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Fire Ecology

TECHNICAL NOTE

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Observed versus predicted fire behavior in an Alaskan black spruce forest ecosystem: an experimental fire case study

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Abstract

Background: Fire managers tasked with assessing the hazard and risk of wildfire in Alaska, USA, tend to have more confidence in fire behavior prediction modeling systems developed in Canada than similar systems developed in the US. In 1992, Canadian fire behavior systems were adopted for modeling fire hazard and risk in Alaska and are used by fire suppression specialists and fire planners working within the state. However, as new US-based fire behavior modeling tools are developed, Alaskan fire managers are encouraged to adopt the use of US-based systems. Few studies exist in the scientific literature that inform fire managers as to the efficacy of fire behavior modeling tools in Alaska. In this study, I provide information to aid fire managers when tasked with deciding which system for modeling fire behavior is most appropriate for their use. On the Magitchlie Creek Fire in Alaska, I systematically collected fire behavior characteristics within a black spruce (*Picea mariana* [Mill.] Britton, Sterns & Poggenb.) ecosystem under head fire conditions. I compared my fire behavior observations including flame length, rate of spread, and head fire intensity with fire behavior predictions from the US fire modeling system BehavePlus, and three Canadian systems: RedAPP, CanFIRE, and the Crown Fire Initiation and Spread system (CFIS).

Results: All four modeling systems produced reasonable rate of spread predictions although the Canadian systems provided predictions slightly closer to the observed fire behavior. The Canadian fire behavior prediction modeling systems RedAPP and CanFIRE provided more accurate predictions of head fire intensity and fire type than BehavePlus or CFIS.

Conclusions: The most appropriate fire behavior modeling system for use in Alaskan black spruce ecosystems depends on what type of questions are being asked. For determining the rate of fire movement across a landscape, REDapp, CanFIRE, CFIS, or BehavePlus can all be expected to provide reasonably accurate estimates of rate of spread. If fire managers are interested in using predicted flame length or energy produced for informing decisions such as which firefighting tactics will be successful, or for evaluating the ecological impacts due to burning, then the Canadian fire modeling systems outperformed BehavePlus in this case study.

Keywords: Alaska, BehavePlus, Canadian FBP, CFIS, fire behavior modeling, fire behavior observations

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Resumen

Antecedentes: Los manejadores del fuego a quienes se les encomienda determinar el peligro y riesgo de incendios en Alaska, EEUU, tienden a confiar más en los sistemas de modelado predictivo desarrollados en Canadá que en aquellos similares desarrollados en los EEUU. En 1992, los modelos de comportamiento del fuego fueron adoptados para modelar el peligro y riesgo de incendios en Alaska, y son usados por los especialistas en supresión y planificadores en el tema fuegos que trabajan en ese estado. Sin embargo, al desarrollarse en EEUU nuevas herramientas para predecir el comportamiento del fuego, se promueve que los manejadores de incendios adopten el uso de los sistemas estadounidenses. Pocos estudios existen en la literatura científica que informen a los manejadores de fuegos sobre la eficacia de las herramientas de modelado de predicción del comportamiento del fuego en Alaska. En este estudio, proveo de información que ayudaría a los manejadores de fuegos en su tarea de decidir cuál es el sistema de modelado del comportamiento del fuego que es más más apropiado para su uso en Alaska. En el incendio llamado "Magitchlie Creek Fire" en Alaska, colecté sistemáticamente las características del comportamiento del fuego dentro de un ecosistema dominado por picea negra (*Picea mariana* [Mill.] Britton, Sterns & Poggenb.), en condiciones de un fuego frontal. Comparé mis observaciones sobre el comportamiento del fuego, incluidas la longitud de llama, la tasa de propagación, y la intensidad de línea con las predicciones del sistema Estadounidense BehavePlus, y tres de los sistemas canadienses: RedAPP, CanFIRE, y el llamado Crown Fire Initiation and Spread System (CFIS).

