models

Table A3-1: Custom fuel models – surface fuel loading inputs.

Site ID	Stand Age (years)	Fuel model 1* 1-hr dead fuel load (tonne ha^{-1})	Fuel model 2* 1-hr dead fuel load (tonne ha^{-1})	10-hr dead fuel load (tonne ha^{-1})	100-hr dead fuel load (tonne ha^{-1})	Live herbaceous fuel load (tonne ha^{-1})	Live woody fuel load (tonne ha^{-1})
31	2	0.20	1.98	0.48	2.07	0.41	0.85
25	12	0.23	2.24	1.33	7.12	0.72	0.50
29	22	0.29	5.51	1.88	4.63	0.46	3.53
32	34	0.24	5.13	1.05	2.83	0.57	2.04
27	38	11.80	6.31	0.78	1.24	0.94	3.05
26	38	13.18	4.83	0.77	5.74	0.87	2.22
34	39	17.87	9.17	2.63	2.90	0.43	1.99
30	46	9.44	5.82	0.54	0.14	0.50	2.56
2	57	18.67	2.03	0.74	2.23	2.06	0.10
17	72	12.77	4.07	0.65	1.08	1.12	3.35
28	81	10.23	3.11	0.96	2.70	0.89	2.12
23	93	9.16	2.75	0.40	0.52	0.42	1.44
20	97	16.03	1.47	0.15	0.69	0.63	0.93
10	101	14.97	0.75	0.54	0.23	1.28	1.25
22	104	9.59	8.11	0.39	0.57	0.89	1.54
33	104	14.00	10.26	1.05	1.11	0.53	1.41
14	105	13.76	8.77	0.32	1.04	0.76	1.10
9	112	13.41	0.19	0.11	0.23	1.09	2.78
11	114	16.52	4.07	0.60	0.79	0.90	0.67
3	122	13.43	1.00	0.40	0.17	0.79	2.38
4	139	13.83	5.18	0.45	0.97	0.68	1.67
13	169	13.69	5.33	0.41	0.88	0.60	0.20
5	184	13.60	3.47	0.22	0.00	1.08	2.12
7	227	14.68	25.16	0.97	0.46	0.82	2.47

*Fuel model 1 and 2 refer to forest floor surface material properties that were divided for the purpose of two-dimensional spread rate modeling described in the *Model Inputs* section of *Chapter 3*. The properties of fuel model 1 and 2 are described further in table A3-4 in this appendix.

Table A3-2: Custom fuel models – *SAV* ratio inputs.

Site ID	Stand Age (years)	Fuel model 1 1-hr *SAV* ratio* (m^{-1})	Fuel model 2 1-hr *SAV* ratio* (m^{-1})	10-hr *SAV* ratio (m^{-1})	100-hr *SAV* ratio (m^{-1})	Live herbaceous *SAV* ratio (m^{-1})	Live woody *SAV* ratio (m^{-1})
31	2	1247	4672	295	98	9795	5509
25	12	1247	4670	295	98	9795	5509
29	22	1247	4863	295	98	9795	5509
32	34	1247	4885	295	98	9795	5509
27	38	12,586	4971	295	98	9795	5509
26	38	12,446	4802	295	98	9795	5509
34	39	12,518	4923	295	98	9795	5509
30	46	12,613	4997	295	98	9795	5509
2	57	12,540	4473	295	98	9795	5509
17	72	12,213	4520	295	98	9795	5509
28	81	12,475	4780	295	98	9795	5509
23	93	12,264	4543	295	98	9795	5509
20	97	12,416	3918	295	98	9795	5509
10	101	12,690	4775	295	98	9795	5509
22	104	12,265	4878	295	98	9795	5509
33	104	12,378	4901	295	98	9795	5509
14	105	12,568	4976	295	98	9795	5509
9	112	12,572	1247	295	98	9795	5509
11	114	12,422	4643	295	98	9795	5509
3	122	12,359	3401	295	98	9795	5509
4	139	12,620	4962	295	98	9795	5509
13	169	12,211	4616	295	98	9795	5509
5	184	12,534	4804	295	98	9795	5509
7	227	12,361	4990	295	98	9795	5509

**SAV* ratios are weighted averages based by loading for *SAV* ratios reported for 1-hr dead fuel components in *Appendix 1*, table A1-3.

Table A3-3: Custom fuel models – miscellaneous inputs.

Site ID	Stand age (years)	Fuel model 1 Fuel-bed depth* (m)	Fuel model 2 Fuel-bed depth* (m)	Dead fuel moisture of extinction† (%)	Dead fuel heat content◊ (kJ kg^{-1})	Live fuel heat content◊ (kJ kg^{-1})	Canopy base height (m)	Canopy bulk density (kg m^{-3})
31	2	0.14	0.11	25	18,683	20,714	-	0.00
25	12	0.09	0.10	25	18,685	19,821	-	0.00
29	22	0.19	0.13	25	18,665	21,423	0.17	0.00
32	34	0.16	0.13	25	18,656	21,078	0.10	0.01
27	38	0.18	0.17	25	18,637	21,018	0.25	0.00
26	38	0.14	0.12	25	18,657	20,863	0.21	0.03
34	39	0.16	0.11	25	18,645	21,220	0.08	0.02
30	46	0.27	0.26	25	18,626	21,265	0.32	0.09
2	57	0.14	0.09	25	18,633	18,596	0.09	0.20
17	72	0.19	0.16	25	18,630	20,966	0.02	0.16
28	81	0.16	0.14	25	18,647	20,818	0.78	0.21
23	93	0.13	0.11	25	18,629	21,048	0.42	0.17
20	97	0.16	0.12	25	18,625	20,454	0.90	0.23
10	101	0.14	0.09	25	18,623	20,108	0.37	0.30
22	104	0.15	0.12	25	18,627	20,576	0.47	0.28
33	104	0.16	0.12	25	18,630	20,889	0.73	0.35
14	105	0.13	0.10	25	18,627	20,431	0.37	0.18
9	112	0.17	0.12	25	18,621	20,864	0.52	0.16
11	114	0.13	0.07	25	18,626	19,885	0.84	0.38
3	122	0.13	0.09	25	18,623	20,976	0.20	0.17
4	139	0.14	0.10	25	18,627	20,836	0.40	0.13
13	169	0.10	0.06	25	18,626	19,287	0.82	0.34
5	184	0.13	0.10	25	18,620	20,670	0.30	0.26
7	227	0.14	0.15	25	18,626	20,976	0.31	0.29

*Fuel-bed depth was calculated by taking the loading-based weighted average of the groundcover, 1-hr DWD, 10-hr DWD, and 100-hr DWD fuel components. The result was then added to the forest floor surface material fuel component.

†A 20-25% moisture of extinction has been used for multiple times for research using the Rothermel (1972) surface spread model to predict fire behavior in boreal forests (Norum 1982, Bessie & Johnson 1995, Schimmel & Granstrom 1997, and Theisen 2003).

◊Heat content was calculated based on the load weighted means of values reported in *Appendix 1*, table A1-3.

Table A3-4: Two-dimensional spread model percent cover values.

Site ID	Stand age (years)	No surface material percent cover (%)	Litter surface material percent cover (%)	Feathermoss surface material percent cover (%)	Fuel model 1 Percent cover (%)	Fuel model 2 Percent Cover (%)	Dominant Fuel Model
31	2	81	15	4	81[NS]	19[L, F]	1
25	12	17	82	1	17[NS]	83[L, F]	2
29	22	16	83	1	16[NS]	84[L, F]	2
32	34	20	74	6	20[NS]	80[L, F]	2
27	38	1	86	13	13[F]	88[L, NS]	2
26	38	-	69	31	31[F]	69[L]	2
34	39	2	67	31	31[F]	69[L, NS]	2
30	46	5	63	32	32[F]	68[L, NS]	2
2	57	3	20	76	76[F]	24[L, NS]	1
17	72	3	19	78	78[F]	22[L, NS]	1
28	81	3	43	54	54[F]	46[L, NS]	1
23	93	9	33	58	58[F]	42[L, NS]	1
20	97	-	44	56	56[F]	44[L]	1
10	101	-	6	94	94[F]	6[L]	1
22	104	-	19	81	81[F]	19[L]	1
33	104	1	14	85	85[F]	15[L, NS]	1
14	105	2	16	82	82[F]	18[L, NS]	1
9	112	-	5	95	95[F]	5[L]	1
11	114	2	7	92	92[F]	8[L, NS]	1
3	122	1	15	84	84[F]	16[L, NS]	1
4	139	-	5	95	95[F]	5[L]	1
13	169	0	7	92	92[F]	8[L, NS]	1
5	184	-	13	87	87[F]	13[L]	1
7	227	0	3	97	97[F]	3[L]	1

Of the three major forest floor surface material types (columns 3-5 of this table) the minority percent cover was added to the most appropriate fuel model. Superscripts in columns 6 and 7 refer to forest floor fuel types represented by fuel models 1 & 2. Superscripts are defined below:
NS: No Surface Material Forest Floor Type. Forest floor is charred duff or mineral soil and 1-hr fuels only include those contributed by 1-hr DWD.
L: Litter layer. Fuels are described in table 3-2.
F: Feathermoss. Fuels are described in table 3-2.

Appendix 4: List of abbreviations used in this report

Table A4-1: Glossary of acronyms.

Acronym	Description
AIFMC	Alaska Interagency Fire Management Council
AFS	Alaska Fire Service
AWFCG	Alaska Wildland Fire Coordinating Group
C-1 Fuel Model	CFFDRS Spruce Lichen Woodland Fuel Type
C-2 Fuel Model	CFFDRS Boreal Spruce Fuel Type
CFFDRS	Canadian Forest Fire Danger Rating System
CSU	Colorado State University
DBH	Diameter at breast height
DWD	Dead downed woody debris
FBP System	Canadian Forest Fire Behavior Prediction System
ICFME	International Crown Fire Modeling Experiment
NIFC	National Interagency Fire Center
PWFSL	Pacific Wildland Fire Sciences Laboratory
RAWS	Remote Automatic Weather Station
TU-04 Fuel Model	Dwarf Conifer with Understory Standard Fuel Model
WUI	Wildland Urban Interface

Table A4-2: Glossary of terms.

Term	Definition
CAC	Criterion for active crowning
CBD	Canopy bulk density (kg m^{-3})
CBH	Canopy base height (m)
$CROS_A$	Active crown fire rate of spread (active crown fire model output) (m min^{-1})
$CROS_P$	Passive crown fire rate of spread (passive crown fire model output) (m min^{-1})
EFFM	Fine fuel moisture content (%)
F_{Active}	Active crown fire-line intensity (kW m^{-1})
FLI	Fire-line intensity (kW m^{-1})
FMC	Foliar moisture content (%)
$F_{Passive}$	Passive crown fire-line intensity (kW m^{-1})
$F_{Surface}$	Surface fire-line intensity (kW m^{-1})
F_{Total}	Total surface fire-line intensity, includes influence of all fuels and weather (kW m^{-1})
H	Heat content (kJ kg^{-1})
HPA	Heat per unit area (kJ m^{-2})
I_O	Critical fire-line intensity (kW m^{-1})
I_R	Reaction intensity (kW m^{-2})
Q_{ig}	Heat of pre-ignition (kJ kg^{-1})
R_O	Critical rate of spread (required to support an active crown fire) (m min^{-1})
ROS	Rate of spread (m min^{-1})
$R_{Surface}$	Surface fire rate of spread (m min^{-1})
R_{Total}	Total surface fire rate of spread, includes influence of all fuels and weather (m min^{-1})
S	Minimum mass flow rate (kg m^{-2} sec^{-1})
SAV	Surface area to volume ratio (m^{-1})
t_R	Flame residence time (min)
U_{10}	10-meter windspeed (km hr^{-1})
W	Mass of fuels consumed (kg m^{-2})
Wc	Mass of fuels available for consumption (kg m^{-2})
Wc_A	Mass of available canopy fuels (kg m^{-2})
W_{ff}	Mass of fine (< 64 mm diameter) canopy fuels (kg m^{-2})
B_1, B_2, B_3, B_4	Active crown fire model coefficients
$Ø_s$	Slope coefficient
$Ø_w$	Wind coefficient
ε	Effective heating number
ζ	Propagating flux ratio
ρ_b	Oven-dry fuel-bed bulk density (kg m^{-3})

Appendix 5: Review of Fire Behavior Models Used to Run the Linked Model

Surface Fire Modeling

The surface fire component of the BehavePlus3 program is a deterministic physical model that predicts fire behavior based on the dynamic relationships between a series of inputs and fire behavior. The core of the BehavePlus3 surface fire component is the surface fire spread model developed by Rothermel (1972) and slightly modified by Albini (1976). Rothermel's spread model is in turn heavily based on the theoretical properties of fire (Frandsen 1971). Rothermel's surface fire spread model is essentially a ratio. Variables in the numerator have a positive relationship with surface fire rate of spread ($R_{surface}$) and variables in the denominator have a negative relationship with $R_{surface}$. $R_{surface}$ with an upslope wind for a head fire is expressed as:

[5-1]

$$R_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

where:

I_R = Reaction Intensity (kW m^{-2})

ξ = Propagating flux ratio

ϕ_w = Wind Coefficient

ϕ_s = Slope Factor

ρ_b = Oven-dry Fuel-bed Bulk Density (kg m^{-3})

ε = Effective Heating Number

Q_{ig} = Heat of Pre-ignition (kJ kg^{-1})

$R_{surface}$ = Rate of Spread for a Surface Fire (m min^{-1})

There are four variables in the numerator: I_R is the rate of energy released per given area of the fire; it is a product of both intrinsic and extrinsic fuel-bed properties and is mainly influenced by two extrinsic properties: the packing ratio (similar to bulk density but expressed as a percentage of the fuel-bed volume occupied by the fuel) and the *SAV* ratio. This variable has a positive affect on $R_{surface}$ because a faster release of energy means fuels with closest proximity to the fire are heated to ignition more quickly. The ζ is a measure of forward heat transfer – it is essentially a percentage that expresses the proportion of the heat from the fire that is affecting the unburned fuels; the higher it is, the more efficiently the fire is pre-heating the fuels. This variable has a positive relationship with $R_{surface}$, however, to make things more confusing, the denominator used to calculate ζ is I_R. This means the I_R both positively and negatively impacts $R_{surface}$ at the same time. The negative impacts of I_R are most pronounced for coarse fuels while the positive impacts are most pronounced for fine fuels. The $Ø_w$ and $Ø_s$ are dimensionless measures of wind and slope. Increases in wind and slope would clearly increase $R_{surface}$. However, there are not direct relationships between measures of wind and slope and their respective coefficients. Both coefficients are modified by fuel properties. For example, wind more effectively spreads fire through grass than through logging slash, so the relative impact of wind is tempered by the *SAV* ratio.