Resultados: Los cuatro modelos utilizados proveyeron de predicciones razonables para la tasa de propagación, aunque los sistemas canadienses brindaron aproximaciones más cercanas a los valores de comportamiento observados. Los modelos canadienses de predicción del comportamiento RedAPP y CanFIRE produjeron predicciones más precisas de la intensidad de línea y tipo de fuego que el BehavePlus o el CFIS.

Conclusiones: El sistema de modelo de comportamiento más apropiado para su uso en ecosistemas de bosques de picea negra depende del que tipo de pregunta nos estamos haciendo. Para determinar el movimiento del fuego a través del paisaje, tanto REDapp, CanFIRE, CFIS, o BehavePlus pueden proveer de estimaciones razonables de la tasa de propagación. Si los manejadores están interesados en predecir la longitud de llama o la energía producida para informar sobre las decisiones y tácticas para el combate que sean más exitosas, o para evaluar los impactos ecológicos debido al fuego, los sistemas de modelado canadienses superan al BehavePlus en este estudio de caso.

Abbreviations

CFFDRS: Canadian Forest Fire Danger Rating System
CFIS: Crown Fire Initiation and Spread System
FBP: Canadian Forest Fire Behavior Prediction System
FWI: Canadian Forest Fire Weather Index
RAWS: Remote Automated Weather Station
Rh: Relative humidity
WAF: Wind Adjustment Factor
WFDSS: Wildland Fire Decision Support System

Introduction

Fire is the most important environmental disturbance factor in Alaskan black spruce (*Picea mariana* [Mill.] Britton, Sterns & Poggenb.) ecosystems (Viereck 1973). Wildfires in black spruce tend to be large fires that kill overstory trees and remove most, if not all, aboveground vegetation (Viereck 1983). Most plant species associated with black spruce are adapted to repeated stand-replacement fires, and black spruce ecosystems in Alaska tend to be perpetuated by fire (Viereck 1983). Fire's importance in these ecosystems leads to a need to understand how fire behaves in black spruce and to be able to predict how an area would burn during a wildfire event, especially with the realization that 80% of the population in Alaska lives in areas at risk from wildland fire (Little et al. 2018).

Beginning in the early to mid 1970s, mathematical models for predicting fire behavior started to become available in North America (Rothermel 1972; Van Wagner 1973; Albini 1976). A difference in approaches between fire scientists in Canada and the United States has led to several separate fire behavior modeling systems (Van Wagner 1985). Canadian researchers took a more empirical approach by which predictive algorithms were developed from observations of field experimental fires and wildfires in boreal ecosystems (Van Wagner 1983), while US scientists developed their predictive algorithms based on physical heat transfer theory and laboratory fires (Rothermel 1972; McAlpine and Andrews 1998). Each approach has its strengths and weaknesses; only by direct comparison with observed fire behavior can fire managers decide which system works best in their area of interest for informing their land management decisions.

Determining which approach or system to use in Alaska is an ongoing debate. Although largely settled in 1992 when the Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al. 1989) and its two major subsystems, the Canadian Forest Fire Weather Index

(FWI) system (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) system (Forestry Canada Fire Danger Group 1992; Wotton et al. 2009), were officially adopted for use in Alaska (Alexander and Cole 1995), the development of the Wildland Fire Decision Support System (WFDSS; Noonan-Wright et al. 2011) has altered the Alaskan fire management landscape. Federal fire managers are currently required to use WFDSS on most fires on federal lands including Alaska (ISFFAOG 2018). Fire behavior analysis tools available in WFDSS for evaluating fire risk and predicting fire behavior across landscapes are based on the Rothermel fire spread models developed in the US (Rothermel 1972; Rothermel 1991; Noonan-Wright et al. 2011) and do not include the tools for analyzing fire behavior potential developed in Canada. The general consensus by Alaskan fire managers is that the Canadian FBP systems outperform US fire behavior modeling systems in Alaska, although few direct comparisons between observed and modeled fire behavior exist in the scientific literature.

This case study was conducted to provide information for evaluating if US modeling systems performed as well in Alaska as Canadian-produced systems. I compared direct observations of vegetation, weather, and fire behavior collected on the 1997 Magitchlie Creek Fire with fire behavior prediction systems currently in use operationally in the US and Canada. The BehavePlus V6 (Andrews et al. 2008) modeling system (https://www.firelab.org/project/behaveplus) was chosen to represent US-based fire behavior prediction systems as it contains the core Rothermel equations used in the fire behavior modules in WFDSS. Canadian fire behavior prediction research was represented by the REDapp V6.2.3 modeling system (http://redapp.org/; McLoughlin 2016), CanFIRE V2.08 (http://www.glfc.forestry.ca/canfire/), and V4 of the Crown Fire Initiation and Spread System (CFIS: http://www.frames.gov/cfis; Alexander et al. 2006).

Methods

Study area

The Magitchlie Creek Fire (Alaska Wildfire B309), was first reported on 10 June 1997 at latitude 63.633333, longitude −158.416667, burning in open black spruce stands within a spruce, shrub, and bog mosaic (Fig. 1). The fire continued burning within the Innoko National Wildlife Refuge for several months and was officially declared out on 16 October 1997, after burning approximately 124 960 ha.

On 26 June 1997, we traveled to the fire via helicopter from the village of Galena. At that time, the fire was burning in topography that has been described as