There are three variables in the denominator and all represent a heat sink, variables that slow $R_{surface}$: ρ_b is a measure of compactness. High compactness (i.e. high ρ_b) reduces availability of oxygen and thus slows overall $R_{Surface}$. However, there is also an upper limit to this variable. If the fuels are spaced too far apart it reduces the ability of the flames to move from particle to particle. ρ_b is influenced by available fuel loading and fuel-bed depth. ε is a measure of the fraction of fuel particles that will be heated to ignition in the fire. Essentially as *SAV* ratio decreases (fuels become coarser), a smaller portion of the fuel will burn in the flaming front and ε decreases. An ε of one means that 100% of the fuel has burned which is essentially true for fine fuels such as pleurocarpous mosses. It is counter-intuitive to think that fuels with a higher *SAV* ratio would slow the $R_{surface}$. It helps to think of equal weights of grass and wood chips. Say 100 kilograms. Of the grass, about 95 of the 100 kilograms will ignite in a flaming front. By contrast only about 70 of the 100 kilograms of wood chips would ignite in a flaming front (though the rest may burn during smoldering). More energy is required to heat 95 kilograms over 70 kilograms, this actually slows the flaming front because the unburned grass, in a way pulls energy from the flaming front until it has all been heated to the ignition temperature. Thus, this property of fine fuels slows the forward progression of fire. However, other properties of fine fuels cause fire to move faster and outweigh the negative of ε. Q_{ig} essentially represents the amount of moisture within the fuel. As the fuel moisture increases more heat is required to heat the fuel to ignition. This increase in the Q_{ig} dampens the $R_{surface}$.

Unfortunately, the variables of Rothermel's spread model often depend on the same fuel variables, thus it is not possible to determine a direct relationship between fuel variables and $R_{surface}$ unless all other fuel variables are kept constant.

The predicted $R_{surface}$ value is in turn used as a variable in the model used to calculate surface fire-line intensity ($F_{Surface}$) in BehavePlus3 (eq. 5-2). Fire-line intensity (*FLI*) (kW m^{-1}) is a measure of the rate of energy release along the fire line. It is similar to I_R except *FLI* is a measure of rate of energy release along a linear line while I_R is a measure of energy release from a two-dimensional area. $R_{surface}$ can be used to calculate $F_{Surface}$ from the following equation:

[5-2] $$FLI = \frac{HPA * ROS}{60}$$

Where *HPA* is heat per unit area (kJ m^{-2}), *ROS* is rate of spread (m min^{-1}), and 60 is used to convert kJ m^{-1} min^{-1} to kW m^{-1}. *HPA* is calculated by multiplying I_R by flaming residence time (t_R). Or, put another way, *HPA* is equal to the total available energy per unit area times the rate of energy release from that area times the length of time that energy is being released from the same area (Andrews 1986):

[5-3] $$HPA = I_R t_R$$

This equation is based on a proposed model of flame residence time and particle size (where *SAV* ratio is a proxy for particle size) (Anderson 1969), the flame residence can be predicted based on *SAV* ratio:

[5-4] $$t_R = \frac{1259.5}{SAV}$$

Where t_R is measured in minutes.

Equation 5-2 was derived from another *FLI* model (Byram 1959). Byram's *FLI* model was not directly used to predict $F_{Surface}$ in BehavePlus3 because it is difficult to a priori determine fuel consumed by the flaming front, a requirement of Byram's *FLI* model.

[5-5] $$FLI = \frac{H * W \ * ROS}{60}$$

Where *H* is the heat content of fuel (kJ kg^{-1}) and *W* is the mass of fuel consumed (kg m^{-2}). The FBP System uses Byram's *FLI* equation to compute *FLI* and because some portion of coarse fuels (i.e. duff) are consumed as part of the head fire in boreal forests, the FBP System uses total available fuels (W_a) to compute *FLI*. In BehavePlus3, *FLI* is calculated from I_R; this method yields consistently lower *FLI* than Byram's *FLI* model. This difference can be attributed to differences in how coarse fuels burn in fuel types common to Canada and the U.S. In Canada most coarse fuels are contained in the duff layer of the deep organic mat frequently found in boreal forests. Duff can be consumed as part of the flaming front and can significantly increase *FLI*. In the U.S., coarse fuels exist as DWD and typically are consumed well after the flaming front has passed.

Crown Fire Initiation Criteria

A crown fire initiation and spread model developed by Van Wagner (1977) uses empirical observations to predict when a surface fire will become a crown fire, and crown fire type (i.e. passive or active). The model consists of two equations that will be referred to as the crown fire initiation criteria and the active crown fire spread criteria. The model inputs for the crown fire initiation model are easy to derive from field measurements.

Van Wagner (1977) defines two types of crown fires: passive and active. Passive crown fires occur when the canopy is being consumed and the fire is not a solid wall of flames. By this definition passive crown fires include a wide range of fire behavior from surface fires with occasional torching to fires with a high frequency of torching that borders on the line of an active crown fire. An active crown fire is separate from a passive crown fire because the canopy is being consumed in a solid wall of flames. Van Wagner’s definition of an active crown fire should not be confused with another class of crown fires, independent crown fires. Independent crown fires are different from active crown fires because canopy fuels in independent crown fires burn regardless of the energy supplied by the surface fuels. The concept of independent crown fires is not considered here because they are by all accounts rare in boreal forests and difficult to measure. Active crown fires are completely dependent upon surface fuels (Van Wagner 1977) and are common in boreal forests. The crown fire initiation criteria is:

[5-6]
$$I_O = \left[\frac{CBH(460 + 25.9FMC)}{100} \right]^{3/2}$$

Where *CBH* is canopy base height (m), *FMC* is the foliar moisture content, and I_O is the critical fire-line intensity (kW m^{-1}) that must be generated by the surface fuels to initiate crown activity. I_O is compared to the $F_{Surface}$: if $I_O > F_{Surface}$ the fire will be a surface fire, if $I_O < F_{Surface}$, crown fire activity will initiate. The bracketed section of the numerator is derived from previous research on the relationship between surface fires and crown fires (Van Wagner 1968). It is clear that increases in *FMC* correspond to increasing heat of ignition hence, the energy needed to initiate ignition of the canopy increases. The first term in the numerator, *CBH* also has a positive relationship with I_O. This relationship should also be quite clear; as the canopy fuels are raised higher above the surface fire, the energy release required to ignite them will increase. The constant value in the denominator is based on the estimated $F_{Surface}$ from three fires in red pine plantations as a fire was transitioning from a surface fire to a crown fire (Van Wagner 1977).

A fire classified as a crown fire cannot be classified as passive or active until it has been evaluated against the active crown fire spread criteria. The active crown fire spread criteria equation is used to determine if active crown fire behavior can be expected. This equation is:

[5-7]
$$R_O = \frac{S}{CBD}$$

Where R_O is the critical *ROS* (m min^{-1}) required to maintain an active crown fire and *S* is the minimum mass flow rate (kg m^{-2} sec^{-1}) that can support a solid wall of flames in the canopy (mass flow can be visualized as the rate that fuels are being fed into a stationary fire front, of course in reality, the opposite is occurring). Based on one observation during an experimental crown fire in a red pine plantation Van Wagner (Van Wagner 1977) determined that *S* equals 0.05 kg m^{-2} sec^{-1}. Re-arranging equation 5-6 and multiplying S by 60 to convert seconds to minutes R_O can be calculated as follows:

[5-8] $$R_O = \frac{3.0}{CBD}$$

Where *CBD* is canopy bulk density (kg m^{-3}). R_O must be compared against the *ROS* of an active crown fire ($CROS_A$); this can either be the observed or predicted. If R_O is exceeded by either the observed or predicted $CROS_A$, then the fire is classified as an active crown fire; if not, the fire is classified as a passive crown fire so long as $I_O < F_{Surface}$.

Crown Fire Model

The active and passive crown fire models used in this analysis were developed by Cruz et al. (2005). The active crown fire behavior component is an empirical model developed using data from 24 experimental fires classified as active crown fires. The fires occurred in a range of fuel types including jack pine, black spruce and red pine. Cruz et al. (2005) considered 9 variables in the development of the model and found that the 10-meter windspeed (U_{10}), fine fuel moisture content (*EFFM*), and *CBD* where the most influential.

The proposed model for active crown fire behavior (Cruz et al. 2005) is:

[5-9] $$CROS_A = I\beta_1 U_{10}^{\beta_2} x CBD^{\beta_3} x e^{(-\beta_4 EFFM)}, U_{10} > 0$$

Where $CROS_A$ is measured in m min^{-1}, U_{10} (km hr^{-1}) must be > 0, *EFFM* is measured as a percent, and β_{1-4} are constants that equal 11.02, 0.90, 0.19, and 0.17, respectively. The model was successfully tested against 11 separate fire behavior observations collected from the International Crown Fire Modeling Experiment (ICFME), conducted in boreal forests of the Northwest Territories with a jack pine overstory and black spruce understory (Stocks et al. 2004).

The number of observations from passive crown fires was too small to develop an empirical model to predict passive crown fire behavior. As an alternative Cruz et al. (2005) linked passive crown fire behavior to predictions from the active crown fire behavior model. They assumed that *ROS* for passive crown fires was correlated primarily with *CBD* and used the ratio of the crown fire *ROS* (observed or predicted) to the active crown fire spread criteria (Van Wagner 1977) as an adjustment factor. The ratio is expressed as:

[5-10] $$CAC = \frac{R_C}{R_O}$$

where *CAC* is the criterion for active crowning, R_C is the predicted or observed crown fire *ROS*. The passive crown fire behavior model is:

[5-11] $$CROS_P = CROS_A x e^{(-CAC)}$$

where $CROS_P$ is the passive crown fire *ROS* (m min^{-1}). The passive crown fire behavior equation was tested against independent passive crown fire observations. The model over-predicted *ROS* for fire observations from the open black spruce woodland (C-1) fuel type, but otherwise predicted fire behavior within an acceptable range. The observed fire behavior in black spruce woodland was not predicted correctly most likely because the crowns are aggregated rather than spread evenly. The clumped nature of the canopy fuels combined with already high *CBD* values decreased R_O enough so the fires were classified as active fires even though the heterogeneous nature of the canopy fuels kept the fires burning as passive crown fires.

Appendix 6: Bureau of Land Management – AFS Draft Study Plan

DRAFT STUDY PLAN – July 10, 2000

PROJECT TITLE: **Assessing flammability *vs.* time-since-fire in black spruce fuels of the Tanana Zone**

PROBLEM STATEMENT

Fire managers know intuitively that there is a several-year lag time from burning of black spruce (*Picea mariana*) fuel types before it becomes susceptible to fire. In general, the older the spruce stand, the more flammable it becomes due to increased crown densities, down woody debris, "layering" growth form of spruce into a thicked organic mat which provides better ladder for fire spread to the canopy, and growth of arboreal lichen in the dead and dying lower branches. Although there is little quantitative data on the length and magnitude of the period of fire resistance after burning, the principle is regularly used in pre-suppression planning, tactics, and risk management.

OBJECTIVES

The overall goal of this research is to improve our understanding of fire resistance on recently burned boreal spruce using semi-quantitative methods. Resulting data will assist managers with large-fire risk management and hazard fuel assessment.

STUDY AREA

In order to reduce variance from factors other than age-since-burn, the study area will be chosen in a location which has access to diverse-aged stands with a good fire history and similar ecoregion and climatic influence. A series of six previous burns will be selected to cover that series of years the fire manager believes are critical to the curve of return from zero to full flammability post-burn. Sampling sites will be randomly selected with rejection criteria to ensure they are placed within boreal spruce fuel type or in a location that has the *site potential* to develop boreal spruce (*i.e*. burn poles indicate that the original fire burned in spruce).

METHODS

1) Record fuel data using Alaska Natural Fuels photoseries.
Include elements which contribute to flammability–vegetation type, crown closure, down & woody in various size classes, unit biomass.

2) Experienced fire manager rank flammability on a scale of 0-10, with 0 unable to carry fire under any conditions and 10 representing the most flammable black spruce fuel conditions.

3) Samples collected inside and outside burn perimeter for duff moisture at 0-5, 5-10, and 10-15 cm. A total of 10 samples will be required (5 inside and outside the perimeter).

4) Collect weather data at time of sampling: Temp, RH, wind, % cloud cover.

5) Approximate the original burn severity using unburned "control" site to gauge the duff reduction in the burned stand.

LITERATURE CITED

Adams, L.G. and B.A. Connery. 1983. Buckland River reindeer/caribou conflict study final report. BLM-AK Open File Report 8. 169 pp.

Part II: Field-based assessment of fire behavior prediction models in boreal forests of Alaska (Colorado State University)

Brief Synopsis of Fire Behavior Findings

Using videography to sample fire behavior on six wildland fires in black spruce forests of Interior Alaska, we found that the flame lengths and rates of spread observed on video differed from predictions by both BehavePlus3 and the Canadian Forest Fire Behavior Prediction System (p-values ranging from 0.0532 to < .0001). Scott and Burgan's fuel model TU04 used in BehavePlus3 predicted surface fire flame lengths and rates of spread with accuracy appropriate for limited use in decision support. However, TU04 and BehavePlus3 failed to adequately predict flame lengths, rates of spread or fire type for active crown fires. Using fuel moistures gathered in the field, BehavePlus3 under-predicted crown fire flame lengths by an average of 14.5 ± 4.9 ft. This difference in flame lengths overwhelms the threshold of four feet typically used in decision support to distinguish between fires that can be addressed using hand tools and those that require additional resources (Andrews and Rothermel 1982, Albini 1976). In general, BehavePlus3 under-predicted fire type with 86 percent frequency.

Because crown fire behavior is common in the black spruce forest fuel type, and because fire practitioners rely on predictive capabilities for intense fire behavior, we view the utility of the TU04 model used in BehavePlus3 as limited and generally insufficient for decision support. While the Rothermel (1972) model was never intended to predict crown fire behavior, a computer user can operate the crown fire module in BehavePlus3 using the TU04 model. During the course of this study, Joe Scott (pers.com.) informed us that the TU04 model is mathematically derived from Norum's 1982 empirical adaptation of BEHAVE to black spruce fuels. As such, it is not currently designed to provide the active crown fire predictions that are possible to generate in BehavePlus3. To avoid invalid predictions, we respectfully recommend that the authors of BehavePlus3 block the user from connecting the TU04 fuel model with the crown fire module, or at least produce a cautionary on-screen "pop-up" notice to the user.

The C2 fuel model used with the Canadian Forest Fire Behavior Prediction System (CFFBPS) over-predicted flame lengths by an average of 10.7 ± 8.7 ft and rates of spread by an average of 14.3 ± 26.0 ft. Most of the over-prediction occurred in fires that were observed to be of the surface and torching types. CFFBPS matched the observed (video) fire type with 57.14 percent frequency. CFFBPS under-predicted fire type with 19.05 percent frequency and over-predicted fire type with 23.81 percent frequency. The empirically-derived CFFBPS needs to be further calibrated for use in Alaska's black spruce forests; however, we view the structure and function of this model as promising compared to the TU04 model.

Field Locations

We took video footage on six wildland fires in Interior Alaska during the 2004-2005 fire seasons. We provide Global Positioning System (GPS) coordinates for each filming site in the electronic data set submitted with this report. Nearby towns to these fires included Tok, Eagle, Coldfoot and Chicken, Alaska.

Introduction

Fire practitioners in Alaska utilize two recognized systems of fire behavior prediction: the US - based BehavePlus (BEHAVE) system (Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984) and the Canadian Forest Fire Behavior Prediction (CFFBP) system (Forestry Canada Fire Danger Group 1992). Fire management practitioners as well as fire ecologists share an interest in field data to help compare the relative utility of each system as it relates to fire behavior and effects in Alaska black spruce fuels.

Scott and Burgan (2005) recently published a new fuel model designed to describe black spruce fuels in Alaska. In this model (TU04), fire behavior prediction follows the mathematical modifications of BEHAVE outputs for fire behavior prediction published by Norum (1982) for black spruce forests in Alaska (Scott, pers.com.).

While both prediction systems (BehavePlus3 and CFFBPS) are widely used, practitioners and fire behavior researchers including Rothermel, Norum and Scott have requested additional field observations for comparison of actual fire behavior with model outputs. In the fire behavior portion of this study, we use three methods of collecting fire behavior observations using videography of live fires. The video photography was taken during free-burning live fires in a variety of conditions, in wildland settings during the summers of 2004-2005 in Interior Alaska. Table 1 provides a summary of our activities on those fires. We used a combination of three video methods to gather samples of fire behavior.

Table 1. Wildland fires studied using videography to record fire behavior in Interior Alaska, 2004-2005.

Year	Fire name	Dates of data collection and filming	Number of video fire behavior observations
2004	Chicken	June 24-25	2
2004	Porcupine Creek	June 27-30, July 14-16	7
2004	King's Creek	July 12	1
2005	Chapman Creek	June 21-26	17
2005	Lost Horse Creek	June 30	6
2005	Boundary Creek	July 15-24	9
Total	**6 fires**	**37 days of filming**	**42 sample observations**

Methods

Here we describe our methods in three segments: coordination with the fire organization, field data collection, data preparation and data analysis. A step-by-step list of tasks involved in our research process is provided in Appendix A.

1. Coordination with the fire organization.

As in all work related to wildland fire, we emphasize safety first. By definition, taking data on flames during a wildfire event involves working "near the orange," an inherently dangerous situation. The researcher must work within the fire organization, which takes responsibility for all activities and the safety of everyone involved in the fire incident. The fire organization on site is typically complex and rapidly changing; the Incident Command Team nearly always operates in a high pressure environment. As a result, accommodating fire behavior research during a wildfire event can add unwelcome complexity and risk on a fire if it is not carefully coordinated. On the other hand, on Wildland Fire Use incidents, videography and associated measurements can provide information essential to the monitoring efforts of the incident management team.

In Appendix B we provide a list of procedures that we developed together with the Incident Commander and the Incident Commander Trainee of the Northern Idaho Type 2 Incident Management Team, and the Assistant Fire Management Officer for the Alaska Fire Service while researching fire behavior on the Boundary Creek Fire. We provide it here for future researchers, as a documentation of one effective method for coordinating activities.

2. Field data collection

A major focus of the fire behavior portion of this study was to experiment with the relatively new technique of using of video photography to obtain estimates of flame length and rate of spread in Alaska black spruce. As expected, our methods improved as the study progressed. We present the details of lessons learned in videographing wildland fire in Alaska black spruce in Appendix C. Field data collection consisted of three stages: scouting suitable filming sites in advance of the fire's movement; taking film and site data; and collecting post-burn measurements. We name our three videography methods as follows: the firebox method, the handheld video method, and the video review method. We supplemented video photography with still photography as time and safety conditions allowed. Using these methods, we documented three primary fire behavior variables: flame length, rate of spread and fire type. We present our supply list for conducting all three video sampling methods and the camera settings we used in Appendix D. These methods will undoubtedly change with advances in technology.

Fire behavior observations are by nature fleeting and risky to secure. As such, we used a combination of methods to secure as much fire behavior data as possible whenever safe opportunities occurred. While fire behavior field data is rarely repeatable, we relied on video filming and still photography to make the interpretation of our fire observations available for peer review and re-examination by others now and in the future. For all methods, we considered a fire captured on film to be a valid fire behavior data sample if the following conditions were met:

1. The fire was photographed on film, either in an unedited still photograph or unedited video that could be made available for others to examine.

2. Weather data were available from within three hours of the time the video was taken, assuming there was no major weather change. (We prefer within a half hour, and our average time lag was 60 minutes.)

3. GPS coordinates were taken of the fireboxes, and of a subset of the camera locations for the roving handheld methods.

This study originally proposed using a single method to explore the use of videography to research fire behavior. This method evolved into what we now call the firebox method. During the course of the study we arrived at two additional methods that provided a valuable complement to the firebox method. Appendix C describes each method in detail and offers lessons learned in the field.

a. The firebox method

The “fireproof” camera boxes we used were developed and constructed by the Photographic Services section of the USDA Forest Service’s Missoula Technology Development Center. We used two boxes during each fire during the course of the study. The dimensions of each box are approximately 12” x 8” x 9”. Each box weighs roughly 45 lbs. without the camera inserted. Due to the weight of the boxes, we carried each on a metal frame pack (Figure 1a). For setup, the box attaches to a steel base, into which three lengths of steel conduit are inserted to create a tripod (Figure 1b). The focal height of the camera lens inside the box was approximately four feet above the ground surface (Figure 1c).

Figures 1a-1d. Firebox camera equipment.

Figure 1a. Equipment for one firebox camera plot packed for travel on foot.

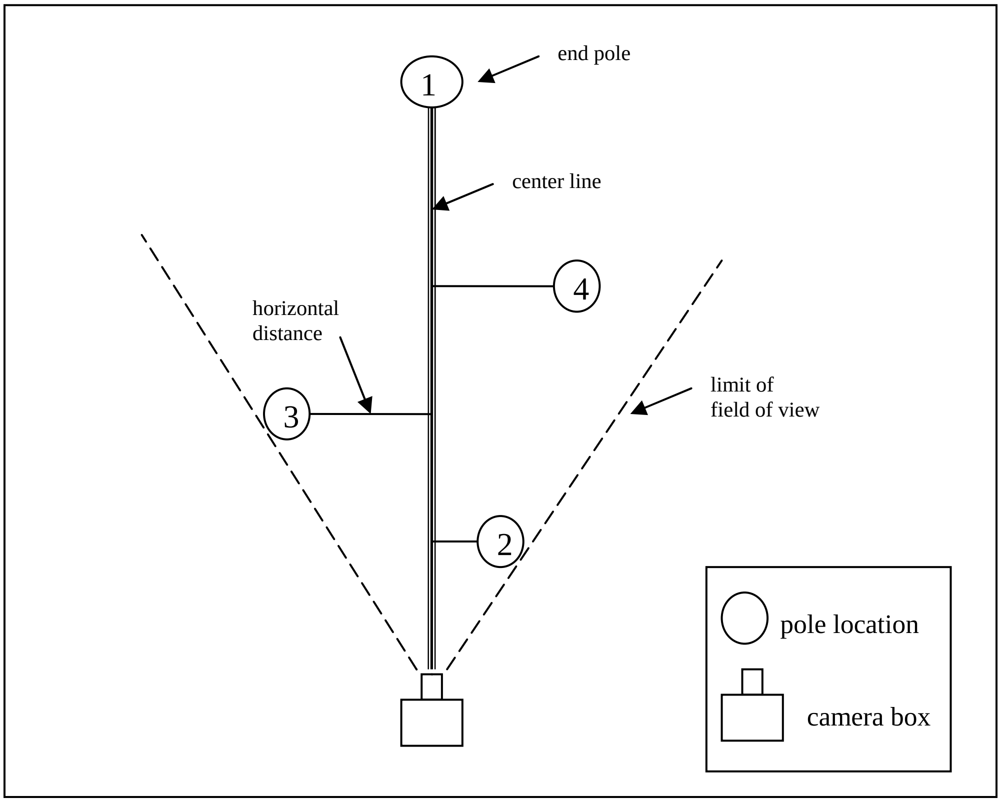
Figure 1b. The firebox with camera inside.

Figure 1c. Height of camera.

Figure 1d. Post-burn hazards: smoldering duff, burning stump holes, falling trees.

In this method, we scout locations for filming an hour or two in advance of the fire's arrival at the site. We set up the camera and reference markers (metal poles) which together form the "camera plot" (Figure 2). We take as many of the site measurements before the burn as safe timing will allow. Within about 45 minutes of the fire's arrival, we return to the site and turn on the camera. We retrieve the equipment after the fire when the site has cooled sufficiently to allow us to work safely. In Alaska black spruce, smoldering duff, burning stump holes and falling trees are ubiquitous hazards (Figure 1d). See Appendix C for detailed instructions and tips for using this method.

Figure 2. Overhead view of example camera plot for the firebox method with four reference pole locations.



b. The roving handheld video method

The roving handheld video method entails two people filming fire behavior on foot or from a lookout position. One person operates the camera while the other person looks for hazards, takes weather and site measurements and otherwise assists the camera person. The data collection concept is to take advantage of whatever fire behavior occurs that you can safely capture on film while locating physical reference points in the camera's view. The photographer narrates his or her observations of fire behavior during filming, including estimates of flame lengths and rates of spread. The team returns to the site to measure any distances needed, including tree heights, to later calculate ROS and flame lengths from the video footage.

c. The video review method.

The video review method involves reviewing the film taken via the firebox and roving handheld video techniques and returning to the site afterwards. As the photographer or other analyst combs through the film, he or she will notice fire behavior and reference points that were not obvious during filming. If suitable weather data were taken to accompany the video footage, and if site information can be gathered after the fire, these fire behavior scenes can provide additional fire behavior data.

Figure 3 provides sample video frames that illustrate this method. In Figure 3a, the fire is approaching. In Figure 3b the trees in the background on the right have ignited, but not the tree on the left. In Figure 3c, the tree on the left has ignited, and by Figure 3d the fire has burned though the entire plot, but the duff is still burning. By comparing the times of each video frame and measuring distances between trees and the camera after the fire, the researcher can estimate rates of spread, as well as flame length and fire type.

Figure 3a. Prior to the fire's arrival.

Figure 3b. Tree burning in background right.

Figure 3c. Tree burning in foreground left.

Figure 3d. Flaming front passed, duff burning.

Using a combination of the three video methods: firebox, handheld and video review methods, we were able to capture video observation of a variety of fire behavior situations in Alaska black spruce under a wide range of topographic, weather, and fuel moisture conditions at various times during Alaska's long summer days.

In addition to filming fire behavior, we gathered a suite of 20 standard weather and topography measures for each site that are required for simulation of fire behavior using both prediction systems. These variables and the ranges of their values that became included as a result of research on various fires are listed in Appendix E.

Most variables were measured on site during the fires, but we used surrogates to supplement field measures when necessary. For example, 20 ft wind speed was taken from RAWS station data in order to run the crown fire module in BehavePlus. Slope and aspect were generated using digital elevation models and ArcGIS; and our computer-based fuel moistures were calculated by Behave using onsite weather data. Yale University graciously provided 1-hr and 10-hr fuel moistures, live woody fuel moisture, live foliar moisture, canopy base height and canopy bulk density estimates based on its field sampling during the project.

2. Data preparation

Data preparation consisted of extracting segments of useable fire behavior from the videos and calculating estimates of flame length, rate of spread and fire type from each sample. Typically, the photographer recorded her estimates of flame lengths during filming; and where she gave multiple estimates as the fire burned during a single video clip we averaged those estimates.

For estimating rate of spread, we reviewed each video clip multiple times, tracking the fires' movement from point to point within the camera's field of view. We recorded the time it took the fire to go from point to point using the camera timer embedded in the video file or using a stopwatch. Knowing the location of each pole in a firebox plot, we calculated distances directly if the fire burned directly from pole to pole, or using right triangle geometry (Pythagorean Theorem) if the fire moved across the plot at an angle. The ability to operate the video playback frame by frame allowed us to estimate rate of spread at a precision of about a foot per second, which is more precise than the modeling programs' foot per minute resolution.

We collected information for 20 inputs related to weather, fuels and topography. These variables are listed in Appendix E together with minimum and maximum values and the source of information for each variable (e.g., field measure, RAWS, or digital elevation model). The goal was to match model inputs as nearly as possible with the timing and conditions that were present during the filming. We took most weather information with a belt weather kit and plot location with a handheld GPS unit. The average time difference between belt weather kit weather data and video footage was 60 minutes.

We prepared data for two scenarios of the BehavePlus3 model. For Scenario A, we used fuel moistures that Yale University gathered in the field on four of the six fires, two in each of 2004 and 2005. For Scenario B we used 100 percent for live woody fuel moisture per instructions by Joe Scott (pers.com.); 100 percent for live herbaceous and live foliar moistures; and fine dead fuel moistures calculated from our weather and elevation inputs by the "Behave by Remsoft, Inc." software. On average, the fine dead fuel moistures were 3.8 ± 1.6 percent lower than the fine fuel moistures measured in the field by Yale.

To utilize the CFFBPS, some mathematical conversions were necessary. Mid-flame windspeed had to be converted to 10 meter windspeed (Turner and Lawson 1978). Degrees slope had to be converted to percent slope, and the CFFBPS output of total fire intensity had to be converted to flame length (Ryan 1981). The required inputs of fine fuel moisture code (FFMC) and buildup index (BUI) were downloaded from the best available RAWS sites for the date and time closest to each video observation. The best available RAWS was either a RAWS near the fire or one located in a topographic situation similar to the fire site, which ever was more representative of what the fire experienced (Sharon Alden, pers.com.).

In preparing our data for statistical analyses, we found that flame length and ROS data satisfy tests for normality when transformed to a log scale. Consequently, flame length and rate of spread data that CFFBPS and BehavePlus3 predicted to equal zero presented a mathematical dilemma. For data points in which BehavePlus3 predicted zero ft flame lengths and zero ft/min rates of spread, we arbitrarily substituted small values that would enable us to include these data in the analyses. For both parameters, we used substitute values equal to half of the lowest values observed on video. Thus in place of zero ft flame lengths, we substituted 0.2 ft, which is half of the lowest video observation of 0.4 ft. For zero ft/min rates of spread, we substituted 0.1 ft/min, which is half the value of the lowest video observation of 0.2 ft/min. The log of 0.2 ft = (-0.7) and the log of 0.1 ft/min = (-1).

3. Data analysis

We analyzed the data according to the following assumptions:

1. The video segments represent random samples of actual fire behavior.
2. The video data and model data are dependent and paired because they use the same weather and topographical data.
3. The distributions of fire behavior data are normal when transformed to a log scale.
4. Surface fires, torching fires and crown fires are legitimate and distinctive fire types in the target fuel models (TU04 and C2).
5. For definition purposes, torching fire behavior is the same as intermittent crown fire and passive crown fire; crown fire behavior is the same as continuous crown fire and active crown fire behavior. We avoided the terminology of dependent and independent crown fires.