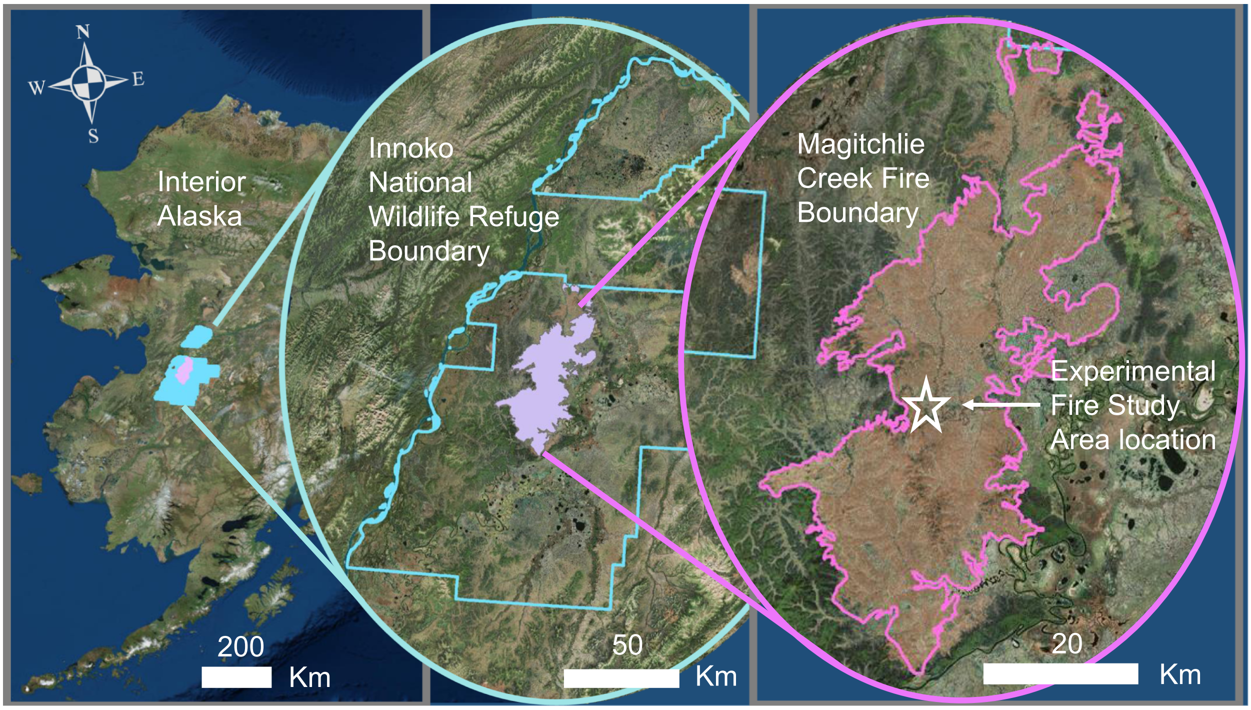

Fig. 1 Location of the 1997 Magitchlie Creek Fire in interior Alaska, USA. From left to right, left frame shows general location of fire area (pink) within the Innoko National Wildlife Refuge in interior Alaska (blue). Middle frame zooms in on the refuge boundary (blue) and shows general location of the approximately 125 000 ha burn area (purple). Right frame zooms to the Magitchlie Creek Fire boundary (purple). Star marks experimental fire location. High resolution imagery (10 m accuracy) dated 16 August 2016 downloaded from Digital Globe using ArcGIS 10.3 on 17 October 2018

interior bottom lands (Gallant et al. 1995). The fire was concentrated in lowland black spruce stands that formed slightly raised islands within a sea of sphagnum moss (*Sphagnum* L. spp.) (Additional file 1). In a normal year, the sphagnum moss areas would be inundated with water, but in the summer of 1997, these areas were relatively dry. After aerial reconnaissance, we selected one of the larger black spruce islands at the rear of the fire as the Magitchlie Creek Experimental Fire study site.

On 27 June 1997, a weather station, biomass inventory plots, and fire behavior observation plots were set up. At 1744 Alaska Daylight Time (ADT) on 28 June 1997, the study area was hand ignited with the wind along a 100 m ignition line, creating a running head fire within seconds post ignition (Fig. 2). The experimental fire merged with the backing and flanking fire from the Magitchlie Creek Fire at approximately 2100 ADT.

Weather

Onsite air temperature (°C), relative humidity (Rh; %), wind speed (km h^{-1}), and wind direction (°) data were collected 2.0 m above ground every three minutes using a portable Campbell Scientific remote weather station (Campbell Scientific, Logan, Utah, USA). The weather station was located in a very open area covered with short grass, approximately 300 m from the experimental plot areas. Additional weather data was collected 26.7 km south of the burn site from the Innoko Flats remote automated weather station (RAWS).

Biomass inventory

Standing trees and tall shrubs

All standing woody stems (stems ≥1.37 m tall) on six 20 m^2 circular plots were individually tallied, identified to species, and tagged with numbered metal tags (Additional file 2). The diameter at breast height (dbh; cm), total height (m), ladder fuel height (height to dead branches; m), height to live crown (m), condition (live or dead), and basal diameter (cm) were recorded for each stem. Seedlings (stems <1.37 m tall) were sampled on 4 m^2 circular plots nested within each standing stem plot.

Fig. 2 Line ignition of Magitchlie Creek Experimental Fire plot, Innoko National Wildlife Refuge, Alaska, USA, at 1744 hours ADT on 28 June 1997. Photo was taken from helicopter 30 seconds after fire was ignited. Fire was a running head crown fire seconds after ignition. Photo credit: S. Drury

Low shrubs

All low shrubs <1.37 m tall on six 0.25 m^2 plots (one plot located 4.6 m due west from the plot center of standing stem plot) were clipped at the base and collected for later drying in the lab. Belowground shrub biomass was not collected. Daubenmire (1959) cover class and frequency values for low shrubs and surface material were collected on two 0.25 m^2 plots per standing stem plot.

Forest floor

Surface moss, litter, and duff biomass depths (mm) were measured at eight randomly chosen locations within each plot area and converted to biomass using bulk density conversion factors developed for the 1996 Alaska Photoseries (Ottmar and Vihnanek 1998).

Woody fuels

Woody fuel loadings were determined by sampling all woody fuels along three 9.1 m transects per tree plot using the planar line intersect method (Brown 1974). Each transect radiated out from the plot center of the tree plot (Additional file 2). The direction of the first line (in degrees) was determined randomly using a random-number table. The subsequent two lines were located 120 degrees from the first line and 120 degrees from one another. The diameter, species, and decay class of each intersected 1000-hour fuel (≥7.6 cm diameter) were recorded along the entire 9.1 m length of each line. Hundred-hour fuels (≥2.5 and <7.6 cm in diameter) were tallied along the entire length of each 9.1 m line. Ten--hour fuels (≥ 0.6 and <2.5 cm in diameter) were tallied within the initial 2.0 m of each line.

Fuel moisture

One forest floor fuel moisture plug was collected approximately two meters northeast of the plot center of each tree plot thirty minutes prior to the ignition of the experimental fire plot. Each plug was sectioned into 2-centimeter layers based on Lawson and Dalrymple's (1996) forest floor sampling methodology and collected for later drying in the lab. No forest floor samples were collected below 12 cm due to moisture saturation (standing water) of the duff layers below this depth. Additional fuel moisture samples were subjectively located in surface material types that were underrepresented during the initial sampling. Shrub moisture content was determined using the material collected from the biomass clip plots. Live foliar moisture content for the standing live trees was obtained by collecting samples of the last year's needles, *sensu* Norum and Miller (1984). Due to the lack of downed and dead woody material, no downed and dead woody fuel moisture samples or spruce litter moisture samples were collected. Woody fuel moisture inputs (1-hour, 10-hour, 100-hour) for fire behavior modeling were inferred from the moss, lichen, and duff moistures. All samples were oven dried for 24 hours at 100 °C.

Fire behavior observations

Fire type (surface, torching, crown fire), flame lengths (m) as measured from the ground to the flame tip, and fire rate of spread (m min^{-1}) were visually observed and recorded every minute using a helicopter as a mobile observation platform. Large black spruce trees located approximately 20 m apart were marked with red, white, and blue flagging to serve as rate of spread markers. When visible from the air, the time it took for the flaming front to spread the 20 m between marked trees was recorded. Additionally, the time for the flaming front to travel the total length of the area under study (approximately 80 m) was recorded. Flame lengths were visually estimated using a maximum tree height of 8 m for scale.

Data analysis and fire behavior modeling

Fire behavior prediction modeling systems require biomass estimates (fuel available to burn) either as direct fuel model inputs or to inform fuel model or fuel type selection (Anderson 1982; Forestry Canada Fire Danger Group 1992; Scott and Burgan 2005). Field-sampled vegetation for each fuel strata (canopy trees, shrub, and forest floor strata) were summarized as follows.

Trees and shrubs

Mean values for preburn stem density (trees per hectare), dbh, total height, ladder fuel height, height to live crown, and biomass were calculated for all standing trees. Foliage biomass (kg m^{-2}) for an individual tree was estimated using linear regression equations developed by Barney et al. (1978) and summed by plot to obtain canopy fuel loading (CFL). Mean CFL was averaged at the plot level. Canopy bulk density (CBD; kg m^{-3}) was obtained by dividing CFL by canopy length (*mean total tree height – mean height to live crown = canopy length*) for each plot and averaged across the experimental fire plots. Shrub biomass estimates (kg m^{-2}) were determined after drying all shrub samples for 48 hours at 100 °C and weighing. Cover class and frequency values were calculated for low shrubs and forest floor cover following Daubenmire (1959).

Forest floor: moss, litter, duff, and woody fuels

Forest floor biomass estimates in kg m^{-2} were calculated by multiplying forest floor depths and bulk density multiplication factors of 0.26 kg m^{-2} cm^{-1} for mosses, spruce litter, and reindeer lichen (*Cladonia rangiferina* [L.] Weber ex F.H. Wigg), 0.59 kg m^{-2} cm^{-1} for upper duff, and 9.25 kg m^{-2} cm^{-1} for lower duff (USDA Pacific Northwest Research Station, Seattle Forest Sciences Lab, Seattle, Washington, USA, unpublished 1996 Alaska photoseries study data). Woody fuel loading estimates (kg m^{-2}) were calculated following the procedure outlined in Brown (1974). Paired one-tailed *t*-tests (alpha = 0.05) were used to evaluate significance differences between all preburn and postburn measurements (Zar 1984), unless otherwise indicated.