In an artificial fire environment, we would expect data points to be collected with equal precision and accuracy, using the exact same techniques on each site. This is rarely practical in a rapid response wildfire environment. We learned early in the project that if we were to capture more than a very few data points, we needed to be more flexible in our methods, collecting the greatest number of reasonable fire observations at the expense of some precision and accuracy.

With this philosophy in mind, we accepted the following compromises:

1. The fire behavior that we captured on film was, for safety reasons, typically taken from within 100 meters of a fireline or safety zone. Video samples were not randomly distributed from within the site of an actively burning fire.

2. Weather data were gathered using different methods as safety and time on the fireline allowed. In the best cases, we took weather data at the camera site, within a minute or two of the time the flaming front passed through the camera's view. In other cases we borrowed weather data from the official communications record of the fire. In the worst cases, weather data were downloaded after the fact from nearby or similarly situated Remote Access Weather Stations (RAWS).

3. In our observations, fire type is not as discrete as our data classification would suggest. In a few cases, black spruce fuels exhibited all three types of fire behavior in a mix during a time span of about ten minutes, typically in response to shifts in wind speed, wind direction and fuel configuration. In several cases, the visual portion of the camera recording was focused on surface fire behavior but the accompanying narration acknowledged torching outside of the camera's view.

4. For the firebox technique, the stationary camera's field of view could not capture flame lengths exceeding more than roughly 20 feet. We recorded some data points as "exceeded camera view" and we used 20 ft as a place holder in our quantitative analyses. While we expect the robustness of flame length observations and predictions to be suspect at high values, enabling coarse estimation of flame lengths even to the nearest ten feet would be an improvement in our method. Overcoming this limitation is an important task for further method development.

In pre-processing the data from all three video methods, we were able to glean 51 video clips of fire behavior in the target fuel type (TU04 and C2). Where we had multiple video clips that represented similar fire behavior resulting from the same set of conditions in a single fire environment, we averaged data values. This occurred on two fires where we had the opportunity to film the progress of a backing fire multiple times during a time span of about an hour under steady weather conditions. After averaging these cases, we had 42 fire behavior samples for flame length and fire type and 28 observations from which we could calculate rate of spread.

Using these 42 final fire behavior samples, we performed the analyses shown in Table 2. In each analysis we compared observed (video) fire behavior with model outputs from BehavePlus3 and CFFBPS. We analyzed model predictions from two scenarios of BehavePlus3, one using fuel moistures measured in the field (Scenario A), and one using 100 percent live woody fuel moisture per Scott (pers.com.) and fine fuel moistures generated by the "Behave by Remsoft, Inc." software (Scenario B). For both the paired T-test and linear regression we transformed data to a log scale in order to satisfy tests for normality.

Table 2. Analyses performed on three fire behavior indicators: flame length, rate of spread and fire type.

	Graph	Mean differences	Paired T-test	Linear Regression	Frequency of Agreement
Flame length	X	X	X	X	
Rate of spread	X	X	X	X	
Fire type	X				X

For flame length and rate of spread we first graphed values of sample data (Figures 4 and 5). We then calculated mean differences between video observations and model predictions (Table 4).

We conducted regressions of model outputs (Y) on video observations (X). Table 5 and Figures 6 and 7 show the results of this analysis. The assumption is that if model outputs agree perfectly with video observations, then the line of agreement in the regression will be at a 45 degree angle with an intercept of zero (Rothermel and Rinehart 1983, Andrews 1980).

For the categorical variable of fire type, we first graphed a simple comparison of the frequency with which the models predicted surface fire, torching fire and crown fire behavior (Figures 8). For fire type, we also tested for agreement between observations and model predictions using a Weighted Kappa test (Fleiss 1981). We conducted separate tests for agreement in fire type between video observations and CFFBPS predictions, and between video observations and BehavePlus3 Scenario A predictions (Figures 9a-b).

An important consideration in examining fire type is that according to Joe Scott (pers.com.) the TU04 model was mathematically derived to match Norum’s 1982 formula adjustments for using BEHAVE to predict surface fire behavior in Alaska black spruce. To utilize this derived fuel model in the BehavePlus3 modeling program the user must input a standard figure of 100 percent for live woody fuel moisture. Further, Scott (pers.com.) indicates that the TU04 fuel model is not currently compatible with the crown fire module provided in BehavePlus3 since its fuel inputs were derived to match Norum’s 1983 adjustments for surface fires.

- When a computer user tries to utilize the crown model in BehavePlus3, he or she will be asked to provide additional inputs, including canopy base height, canopy bulk density, 20-ft wind speed and a wind adjustment factor. We supplied these inputs based on data gathered by Cronan (unpubl.) and the Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station (PNW), RAWS and Norum (1983), knowing that the results would be questionable, but they would illustrate an important lesson learned.

Results:

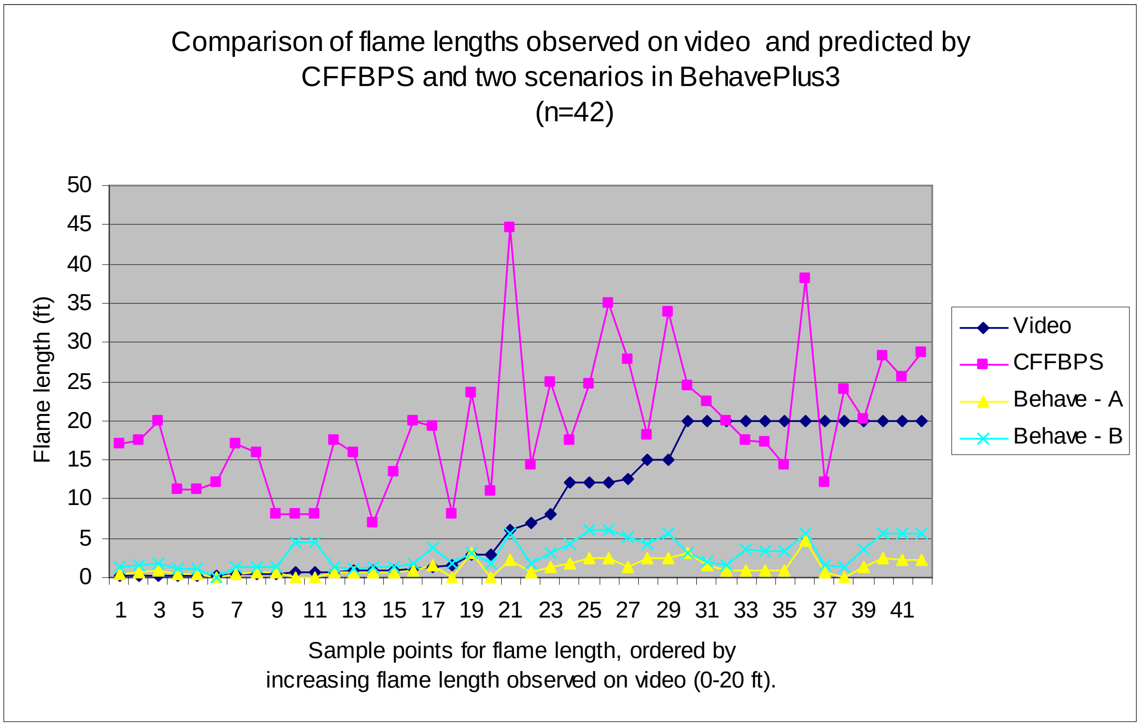
Results are based upon comparing the final 42 video samples of flame length and fire type, and 28 video samples of rate of spread to predicted fire behavior generated from CFFBPS and the two moisture scenarios from BehavePlus3. Minimum and maximum values for flame length, rate of spread and fire type are given in Table 3.

Table 3. Minimum and maximum values for fire behavior observed through videography and predicted by CFFBPS and two scenarios of BehavePlus3. The TU04 model is not currently designed to provide accurate model outputs in BehavePlus3 for active crown fires (Scott, pers.com.).

	Video	**CFFBPS**	**BehavePlus3 Scenario A.**	**BehavePlus3 Scenario B.**
Flame length (ft) n=42				
Minimum	0.3	6	0.0	0.0
Maximum	20	45	5.0	6.1
Rate of spread (ft/min) n=28				
Minimum	0.4	3.5	0.0	0.0
Maximum	157.5	179	10.7	16.0
Fire type n=42				
Minimum	surface	surface	surface	n/a
Maximum	crown	crown	torching	n/a

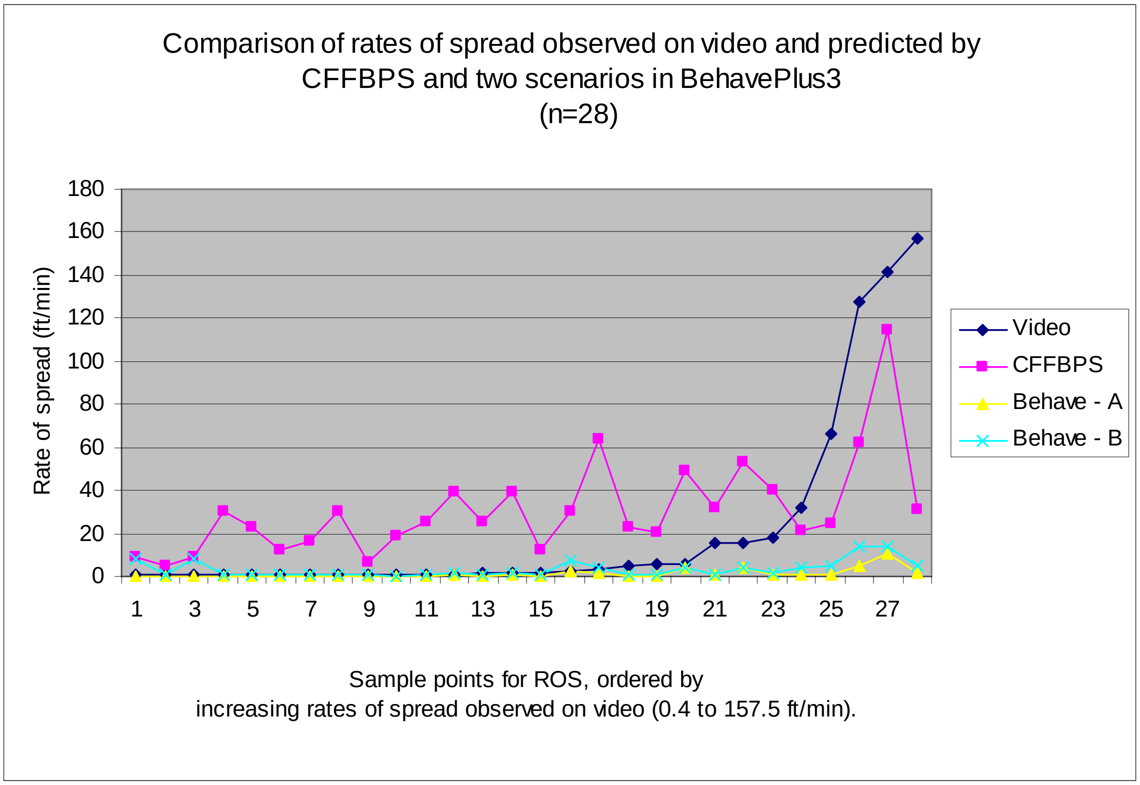
Our comparison of observed flame lengths with model outputs finds that BehavePlus3 predicts flame lengths reasonably well for flames below five feet, but seriously underestimates flame lengths that we observed to be taller than five feet (Figure 4). In contrast, the CFFBPS consistently over-predicts flame lengths observed on video to be 0.3 to 15 ft. While our fireboxes were not able to measure flames above about 20 ft, our field experience and the appearance of the graph leads us to speculate that CFFBPS and observed flame lengths may be closer to one another at higher flame lengths (Figure 4).

Figure 4. Plot of flame lengths observed on video compared to flame lengths predicted by CFFBPS and two scenarios of BehavePlus3. Scenario A uses fuel moistures taken from the field by Cronan (unpubl.) and the Pacific Wildland Fire Sciences Laboratory (PNW). Scenario B uses fuel moistures prescribed by Scott (pers.com.) and generated by the "Behave by Remsoft, Inc." software.



Using a similar graph of rates of spread, we find that BehavePlus3 tracks the observed ROS well until the observed ROS reaches about 15 ft/min, after which observed rates continue to climb, but BehavePlus3 rates stay below 15 ft/min (Figure 5). CFFBPS over-estimates ROS until observed ROS exceeds 30 ft/min, after which the observed rates outstrip the predicted rates. We were surprised that the ROS of Sample #43 was less than the highest ROS predicted by CFFBPS in our dataset, though these two points resulted from different fires. Sample #43 was the firebox video of fire behavior that appeared to be a nearly simultaneous combustion situation, one that was perhaps driven by plume dominated fire behavior or confounded by the ignition pattern of fire operations. For further discussion, see below the section titled "unexpected fire phenomena."

Figure 5. Plots of rates of spread observed on video and predicted by the CFFBPS and two scenarios of BehavePlus3. Scenario A uses fuel moistures taken from the field Cronan (unpubl.) and Pacific Wildland Fire Sciences Laboratory (PNW). Scenario B uses 100 percent live woody fuel moisture prescribed by Scott (pers.com.) and fine fuel moistures calculated by the "Behave by Remsoft, Inc." software.



Scott (pers.com.) indicates that we could expect the TU04 model to predict fire behavior more or less accurately for surface and torching fires in BehavePlus3, but that we would not expect it to work well for active crown fires. Conversely, we noticed that the C2 fuel model in the CFFBPS tended to over-predict fire behavior to a greater degree in the moderate fire types (surface and torching). Table 4 shows the average differences between video observations of flame lengths and rates of spread, separated by fire type. We combined surface and torching fire types in this comparison and we did not include Sample #43.

Table 4. Comparison of simple differences in flame lengths and rates of spread, according to fire type. Sample #43 was not included in this analysis.

Comparison	Mean difference ± 1 std dev	Mean difference ± 1 std dev	Mean difference ± 1 std dev
Flame lengths (ft)			
	Surface and Torching (n=22)	Active Crown (n=19)	All fire types (n=41)
Video - CFFBPS	-12.8 ± 5.5	-8.2 ± 11.1	-10.7 ± 8.7
Video - BehavePlus3 Scenario A	1.4 ± 4.2	14.5 ± 4.9	7.5 ± 8.0
Video - BehavePlus3 Scenario B	0.2 ± 4.4	12.2 ± 5.4	5.7 ± 7.8
Rates of spread (ft/min)			
	Surface and Torching (n=19)	Active Crown (n=8)	All fire types (n=27)
Video - CFFBPS	-22.5 ± 14.6	-3.3 ± 29.9	-14.3 ± 26.0
Video - BehavePlus3 Scenario A	1.7 ± 3.2	37.2 ± 46.6	15.4 ± 34.8
Video - BehavePlus3 Scenario B	0.3 ± 4.5	34.7 ± 45.9	13.4 ± 33.6

The CFFBPS over-predicted flame lengths by an average of 12.8 ± 5.5 ft for the moderate fire types (surface and torching) and by an average of 8.2 ± 11.1 ft for active crown fires (Table 4). BehavePlus3 predictions in both Scenarios A & B were very similar to video observations of both flame lengths and rates of spread for moderate fire types (surface and torching). For surface and torching fires, the mean differences between video observation and BehavePlus3 was only 0.2 ± 4.4 ft for flame lengths and only 0.3 ± 4.5 ft/min for rates of spread. Scenario B used Scott's prescribed 100 percent live woody fuel moisture and fine fuel moistures calculated in by "Behave by Remsoft, Inc." software.

For active crown fires, however, BehavePlus3 under-predicted flame lengths and rates of spread by wide margins. In Scenario A, which uses fuel moistures collected in the field, BehavePlus3 under-predicted flame lengths of active crown fires by an average of 14.5 ± 4.9 ft compared to video observations. In Scenario B the mean difference was 12.2 ± 5.4 ft. CFFBPS performed somewhat better for predicting flame lengths of active crown fires, over-predicting mean flame lengths compared to video observations by an average of 8.2 ± 11.1 ft. Recall that our cameras limited our estimates of flame lengths to no more than 20 ft.

For rates of spread, BehavePlus3 performed better for surface and torching fires (mean difference in Scenarios B = 0.3 ± 4.5 ft/min, while CFFBPS performed better for active crown fires (mean difference = -3.3 ± 29.9 ft/min). Within our data set, the mean differences among observed and predicted ROS for active crown fires were the most widely distributed differences.

The standard deviations for mean differences in ROS of active crown fires were 30 ft/min in CFFBPS and approximately 45 ft/min in BehavePlus3.

Linear Regression

Regression analysis further quantifies the results for flame lengths and rates of spread. In Figures 6 and 7 below, data are transformed into log scale to satisfy tests for normality. Again we see that CFFBPS over-estimates flame lengths in the lower range, but steadily improves in agreement until our camera-limited flame length of 20 ft., at which time CFFBPS and video observations of flame length meet on the line of perfect fit (Figure 7a).

Figures 6a-6c. Regression of flame lengths predicted by CFFBPS and BehavePlus3 on video fire behavior (Andrews 1980). Data are transformed into log scale. The blue diagonal line represents the line of perfect agreement between model outputs and video observations.

Figure 6a. Regression of flame lengths predicted by CFFBPS on video flame lengths. (n=42) R^2 =.36; p-value= <.0001.

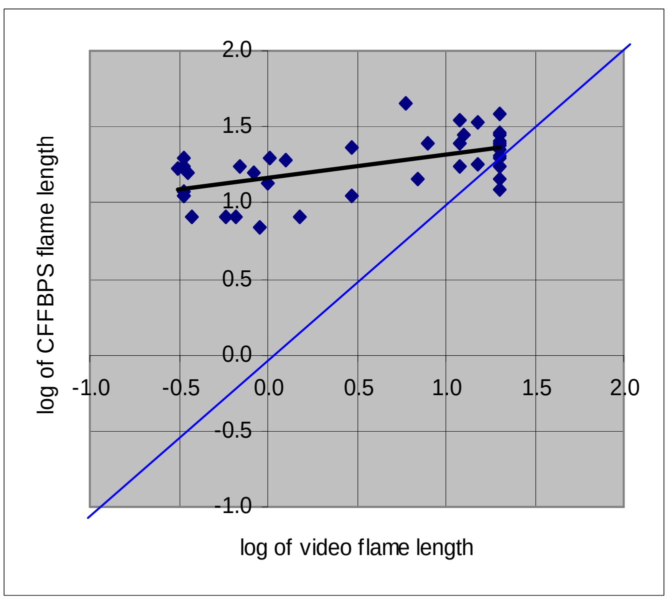


Figure 6b. Regression of flame lengths predicted by BehavePlus3 Scenario A on video flame lengths. (n=42) R^2 =.41; p-value = <.0001.

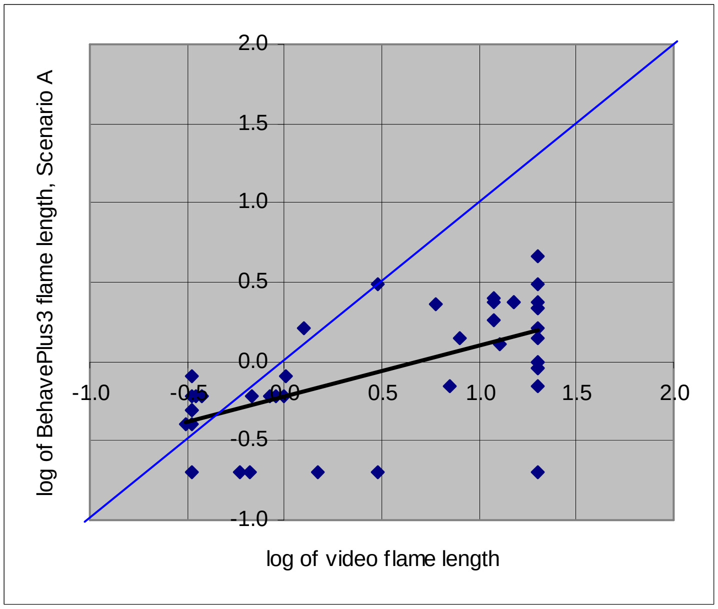
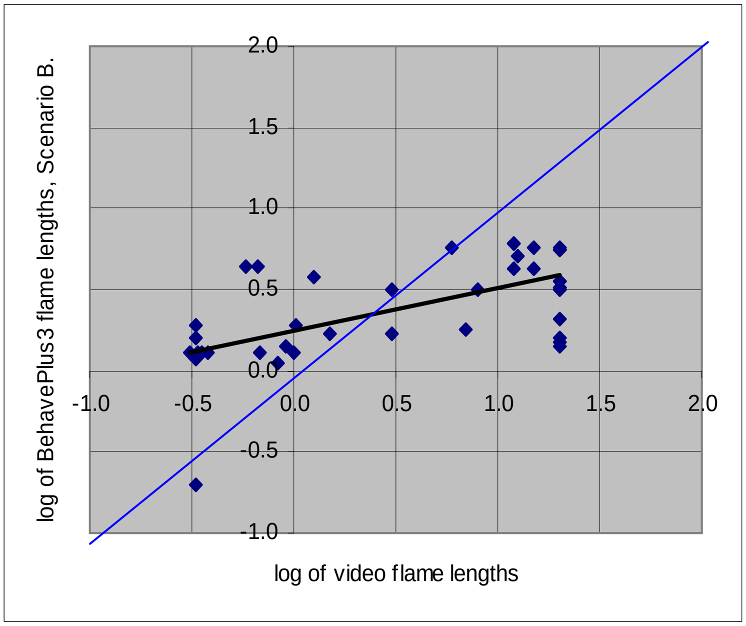


Figure 6c. Regression of flame lengths predicted by BehavePlus3 Scenario B on video flame lengths. (n=42) R^2 =.40; p-value = <.0001.



Figures 7a-7c. Regression of rates of spread predicted by CFFBPS and BehavePlus3 on video fire behavior (Andrews 1980). Data are transformed into log scale. The blue diagonal line represents the line of perfect agreement between model outputs and video observations.

Figure 7a. Regression of CFFBPS rates of spread on video rates of spread. (n=27) R^2 =.38; p-value =.0006.

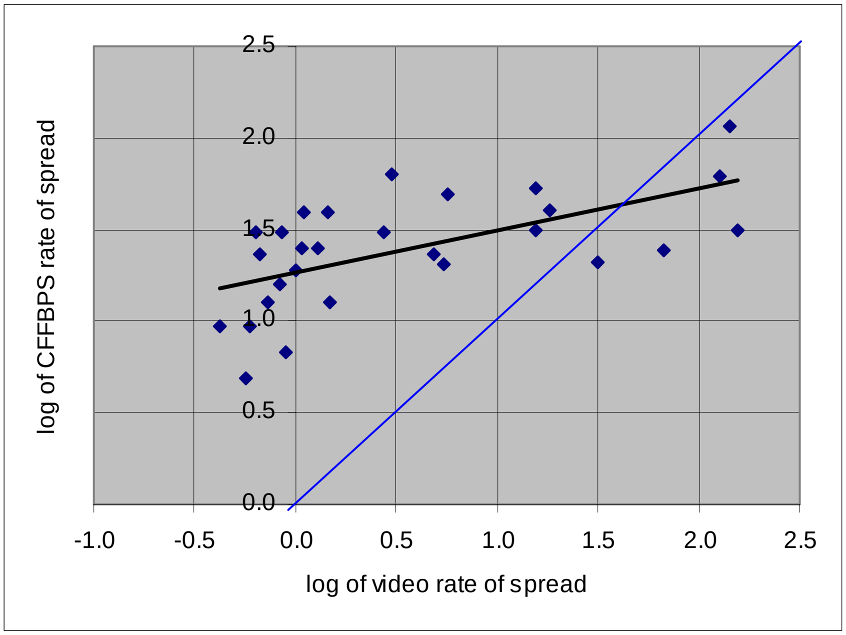


Figure 7b. Regression of BehavePlus3 Scenario A rates of spread (using fuel moistures measured in the field) on video rates of spread. (n=26) R^2 =.63; p-value = <.0001.

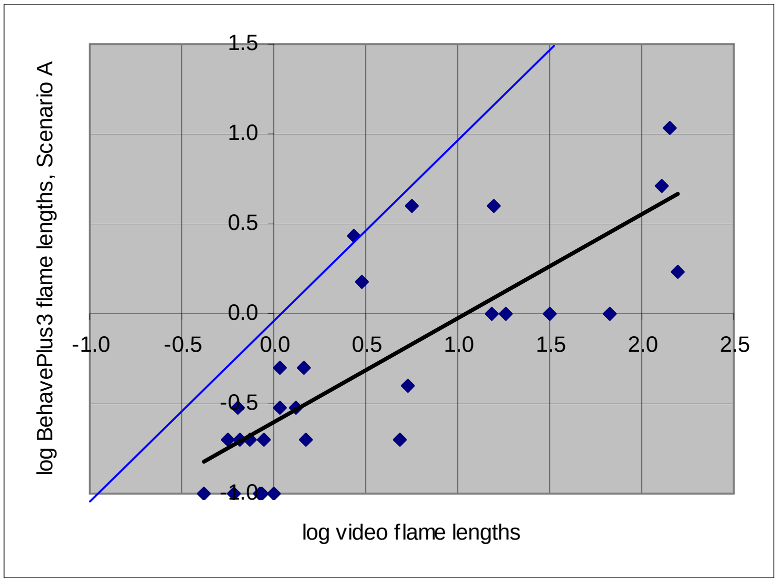


Figure 7c. Regression of rates of spread predicted by BehavePlus3 Scenario B (using fuel moistures prescribed by Scott (pers.com.) and calculated by "Behave by Remsoft" software), on video rates of spread. (n=27) R^2 =.30; p-value = .0028.

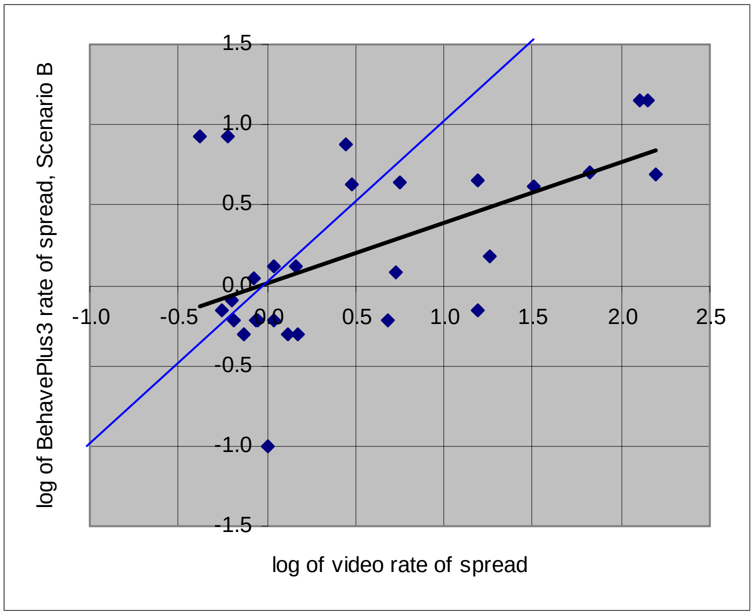


Table 5. Results for regression of model outputs on video observations of flame lengths and rates of spread. Data were transformed into log format to satisfy tests of normality.

Regression of log(y) on log(x)	**Sample size (n)**	**Regression equation**	**R^2 value**	**P-value**
		Flame length		
CFFBPS on video	42	y = 0.1583x + 2.6772	0.3573	<.0001
BehavePlus3 Scenario A on video	42	y = 0.3457x - 0.5244	0.4067	<.0001
BehavePlus3 Scenario B on video	42	y = 0.2659x + 0.5638	0.3962	<.0001
		Rate of spread		
CFFBPS on video	27	y = 0.2368x + 2.8871	0.3809	.0006
BehavePlus3 Scenario A on video	26	y = 0.5743 - 1.3684	0.6333	<.0001
BehavePlus3 Scenario B on video	27	y = 0.3738x + 0.0336	0.3046	.0028

Paired T-tests

Paired T-tests performed for flame lengths and rates of spread on log transformed data indicate that video observations and model predictions were statistically different, with p-values for all comparisons ranging between 0.0532 and < .0001 (Table 6). CFFBPS over-predicted log flame lengths by one and a half times (mean difference of video minus CFFBPS = -1.55). Using fuel moistures collected in the field (Scenario A), BehavePlus3 under-predicted log video flame lengths by almost one and a half times (mean difference = 1.40). Using Scott's prescribed live fuel moistures (Scenario B), however, BehavePlus3 under predicted by a much narrower margin (mean difference = 0.42).

The CFFBPS over-predicted the log rates of spread observed on video by nearly two times (mean difference of log video minus log CFFBPS = -1.87). BehavePlus3 under-predicted log rates of spread by nearly two times in Scenario A, and under-predicted by much less in Scenario B (mean differences = 1.96 and .80, respectively). When interpreting these results, remember that our video observations of flame lengths were limited to a maximum of 20 feet, while the Canadian system predicted flames up to 45 ft.