Fire behavior

Observed head fire rates of spread, flame lengths, and calculated head fireline intensity values were compared with predicted values from the software associated with four fire behavior modeling systems commonly used in North America: BehavePlus 6, REDapp V6.2.3, CanFIRE V2.0, and the CFIS V4.0. Head fireline intensity values were calculated from my observations following Byram's (1959) fire intensity equation: $I = Hwr$, where I equals fire intensity (kW m^{-1}), H equals net low heat of combustion (18 000 kJ kg^{-1}), w equals weight of fuel consumed per unit area (kg m^{-2}) in the active fire front, and r equals rate of spread (m s^{-1}). Wind speeds were input into each modeling system as an estimate of the 10-meter winds based on the 2-meter observed winds (surface wind speeds measured 2 m or 10 m above the ground or average vegetation height). Wind speeds were adjusted upwards from 2-meter to 10-meter winds using the inverse of a 0.7 wind adjustment factor (WAF) following procedures described in Andrews (2012) and Lawson and Armitage (2008). When modeling with BehavePlus, a 0.4 WAF was used to reduce 10-meter wind speeds to mid-flame wind speeds (Andrews 2012). Fuel moisture inputs were direct field measures or were inferred based on my field-measured fuel moistures as is a common practice in Alaska when few woody fuels are present. Onsite FWI system fuel moisture codes for REDapp and CanFIRE were calculated using the 8 June 1300 ADT onsite weather and initiated with the 27 June 1997 FWI System fuel moisture codes from the Innoko Flats RAWS (Forestry Canada Fire Danger Group 1992).

Results

Weather

Observed 2-meter winds were generally out of the west with wind speeds fluctuating from 2 to 10 km h^{-1} in the afternoon prior to ignition (Table 1, Fig. 3). During the period of fire spread from 1744 to 1752 ADT, 2-meter winds averaged 7.2 km h^{-1} (4.6 mi h^{-1}; Fig. 3) and 11.8 km h^{-1} when adjusted to 10-meter open height (0.7 WAF). Onsite air temperature averaged 20 °C during the burning period with a value of 19 °C at the time of ignition (Fig. 3). Relative humidity was approximately 31% when the fire was ignited and averaged 29% during the burn period (Fig. 3).

Table 1 Onsite weather observations on 28 June 1997, when Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA, was ignited. Onsite Canadian Forest Fire Danger Rating System Fire Weather Index values were calculated using the 27 June 1997 FWI from the Innoko Wildlife Refuge Remote Automated Weather Station and the onsite 1300 ADT weather observations for the onsite station. FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, FWI = Fire Weather Index (Stocks et al. 1989), FDFM = Fine Dead Fuel Moisture (input to Crown Fire Initiation and Spread model; Alexander and Cruz 2006)

	Magitchlie Creek Experimental Fire	Innoko Flats RAWS[a]
Location		
Coordinates	63.599, −158.55233	63.38733, −158.81667
Elevation (m)	~30	283
Topography	Bottomlands	On a peak
Weather observations		
Temperature (°C)	19	25
Rh (%)	31	35
Wind speed (km h^{-1})	2 m = 7.2	6.1 m = 8.0
Time (ADT)	1744	1800
Date	28 June 1997	28 June 1997
Last precipitation		8 days since rain
FFMC	90.8	90.1
DMC	71.0	70.9
DC	301.0	302.6
ISI	6.9	6.0
BUI	89.0	89.4
FWI	23.0	21.0
FDFM (%)		9

[a] Innoko Flats RAWS located ~26.7 km at 190 degrees from fire site

Biomass inventory

Trees and shrubs

Black spruce dominated the study area (100% of total stems ≥1.37 m tall; Table 2). Mean tree height averaged 5.1 m with mean live crown height of 1.6 m and a mean CBD of 0.257 kg m^{-3} (Table 2). Dead branches on most trees reached all the way to the ground (ladder fuel heights averaged 0.1 m). The experimental fire killed all trees but only reduced total standing-tree density from 2320 to 2238 stems ha^{-1} since most trees remained standing as much as 1 yr post fire. The nearly complete consumption of foliar biomass significantly reduced total standing-tree biomass from 2.6 to 1.7 kg m^{-2} (Table 2). No seedlings were found on this site.