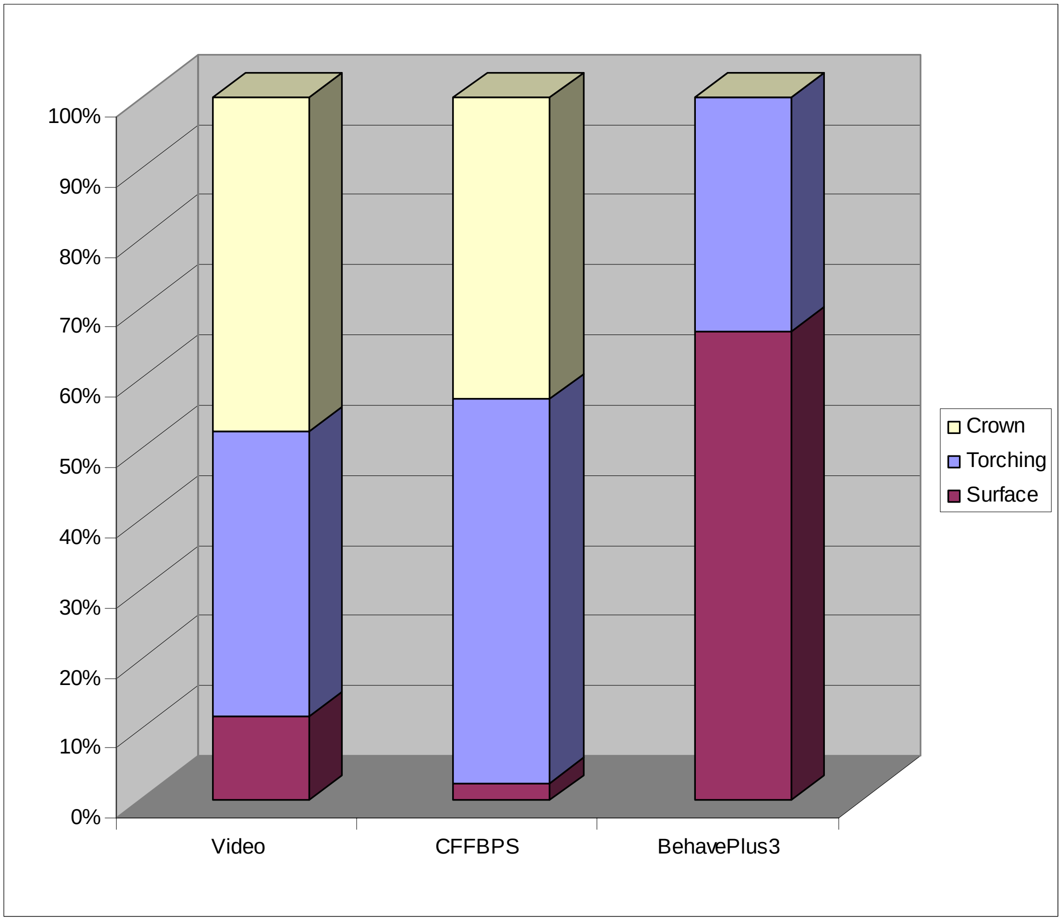
Table 6. Paired T-tests on flame lengths and rates of spread for differences in video observations and model outputs. Data were transformed into log scale.

Paired T-tests	Sample size (n)	Mean difference	Standard deviation	P-value
log of flame length (ft)				
Video-CFFBPS	42	-1.5530	1.4659	<.0001
Video-BehavePlus3 Scenario A	42	1.3987	1.3107	<.0001
Video-BehavePlus3 Scenario B	42	0.4171	1.3579	0.0532
log of rate of spread (ft/min)				
Video - CFFBPS	27	-1.872	1.5399	<.0001
Video-BehavePlus3 Scenario A	26	1.9586	1.1527	<.0001
Video-BehavePlus3 Scenario B	27	0.7990	1.5822	0.0144

Fire type

CFFBPS predicted fire type in similar proportion to video observations of fire type, with some over-prediction of torching when surface fires were observed on video (Figure 8). BehavePlus3 consistently under-predicted fire type, predicting only surface and torching fire types even when active crown fires were observed on video.

Figure 8. Frequency of fire types observed on video and predicted by BehavePlus3 (Scenario A) and CFFBPS. (n=42)



Frequency of agreement for fire type

In the frequency analysis of fire type, the CFFBPS model matched fire type with video samples 57 percent of the time. CFFBPS underestimated fire type 19 percent of the time and overestimated fire type 24 percent of the time, compared with video observations (Table 7a). Thirty-three percent agreement would be expected by chance. The Weighted Kappa exact test of agreement was significant (p=0.010), indicating agreement is greater than chance.

Table 7a. Frequency of agreement between video observations and CFFBPS predictions for fire type. (n=42)

Number of samples in agreement Percent of samples in Agreement		CFFBPS			
		Surface	Torching	Crown	Total
video	Surface	**1** **2.38**	4 9.52	0 0.00	5 11.90
	Torching	0 0.00	**10** **23.81**	6 14.29	16 38.10
	Crown	0 0.00	8 19.05	**13** **30.95**	21 50.00
	Total	1 2.38	22 52.38	19 45.24	42 100.00

Video observations and BehavePlus3 predictions of fire type matched only 14 percent of the time, while BehavePlus3 underestimated fire type 86 percent of the time (Table 7b). Thirty-three percent agreement would be expected by chance. The Weighted Kappa exact test of agreement was not significant (p=0.905), indicating agreement is likely due to chance.

Table 7b. Frequency of agreement between video observations of fire type and BehavePlus3 predictions for fire type. Results are shown for demonstration purposes only. Scott (pers.com.) cautions that the model is not currently designed to function in the BehavePlus3 crown module.

Number of samples in agreement Percent of samples in Agreement		BehavePlus3 using field moistures			
		Surface	Torching	Crown	Total
video	Surface	**5** **11.90**	0 0.00	0 0.00	5 11.90
	Torching	15 35.71	**1** **2.38**	0 0.00	16 38.10
	Crown	7 16.67	14 33.33	**0** **0.00**	21 50.00
	Total	27 64.29	15 35.71	0 0.00	42 100

<u>Unexpected fire phenomena and some qualitative fire behavior observations</u>.

In addition to examining the measured variables described above, our ocular observations on the fireline and our interpretation of the videos revealed several qualitative results. Videography proved particularly helpful in capturing unexpected fire behavior in high intensity fire situations, as described below. These qualitative results are probably familiar to fire practitioners who have spent time watching and working on fires in Alaska.

1. Black spruce trees in Alaska growing in dense stands sometimes ignite from the top down as the flaming front of a headfire approaches (Figures 9b and 9c). While most trees ignite in the wall of flames constituting the headfire front, the videos enabled us to see individual trees volatilizing and igniting from the top down shortly before the arrival of the flaming front.

2. Ember showers are common and play a role in fire propagation and spread. In some cases, copious amounts of sparks and embers rain down from (and upon) the upper canopies of black spruce.

3. Burning tree tops also dropped considerable numbers of burning and unburned pine cones, resinous bud scales, and fragments of dead twigs onto the ground during the fire. This debris can be heard on film like raindrops hitting (and sometimes sticking to) the firebox. To the extent that nearly every tree has a concentration of resinous cones and dead branches persisting in the canopy, and to the extent that these are ignited, falling debris can provide an important source of fire propagation and spread in black spruce forests in Alaska.

4. Living and dead lower branches of Alaska black spruce are frequently layered down into the lichen/feathermoss understory, providing a vertically continuous fuel layer from the duff and surface fuels into the tree canopies.

5. Torching from the bottom upward occurs in Alaska black spruce in a broad spectrum of moderate to mild weather conditions, including conditions under which most of the understory is self-extinguishing. We observed one fire in the fire did not spread into our camera plot, but trees continued to torch quietly, one by one, throughout the vicinity.

6. The fuel moisture of the feathermoss/lichen understory acts alternately like a live herbaceous fuel and a fine dead fuel during the course of a single day. Walking through black spruce forests in the morning, the understory can be spongy, while by early afternoon it can by dry and brittle, breaking into little pieces, scraping the leather right off your boots.

7. We observed long (several-minute) residence times of flames burning in the understory and duff fuel layers. These flames continue to burn independently from the flaming front, after the flaming front has passed (Figure 9d). These flames represent practically a second fire that continues to burn apart from the main fire. It continues to burn in smoldering combustion for periods of twelve to 24 hours (or conceivably longer) over

large areas. While these “second fires” are of less concern for fire control, they would seem likely to have a dominant impact on fire severity as a whole throughout the ecosystem.

8. Tree canopies in Alaska black spruce are narrow and conical in shape. As such, the primary spread mechanisms of fire traveling through open stands may be fundamentally different from fire spread in dense, closed stands. (See discussion section.)

9. Active crown fires in Alaska black spruce become plume dominated rapidly. This has important implications for the applicability of Rothermel’s surface fire spread model and subsequent related models to Alaska black spruce fuels.

10. On two fires, one in 2004 and the other in 2005, the boles of deciduous tree species such as aspen and birch burned more readily in a headfire situation than we expected (See the 2005 Boundary Creek Fire in Figure 9b.) On the King’s Creek Fire in 2004, the bark of aspen trees burned and cracked to a height exceeding 15 feet.

Figures 9a-d. Video frames from Sample #43: firebox video of the Boundary Creek Fire. Neither CFFBPS nor BehavePlus3 could model these fire behavior phenomena. This fire was part of a 30,000-acre burnout operation. Fire operations lit fire both upslope and downslope from this firebox location.

Figure 9a. Point ignition in foreground. Note small deciduous trees in middle ground and dense spruce slope in background.

Figure 9b. Duff burning from ember shower in foreground; hardwood tree boles burning in the canopy on middle ground, and spruce tree igniting from the top down in right foreground.

Figure 9c. Trees in middle ground burning from the top down.

Figure 9d. Trees burning in background as the flaming front advanced.

Discussion:

In this discussion, we offer perspectives on three subjects: field coordination and information sharing, videography methods and fire behavior in black spruce forests in Alaska. In interpreting our results, we acknowledge that both of the years of this study, 2004-2005, were unusually active fire years in Alaska. Although high intensity fire activity is common in black spruce, we do not know the extent to which the fire activity we witnessed was extreme (or anomalous).

<u>Discussion of field coordination and information sharing</u>

In Appendix B we recommend a dozen specifics about coordination and information sharing (See Appendix B.). In general we recommend proactively asking for the opportunity to work side by side with the Incident Command Team of each fire to be videographed, keeping in step with fire operations and sharing each day's films with the fire behavior analyst, planning officers and communications officers as closely as the team will allow. We found that once the Incident Command Team saw the films we were producing on their fires, they were very receptive to working together. Further, for periods in which fire crews are actively igniting burnout areas, we recommend requesting to be assigned officially to that crew or division to "travel with the torches." All of the crews with which we worked on the fireline were generous in their field support.

Finally, after the films are organized and processed, we highly recommend making them available on the internet. On our project website, we asked people who requested permission to download copies of the fire videos to tell us how they intended to use the footage. During the two years of this project, we were contacted by 155 individuals from 30 states in the U.S.A. and eleven foreign countries in North and South America, Europe, Africa and Asia. Sixty-eight percent of these requesters indicated their intent to use the films for training fire fighters and for education (e.g., teaching college courses). An additional eleven percent indicated their intent to use the films for communication and community outreach (Some requesters indicated more than one use, so the response tally exceeds 100 percent). Trainers cited their need to have visual examples of fires with which they could prepare their firefighters, particularly those who might be mobilized from outside of Alaska to work on fires in black spruce.

Discussion of method improvement

The primary improvement to our field methods would be applying technology in remote triggering devices for the cameras in fireboxes, and wireless transmission of digital footage to the computer. This would improve safety, raise the comfort level of the fire organization and produce images less influenced by fireline ignition and control. In addition, remote triggering would allow placement of cameras in a wider variety of settings, for example, in the interior of the fire and on a broader variety of slopes and aspects. Finally, operating a crew of three people per firebox would allow more frequent data collection on site, as well as simultaneous operation of the firebox and handheld video cameras. In addition, temperature-sensitive data loggers would assist in calculating ROS particularly for fire behavior phenomena in which rapid, nearly simultaneous combustion occurs (as in Sample #43, Figure 9).

The primary value of the firebox method is to capture fire behavior that we cannot currently capture by filming the fire in person. We placed our fireboxes with headfires and active crown fires in mind. However, to accurately observe flame lengths, we need a way to "see" flame lengths that exceed the current field of view of the camera (recall our 20 ft limit). Most black spruce trees in Interior Alaska are too short and spindly to provide adequate support for putting a firebox up in a tree. We could try stacking tripods, building a tower, or suspending cameras from cables, but any of these methods would increase the time needed for set up. Measuring more tree heights and making the most use of the roving handheld and video review methods would probably be the most practical, though the precision of the resulting data would still be coarse.

In addition, there were a few cases in which a surface fire moved through the firebox plot. For this we recommend knowing a simple measure: the distance between the camera face and the place on the ground where a low surface fire cannot be seen by the camera. When a surface fire advances from within the plot toward the camera, there is a point at which small flames move out of view. Likewise, when low flames enter the plot from behind the camera, there is a point at which the fire is burning underneath the camera and then into the plot, but cannot be seen. This is not a problem when the flame lengths are at least the height of the camera lens (about 4 ft), in which case the flames burn right up against the glass of the camera window (Figure 1b).

A final methodological issue to consider in this developing technology is the multiple scales of measurement at which video can be employed. A team can film fire at the fine scale of inches and minutes, as in our videos of backing fire; at the intermediate scale of tens of yards and tens of minutes as in our firebox camera plots; and at the large scale of miles and hours, as from a lookout post across a valley, or from inside a helicopter working a fire. While we focused at the small and intermediate scales, we recognize that there are differences in precision with each level. We addressed this in our analysis by keeping our level of precision about the same as what the BehavePlus3 and CFFBPS models use in English units (nearest foot). However, we feel that working at all scales will, over time, give us a more complete understanding of fire behavior, knowing that fire moving across the landscape operates meaningfully at all of these levels, in fuel matrices that can be described for each. We found the intermediate scale to be useful for assessing thresholds for transitions in fire behavior from surface to crown fire and from torching to active crowning.

<u>Discussion of fire behavior</u>

In his work to calibrate the BEHAVE model to fires in Alaska black spruce, Norum clearly and repeatedly stated that his work focused on surface fires (Norum 1982). Because today's TU04 model is the expression of Norum's findings, it is not surprising that BehavePlus3 did not perform well in predicting behavior when the fires we observed on video were actively crowning. Though the TU04 model was not intended to function to predict fire behavior beyond surface and torching fires (Scott, pers.com.), we are concerned that the BehavePlus3 software allows the user to enter inputs and generate outputs as though they functioned with validity. Entering fuel moistures gathered in the field, BehavePlus3 underestimated flame lengths and rates of spread by wide margins for fires we observed to be actively crowning. It did not predict crowning in cases where crown fires were the dominant fire type.

While we do not expect these models to be used in a vacuum, we feel an obligation to note that the TU04 model employed in BehavePlus3 as is, without any disclaimer, could possibly lead an unknowing user to under-predict fire behavior to the extent that some disadvantage to firefighters, to the distribution of resources during a fire event, or to communities preparing for the arrival of an advancing fire could result. In Scenario A, for example, BehavePlus3 under-predicted observed (video) flame lengths by 14.5 ± 4.9 feet. Here we recall the common decision support rule of thumb described by Andrews and Rothermel (1982), that flames up to four feet can be addressed using hand tools. If BehavePlus3 under-predicts flame lengths by at least ten feet, then based on model outputs, a fire planner could easily recommend that a particular fire could be addressed using hand tools when the actual flame lengths could not be. In a worst case, this might lead to inadequate assignment of resources (hand tools vs. bulldozers), putting ill-equipped fire fighters at risk.

The Canadian system of fire behavior prediction over-estimated fire behavior particularly for surface and torching fire types. However, within the limits of our video measurements, it did track the increase in fire activity in all three indicators (flame length, rate of spread and fire type) as fire moved into torching and crown fire behavior. Accurately predicting fire behavior at higher levels of intensity and rates of spread is essential to decision support. Over-predicting fire behavior is better accepted for firefighter safety than under-predicting it. With the exception of Sample #43 (Figures 9a-9d), our most rapid rates of spread, from the Boundary Creek and King's Creek Fires, were predicted reasonably by CFFBPS.

The source of the over-prediction by CFFBPS remains to be explored further. It is reasonable that a system empirically-derived in Canada will need to be calibrated to Alaska's more northern latitudes (Wilmore, 2001). Though empirically derived, the structure of the Canadian prediction system and the C2 fuel model appear fundamentally appropriate to the black spruce forests in Interior Alaska. Together they incorporate fuel loading and moisture conditions of the duff layer and the rapid moisture changes inherent in the living moss layer. Empirically, it adequately predicts fire type.

It is difficult to imagine that the fundamental structure of the BEHAVE model, which is designed for surface fires burning through fuel beds of consistent depth (Rothermel, 1972) can be fully adapted to model the range of fuel conditions and fire behavior that occur in black spruce forests in Alaska. Norum's (1982) empirical adaptation of BEHAVE to predict surface fire behavior seems adequate in our study. In that study, Norum acknowledged that fire in black spruce forests in Alaska "most often burn in the crowns" and that "ignition ahead of the fire front by airborne brands is common." For the practical purpose of serving as a decision support tool, we find that BEHAVE's inability to predict fire behavior beyond the surface fire is a fundamental weakness.

The black spruce forest fuel bed is fundamentally incompatible with Rothermel's surface spread model. Surface fuels and canopy fuels are interwoven through layering of live and dead branches into the moss layer, misfit in a model that clearly separates surface fuels from canopy fuels. Fuel loading and moisture of the thick duff layers are important fuel components, not accommodated in the surface model. The frequency of torching in spruce trees, with the accompanying showers of debris repeatedly advancing fire's movement is not easily accommodated presents a mechanism of fire spread specifically acknowledged by Norum as not included in his predictive equation. The propensity for Alaska black spruce to become plume dominated is a further difficulty. For these reasons, we conclude that the CFFBPS would be our choice for further investment in research and model calibration for use in black spruce forests in Alaska.

Finally, our qualitative observations offer some additional insight and speculation into fire behavior phenomena in Alaska. Norum (1983) recognized that the structure of black spruce stands in Alaska is highly variable. Given our observations about tree branches layering into the understory, ember showers, burning pinecones and cone scales, and the ignition of trees from both the top down and from the bottom up, we consider the influence of tree density within black spruce stands to be particularly influential in predicting how the fire will spread. We postulate two tree ignition scenarios: mild and high intensity.

In the mild scenario, the fire is wind driven and surface fire is the primary fire type. Trees are either by-passed and do not ignite, or they torch as a result of fire spreading through the understory. Short flames climb into the branches of individual trees whose canopy base height is from zero to a couple of feet above the moss layer. Torching is common but not necessarily vigorous. With wind gusts, clumps of trees ignite, but when the wind subsides, the fire returns to the understory. This scenario would take place in moderate to mild fire conditions in stands in which trees are more or less widely spaced. Most of our videos captured fire behaving like this scenario.

In the high intensity scenario, a different picture emerges. Tree density is higher and the canopy is dense. The forest stand occurs on a slope. An ember shower throws sparks across the moss understory, which starts to burn and warm the somewhat stifled air. Trees begin to volatilize and flammable gases accumulate in the stand. Hot air from the fire burning below rises upward, preheating the canopy. Some trees ignite from the top down, while the understory burns below with short flames (<1 ft.). Burning cones, resinous cone scales and fragments of dead twigs continue to rain onto the ground, helping the fire to spread. At some crucial point, the stand ignites almost simultaneously, though we can measure the rapid movement of a wall of flames through the stand. Flames boil out above the treetops, reaching flame lengths twice the heights of the trees. The fire is plume driven. In our video observations, this type of fire occurred in dense stands that were on slopes, with moderate surface wind. We do not know if this fire behavior requires extreme fuel conditions. Such a rapid change from a surface fire to an active crown fire without an apparent torching phase was acknowledged by Scott and Reinhardt in 2001. They asserted that "Even small changes in the fire environment can cause a surface fire to become fully active quickly." (Scott and Reinhardt 2001). We recommend further study of our King's Creek and Boundary Creek Fire videos and the data accompanying them as possible examples of this scenario.

These two hypothetical scenarios represent fire behavior toward two ends of the fire behavior spectrum that we filmed in black spruce forests in Interior Alaska during the 2004-2005 fire seasons. We also filmed fire behavior intermediate between the two, including continuous crown fires moving through a stand in patches, and in a flaming strand several miles long. This leads us back to the issue of scale. Are trees igniting from the top down all along a mile long flaming front? Our firebox plot size is too small to test that. Two what extent does every torching tree provide a shower of resinous debris that leapfrogs the fire ahead? Filming from a helicopter is too far away to detect that. Perhaps over time, using videography at all of these scales, including a combination of methods and electromagnetic signals, will expand our observational abilities of fire in the vast boreal forests of Alaska.

Overall, we find considerable promise in using videography to capture fire behavior data. In the field, fire behavior observations are ethereal, most of the time lasting only in snapshots and in firefighters' memories. Organized fire behavior datasets with accompanying site and weather information are rare. Putting data on film provides, for the first time, the opportunity to examine fire behavior over and over through repeated playback. Data archived on film provides a means to share fire observations with others for their analysis and feedback. Each observer will see information in these frames from the vantage point of their own expertise, experience and perspective. We hope that our films and our interpretation of them will be critiqued by others both now and in the future. We recommend performing similar work in other fuel types, particularly in Alaska and internationally where many fuel types remain untested (Dave Jandt, pers.com.) for their use with decision support systems designed to assist fire practitioners. Finally, as the world's climate changes, we may depend upon such films as benchmarks of fire behavior in a changing fire environment.

In conclusion, video observations of fire behavior during the active fire years of 2004-2005 in Interior Alaska provide both quantitative and qualitative information about the variety and complexity of fire behavior in black spruce forests. Comparing these observations with model outputs, we find cause for concern about using the TU04 fuel model in BehavePlus3. We recommend further calibration of the C2 fuel model in the CFFBP system to best predict fire behavior in Alaska's black spruce forests. Our video observations confirm that the transition between surface fire and active crown fire can occur in this fuel type within a few seconds, in the absence of a discernable torching phase. The potential for rapid transition in fire type and the importance of crown fire activity in decision support in black spruce fuels in Alaska causes us to recommend notifying users of BehavePlus3 about the limitations of using the TU04 model.

Literature cited:

Albini, F. A. 1976. Estimating wildfire behavior and effects. USDA Forest Service Intermountain Forest and Range Experiment Station. Ogden, UT. Gen.Tech.Rep. INT-130.

Andrews, P. L. and C.H. Chase. 1989. BEHAVE: Fire behavior prediction and fuel modeling system – BURN subsystem, part 2. USDA Forest Service, Intermountain Research Station. Ogden, UT. Gen.Tech.Rep. INT-260. 93 p.

Andrews, P. L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system-BURN subsystem part 1. USDA Forest Service Gen.Tech.Rep. INT-194. 130 p.

Andrews, P. L. 1980. Testing the fire behavior model. In Proceedings, Sixth Conference on Fire and Forest Meteorology; Seattle, WA, April 22-24.

Andrews, P. L. and R. C. Rothermel. 1982. Charts for interpreting wildland fire characteristics. USDA Forest Service. Intermountain Forest and Range Experiment Station. Ogden, UT. Gen.Tech.Rep. INT-131.

Burgan, R.E. and R. C. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel modeling system - FUEL subsystem. USDA Forest Service Gen. Tech. Rep. INT-GTR-167.

Fleiss, J. L. 1981. Statistical methods for rates and proportions, 2nd edition. John Wiley & Sons, New York.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep. ST-X-3. Ottawa, Canada: Forestry Canada Science and Sustainable Development Directorate. 63 p.

Norum, Rodney A. 1982. Predicting wildfire behavior in black spruce forests in Alaska. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note PNW-410.

Norum, Rodney A. 1983. Wind adjustment factors for predicting fire behavior in three fuel types in Alaska. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Paper PNW-309.

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service. Intermountain Forest and Range Experiment Station. Ogden, UT. Research Paper INT-115.

Rothermel, Richard C. and G.C. Rinehart. 1983. Field procedures for verification and adjustment of fire behavior predictions. USDA Forest Service. Intermountain Forest and Range Experiment Station. Ogden, UT. General Technical Report INT-142.

Ryan, Kevin C. 1981. Evaluation of a passive flame-height sensor to estimate forest fire intensity. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note PNW-390.

Scott, Joe H. and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service. Rocky Mountain Research Station. General Technical Report RMRS-GTR-153.

Scott, Joe H. and E. D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service, Rocky Mountain Research Station. Research Paper RMRS-RP-29.

Turner, J.A., and B.D. Lawson. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Environ. Can., Canadian Forest Service, Pacific Forest Research Centre, Victoria, B.C.

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

Wilmore, Brenda. 2001. Duff moisture dynamics in black spruce feathermoss stands and their relation to the Canadian Forest Fire Danger Rating System. Thesis. University of Alaska-Fairbanks. Fairbanks, Alaska.

Personal communication:

Alden, Sharon. Meteorologist. Alaska Interagency Coordination Center. Fairbanks, AK. Tel: 907-356-5691 Email: Sharon_Alden@ak.blm.gov

Dollard, Jason. BLM Alaska Fire Service. Fairbanks, AK.
Email: Jason_Dollard@ak.blm.gov

Jandt, Dave. Assistant Fire Management Officer. BLM Alaska Fire Service, Fairbanks, AK.
Tel: 907-356-5562 Email: Dave_Jandt@ak.blm.gov

Scott, Joe. Research Forester. Systems for Environmental Management, Missoula, MT. Tel: 406-549-2340 Email: Joe.Scott@montana.com

Acknowledgements

Filming wildland fire in a rapid response fire environment, processing the resulting video footage and making that footage available to others on the internet required the expertise and assistance of many partners. We gratefully acknowledge the following collaborators:

- Joint Fire Sciences Program, Rapid Response project funds
- Bureau of Land Management
- Alaska Fire Service
- Alaska State Department of Forestry
- Alaska State Department of Natural Resources
- Alaska Type 2 Incident Command Team (Kurth)
- Central Oregon Type 2 Incident Command Team (Goheen)
- Colorado State University, Warner College of Natural Resources Computer Labs
- Colorado State University, Office of Instructional Services
- Colorado State University, WESTFIRE
- Intermountain Fire Sciences Laboratory, Rocky Mountain Research Station
- Missoula Fire Sciences Laboratory, Rocky Mountain Research Station
- Missoula Technology and Development Center, Photographic Services
- National Park Service
- Northern Idaho Type 2 Incident Command Team (Chrisman)
- Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station
- Yale School of Forestry and Environmental Studies
- US Fish & Wildlife Service
- US Forest Service

Appendix A. Summary of steps in the video-based fire behavior research process

1. Prior to field
   a. Request permission by the managing agency to collect data on a particular fire.
   b. When approved, sign in with the Resource Officer on the fire
   c. Meet with IC team to discuss objectives, get maps and read Incident Action Plans (IAP)s.
   d. Conduct site visit to see possible camera locations.
   e. Discuss specific plans for videography with operations chief, safety officer and fire behavior analyst each day.
   f. Make sure that planned camera locations are included on the IAP map.
   g. Correct the settings on each camera, e.g., counter, date, time, recording speed, lens size and manual focus.

2. In the field
   a. Work with a buddy (liaison) assigned from the fire organization.
   b. Check in with division supervisors upon arrival in his/her area of the fire.
   c. Select final camera sites based on safety, operational, fuels and site factors.
   d. Set up fireproof camera boxes and measuring poles
   e. Measure distances between poles and the center line of the camera box.
   f. Flag escape routes from camera boxes to safety zones.
   g. Take site data for camera locations: GPS points, slope, aspect, elevation, azimuth of camera view.
   h. Take handheld video of live fire from the fireline or safety zone, as safety allows.
   i. Take onsite weather (belt weather kit) as near as possible in time and space to video locations (both camera boxes and handheld video), at least every half hour.

3. Back at the Incident Command Post (ICP):
   a. Check in with the Resources Office at the end of each operational period.
   b. Review films for quality and content.
   c. Select segments of video that might be informed by post-burn measurements (e.g., tree heights or distances between trees).
   d. Share video footage with fire behavior analyst and others, as desired.
   e. Attend operational strategy meeting if possible to learn next filming opportunities.

4. Derive video observations of fire behavior
   a. Transfer raw video tapes into digital files; store on computer
   b. View each video multiple times; choose segments of measurable fire behavior.
   c. Return to the camera sites to take post-burn field measurements as necessary.
   d. Clip useable video segments and store them in individual digital files;
   e. Using stopwatch, timer on camera, audible comments on tape, and written field notes, estimate fire behavior in each segment: ROS, flame length, fire type.
   f. Record results in spreadsheet.

Appendix A, continued

5. Model fire behavior in BehavePlus3
   a. Use weather and site data from video locations
   b. If needed, derive slope and aspect for camera locations from DEMs using GIS
   c. Record model outputs in spreadsheet: ROS and flame length
   d. Note that the TU04 fuel model is designed to run in BehavePlus3 always using live woody fuel moisture of 100 percent. The TU04 fuel model is not designed to be used with the crown fire module of BehavePlus3 (Scott, pers.com.).

6. Model fire behavior in CFFBP system (“Behave by Remsoft, Inc.” software)
   a. Download fire weather indices from RAWS stations nearest or most similar to the camera sites.
   b. Use weather and site data from video locations
   c. Model fire behavior using CFFBP
   d. Record model outputs in spreadsheet: ROS, fire intensity, fire type
   e. Calculate estimates of flame length using fire intensity outputs (Ryan 1981).

7. Compare fire behavior results from video observations with BehavePlus3 and CFFBP fire behavior predictions.

Appendix B. Detailed instructions and tips for three methods of wildland fire videography in Alaska black spruce forests.