Low shrubs

Low shrubs formed a fairly continuous understory layer throughout the study area. All shrub species found are listed in the supplemental material (Additional files 3 and 4). Labrador tea (*Ledum palustre* [Jacq.] Michx.) and lingonberry (*Vaccinium vitis-idaea* L.) were the major shrub constituents within the study area as both were observed on all shrub plots with total cover values of 33% and 11%, respectively. All low shrubs were completely consumed by the fire on all of the 0.25 m^2 plots.

Forest floor

Forest floor surface material was characterized by a dense carpet of lichens (*Cladonia* P.Browne spp.), feather moss (*Hylocomium splendens* [Hedw.] Schimp), and sphagnum mosses (Additional file 5). Litter derived from dead tree needles was only a small proportion of the total forest floor biomass (Additional file 5). Downed and dead woody fuel loadings were also low (Additional file 5). Duff layers were primarily composed of dead and decaying sphagnum moss, which composed most of the aboveground biomass (Additional file 5).

Fuel moisture

Fuel moisture values are summarized in Table 3. The surface mosses and lichens were quite dry, ranging from 9 to 15%. Duff moisture content was moderately high (70 to 140%), with some areas overlain by sphagnum moss completely saturated at >500% fuel moisture by weight. Woody fuel moisture inputs to the fire behavior modeling systems of 9% (1-hour fuels), 15% (10-hour fuels), and 20% (100-hour fuels) were estimated from the surface moss, lichen, and duff fuel moisture contents. Needle moisture content was 102%.

Fire behavior observations

Wind speed and air temperature were relatively low when the experimental fire area was ignited, yet the fire rapidly reached the crowns, advancing by continuous crowning with 15 m (50 ft) flame lengths within 30 seconds of ignition (Fig. 2). During the most intense burning phase of the 80 m run under study, the fire moved 20 m in 30 s (40 m min^{-1}) with 15 to 30 m flame lengths (Additional file 6). Eight minutes after ignition, the flaming stage of the fire was complete. The overall rate of spread for the 80 m experimental plot was 8.8 m min^{-1}, with mean flame lengths of approximately 15 m. I was unable to provide an average rate of spread as fire movement for two of the four 20 m segments was obscured