1. The firebox method.

Upon arriving at the selected site, ascertain the direction from which you think the fire will advance. Understand the likelihood of collecting data for a heading, flanking or backing fire, and place the camera window accordingly. Also consider the direction in which the smoke will most likely be traveling, because persistent smoke obscures the camera's view of the flames. Select a view that includes some measurable landmarks, such as specific trees within the field of view. Trim away flammable vegetation within the first 3 feet of the camera, so that smoldering and flaming vegetation right at the camera face or just below it will not obscure the whole shot. Adjust the camera box so that the camera view is approximately parallel to the ground surface, matching the slope. If a cross-slope view is desired, place a small level on top of the box and adjust the legs until it is level.

Tie flagging tape at two foot intervals from the top of each measuring pole. Use a different color of flagging for each pole so the poles will be easy to distinguish on film. In a high intensity fire situation, flagging will be more visible than paint on the poles for observing flame lengths. The flagging will also help monitor wind direction on video before the fire arrives. Make the tape long enough that it will flutter and indicate any changes in wind direction.

Place one marking pole at the farthest visible location within the view of the camera. In Alaska black spruce, this was typically 10-15 meters from the camera face. Place second and third marking poles just inside the left and right edges of the camera's field of view. Place 1-3 additional poles within the plot if they will provide helpful reference points (Figure 2). The idea is to be able to measure the fire's passage no matter the direction in which it travels through the plot. In forest vegetation, place taller poles in locations at the far end of the camera "plot" and shorter poles closer to the camera. In our case, short poles were 5 ft high, and tall poles were three five-foot pole sections connected to total 15 ft. high. Lean tall poles next to trees if necessary. Wrap joints where poles are connected with metal furnace tape to keep joints from melting and separating during the fire. Push both camera tripod legs and measuring poles into the ground, if the soils are appropriate, to assist in stabilizing them during the passing fire front.

In most of the black spruce forests we encountered in Interior Alaska, just pushing the poles about an inch into the mud by hand was sufficient. If you need more stability, usually for longer poles, you can hammer the first pole into the ground – don't forget to protect the connecting end – or you can drive a three-foot length of rebar partway into the ground and slide the bottom pole over that.

Once it appears that the filming opportunity is near, use the appropriate timing for switching the cameras on. If remote switching is unavailable, the camera operator must estimate the time of the fire's arrival and know the life of the camera battery and the length of the video tape. For our equipment, this was about 90 minutes of battery time and one hour of video tape. The operator must allow for ample time to walk through the brush to the camera plot, turn on the camera, insert the "blue ice," close the box, confirm that it is running and return to the safety zone within an generous margin of time for safety. Allow enough time to trip and fall a couple of times, pick up your things and still get out in plenty of time! Bring extra film and batteries in case the film runs out before the fire arrives and you have time to return to refresh the camera and set it again.

Before you put the camera down into the camera box, videotape a short narration to introduce each plot at the beginning of each tape. Scan the immediate area on film. Mention the date and time, camera location, objective of the shot, and pertinent information about the fire (e.g. expected ignition pattern, direction of fire spread). Mention any vegetation trimming that was done near the camera; and take a few still photographs of the scene for reference.

In the closest five (5) meters of the plot, trim limbs or other vegetation that you expect to obstruct the camera's view of the fire (e.g., a spruce limb hanging down in an otherwise workable view). Note such trimming in the data book. Record the azimuth of the camera's view; and measure tree heights and topographic features such as slope, aspect and elevation either before or after the fire. Measure the heights and distances from the camera of additional feature in the plot that will be obvious on film, such as a tall rock or stump. These can serve as reference markers for estimating flame lengths and rate of spread.

After the fire has passed and the ground is cool enough to walk on, return to the firebox and retrieve the equipment. Be especially aware of post-burn hazards such as snags, falling limbs and burning stump holes. Open the firebox and immediately label the video tape and secure it from being erased or damaged. Take any field measurements you need, such as distances to trees or other features that might be more visible after the fire. If there wasn't enough time to take site data such as camera location, azimuth of the camera's view, or distances between poles before the fire, do so before you remove the equipment.

In a rapid response situation, it may not be possible to set up the camera plot well in advance. If safety allows, sometimes it is possible to "plant" the camera and poles in a relatively short time (in our situation this took about 15 minutes), and then to return to the plot post-burn to record the site data.

Another possibility if you have a limited number of cameras on a fire is to set up multiple "camera ready" plots along the fireline; and then move the camera box from pre-set to pre-set as the fire progresses. In preparing these "camera ready" plots, place them far enough apart that you will be able to retrieve the camera from the recently burned plot and set up in the new plot with plenty of time to return to a safety zone. Unused "camera ready" plots are easy to clean up (just remove the poles) if safe timing did not provide an opportunity to use the camera.

2. The roving handheld video method

The handheld video method entails two people filming fire behavior on foot or from a lookout position. We walked along the fireline or within 100 meters of an escape route or safety zone. One person operates the camera while the other person looks for hazards, takes weather measurements and otherwise assists the camera person. Carry a radio, stopwatch, clinometer, wire flags, flagging tape, metal marking poles and a handheld GPS unit along with a light camera pack and PPE. Set the camera to record the date and time sequence of the footage on the raw film.

The data collection concept is to take advantage of whatever fire behavior occurs that you can safely capture on film while locating physical reference points in the camera's view. You can use or create reference points in several ways: use existing physical features such as trees, rocks and trails; create markers by placing metal poles upright into the ground at various distances perpendicular to where you think the flaming front will pass; or throwing markers javelin style into the path of the fire shortly before the flames arrive.
Select a safe filming location near your makeshift "plot" that is out of the way of fire operations and wait for the fire to arrive at your "plot."

For backing fires, especially when the wind is steady, you can often walk along near the fire and film the movement of the backing flames. You can either place wire flags at various intervals perpendicular to the fire's spread, or lay metal poles right on the ground and film the fire as it burns along the length of each pole. Creativity in finding or creating reference markers in advance of expected fire behavior will increase the number of fire behavior data points you can collect, as long as safety is first and as long as you can supply the accompanying site and weather data for each.

While you are filming, narrate your estimates of flame lengths and rates of spread while you are filming; this information may constitute your best estimates of fire behavior. Describe your "plot" setup and what is going on with the fire as a whole. Include observations of weather, wind changes, fuel jackpots or any other relevant information that might be affecting the fire behavior captured on film.

After the flaming front passes, return to the site to measure any distances you need, such as tree heights, the distance from one reference point to another (e.g., from the safe filming location to that rock and that tree, or the distance between poles). Check your data book for any missing information, such slope, aspect, elevation or GPS coordinates. If you are lucky enough to follow the fire traveling along the fireline, filming one makeshift video plot after another, you will need to set aside time to return to the site to complete the necessary measurements. If this is impossible, a second best option is to glean site data from topographic maps, digital elevation models (DEMs) or various forms of satellite imagery. If needed weather data can be borrowed from the communications record of weather measures taken by fire crews during the fire, or from RAWS stations. The researcher will have to judge whether or not such borrowed data are applicable (close enough in time and location) to the fire captured on film.

Filming and collecting data in the midst of fire operations requires prior knowledge of the fire fighting organization, knowing where to be in order to capture good footage while keeping out of the way, and operating safely in a dynamic and risky work environment. Sometimes an all-terrain vehicle, especially one with a cargo bed to carry equipment, can enhance the mobility of the filming operation.

Fire behavior filming opportunities are always fleeting, so do the best you can to be in the right place at the right time, gathering as much data as practical within a generous safety margin.

Maintaining constant radio contact with fire operations is a must. Your ability to predict when and where the fire will arrive and what will make a good filming opportunity will increase with knowledge of fire behavior and with fire experience. Good coordination and earned trust within the fire organization both at the ICP and on the fireline will improve your chances of having reasonable access to filming opportunities.

3. The video review method.

The video review method entails reviewing the film you have already shot and returning to the site afterwards. As you review the film, you will notice fire behavior and reference points that you did not see while you were in the field. You can use these fire behavior scenes provided you can supply accompanying weather and site information. Take your video tape in the camera and go to the site. Replay the tape as needed to locate the scene you captured on film, including the original vantage point of the camera. Your narration from the film will help jog your memory. When you are confident you have found the site, measure ground distances, tree heights, GPS coordinates, slope, aspect, elevation and any other information you need to interpret the scene on film. Borrow weather information either from your data book, the communications record of the fire or a RAWS stations. You will have to use your judgment as to whether or not such borrowed data is near enough in space and time to use. Still photographs can also be used with this method, as long as the time of each snapshot and the exact location from which the snapshot was taken are recorded. Figures 3a-3d provide sample video frames that illustrate this method.

Remember, opportunities to capture fire behavior observations are always ephemeral, so use the video review method in combination with the firebox and the handheld video methods to maximize your field data collection. With ample tapes recorded, you can throw out the ones that are unsuitable because of incomplete data or factors confounding the fire behavior observed. (In one of my firebox films, Sample #43 shown in Figures 9a-9d, a flare from a Very pistol landed right inside of our plot!). Don’t expect every film to be successful. Be patient and remember that there will be another day to film if and only if everyone stays safe and reliably-coordinated on today’s fire.

Appendix C. Coordinating with the fire organization in a rapid response wildfire setting.

Developed by Allen Chrisman, Incident Commander, Doug Turman, IC trainee, Northern Idaho Type 2 Incident Management Team, Dave Jandt, Assistant Fire Management Officer, Alaska Fire Service, and Mary Huffman, Research Assistant, Colorado State University during the Boundary Creek Fire, Eagle Alaska, July 2005.

1. Ask your Host Agency to include you, the researcher, and your project in the Incident Delegation of Authority, or to provide a blanket letter of authorization including what agreements are in place and what level of support the Host Agency is asking the Incident Management Team to provide you on the fire.
2. Provide a one-page brief telling the purpose of your research, your fire experience, and your operational needs.
3. Formally check in with the Planning Section when you arrive on the fire and formally check out when you leave. Ask to be recorded as part of the fire organization, without an “O number.” You will likely be listed as a Specialist.
4. Introduce yourself to the Incident Commander (IC) and ask for a brief opportunity to explain your project. Ask for the IC’s direction about how to conduct your research under the umbrella of his/her Incident.
5. Bring your Red Card and show it to the IC, Safety Officer, Section Chiefs, Division Supervisors and others on the fire as soon as practical.
6. Bring a programmable radio, such as a Bendix-King radio. Check in with the Communications Unit and keep the radio cloned to the correct frequencies. Turn it on while you are in the field (except in aircraft), scanning appropriate channels so you are in communication. Observe proper radio etiquette.
7. Work with the Planning Section to include your daily research activities in the Incident Action Plan (IAP), if appropriate. Provide a map of where you’ll be working each day. Carry a copy of the daily IAP.
8. Have an escort working with you at all times. If you can bring a line qualified escort with you (paid by your project), try that. Tie in with the supervisor of the Division where you will be working each day; and be sure someone in that Division knows where you are at all times. Check in and out with the Division Supervisor when you arrive and leave his/her Division.
9. Coordinate with the Host Agency about how to cover the cost of supporting your activities on the fire (e.g., meals, copies, supplies).
10. Your work can provide fire behavior information to the Incident Command Team; but take care that what you do doesn’t interfere with mission operations.
11. Set a good example. It will help the Incident Management Team and the fire organization to build a positive relationship with the local community.
12. Safety is first for you, the firefighters and the community. Apply all of your firefighter and safety training to your conduct on the fire.

Appendix D. Equipment list and camera settings for videography of wildland fire

I. Equipment List

A. Camera-related equipment

_____ video cameras
_____ still cameras
_____ blank video tapes
_____ video camera batteries
_____ video battery chargers
_____ fireboxes
_____ heat absorbing “picnic coolers”
_____ firebox tripods
_____ firebox carrying racks
_____ cardboard covers to protect firebox glass
_____ wide masking tape
_____ bungee cords, straps
_____ camera cleaning kit
_____ marking pen (for labeling tapes)

B. Non-camera equipment

_____ steel conduit measuring poles (5 ft. lengths of steel conduit)
_____ conduit joiners
_____ metal furnace tape
_____ pipe cutter
_____ compass
_____ GPS
_____ clinometer
_____ flagging tape (4-5 different colors)
_____ wire flags
_____ pocket knife
_____ screw driver
_____ crescent wrench
_____ pliers
_____ extra screws, bolts
_____ data book, pencils

C. Computer equipment and software

_____ laptop computer
_____ video editing software (we used Adobe Premier Pro)
_____ fire wires and other accessories needed for digital video download

D. Personal

_____ Personal protective equipment - see NWCG and your agency’s standards
_____ Programmable radios (one per person) plus extra batteries
_____ bug spray, sunscreen, personal first aid kit

Appendix D, continued.

II. Camera settings and software used for videography of fire behavior in Alaska black spruce fuels, and software used for processing and analyzing video data

A. Camera settings

____ standard play (not long play of the tape)
____ manual focus, set on infinity
____ correct date and time stamp, and turn on
____ set to record the length of tape and turn off, (not wrap recording)
____ specify lens type (35mm or wide-angle)
____

B. Software

____ Picture Perfect (camera's video downloading software)
____ Adobe Premier Pro (video editing)
____ Microsoft Excel
____ Microsoft Media Encoder (video editing)
____ ArcGIS
____ BehavePlus3
____ Behave by Remsoft, Inc. (includes CFFBPS)

Appendix E. Minimum and Maximum values of non-fire variables and notes on data sources.

Variable	**Notes on data sources**	**Minimum value**	**Maximum value**
Date		25 June 2004 21 June 2005	16 July 2004 24 July 2005
Time of Day (nearest hour)		1400	2100
Latitude	Handheld GPS	N 63°21.238'	N 67°09.130
Longitude	Handheld GPS	W141°10.708'	W150°21.508'
Elevation (ft)	From GPS or DEM	1042	3251
Slope steepness (deg)	From DEM	1	36
Slope aspect	From DEM	N, NNE, NE, ENE, SE, SSE, S, SW, WNW, NW, NNW	
Mid-flame wind speed (mph)	Belt wx kit, RAWS	0	7
20-ft wind speed (mph)	RAWS	0	13
Wind direction	Belt wx kit, RAWS	N, NNE, NE, ESE, SS, E, S, SW, NW	
Temperature (°F)	Belt wx kit, RAWS	60	82
Relative Humidity (%)	Belt wx kit, calculated by Behave	28 (belt wx kit) 28 (Behave)	50 (belt wx kit) 72 (Behave)
Fine dead fuel moisture from weather measures (%)	Calculated by Behave, or RAWS	4.2 (Behave) 7.0 (RAWS)	11.0 (Behave) 9.2 (RAWS)
1-hr fuel moisture	Field	7.9	12.7
10-hr fuel moisture	Field	9.3	15.1
Live woody moisture	Field - dwarf shrub layer or 100 percent	115	131
Foliar moisture	Field - black spruce foliage or 100 percent	101	117
Canopy base height (ft)	Field	1.0	1.5
Canopy bulk density (lb/ft^3)	Field	0.0084	0.0240
Fine fuel moisture code	RAWS	89.4	95.7
Build up Index	RAWS	49	184.8