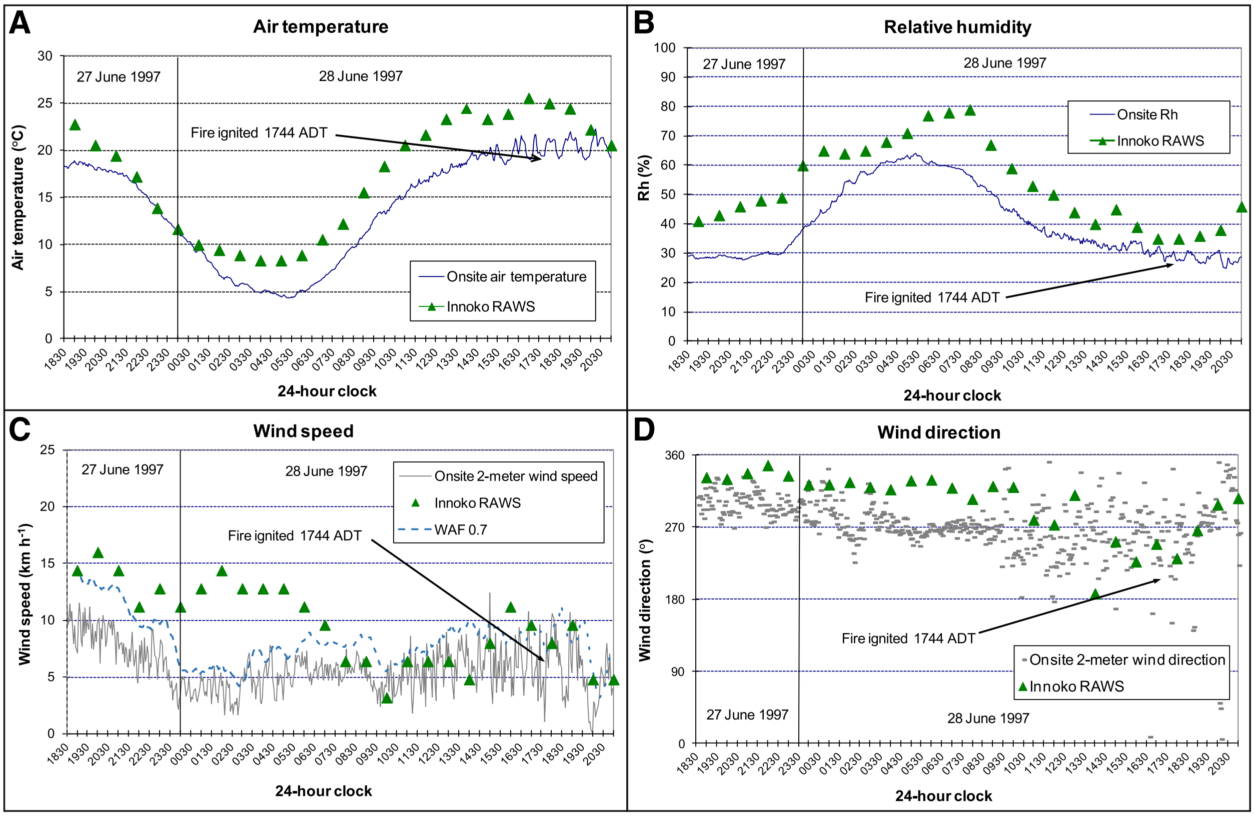

Fig. 3 Weather observations during the 1997 Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA. (**A**) Onsite air temperature, (**B**) relative humidity, (**C**) wind speed, and (**D**) wind direction observations were collected every three minutes at 2 m high using a portable Campbell Scientific weather station. Hourly observations for air temperature, relative humidity, wind speed, and wind direction from the closest Remote Automatic Weather Station (RAWS) were collected from the Innoko Flats RAWS, located approximately 26.7 km from the fire site. Winds were adjusted to 10-meter to serve as input to fire behavior models. WAF = Weather Adjustment Factor

Table 2 Mean density, basal diameter, height, and biomass values (± SE) for all standing woody stems ≥1.37 m tall on six 20 m^2 plots located within the boundaries of the June 1997 Magitchlie Creek Experimental Fire study area, Innoko National Wildlife Refuge, Alaska, USA. Dashes (--) indicate that data was not collected

	Preburn	Consumed	Postburn
Density (trees ha^{-1})	2320 ± 650	--	2238 ± 650
Basal diameter (cm)	7.9 ± 0.8	--	--
Tree height (m)	5.1 ± 0.5	--	--
Live crown height (m)	1.6 ± 0.2	--	--
Ladder fuel height (m)	0.1 ± 0.06	--	--
Foliar biomass (kg m^{-2})	0.9 ± 0.4	0.9 ± 0.4	0.0 ± 0.0
Canopy bulk density (kg m^{-3})	0.257	0.257	0.0
Total tree biomass (kg m^{-2})	2.6 ± 1.2	0.9 ± 0.4	1.7 ± 0.8

by smoke. The fire burned mostly as a shrub-type fire, with tree canopy foliage, shrub, and surface material burning simultaneously.

Fire behavior modeling

Comparisons of observed fire behavior characteristics against fire behavior predictions from BehavePlus, REDapp, CanFIRE, and CFIS are summarized in Table 4. REDapp and CanFIRE slightly overestimated observed

Table 3 Oven-dried preburn fuel moisture values (%) collected on 28 June 1997 at the Magitchlie Creek Experimental Fire study area, Innoko National Wildlife Refuge, Alaska, USA. Duff includes both upper and lower duff. Woody fuel moistures were not collected due to lack of woody fuel onsite

Fuel type	Preburn fuel moisture (%)
Tree foliage (needles)	102
Shrubs	87
Lichens	9
Feather moss	15
Duff	70 to 140

Table 4 Fire behavior model runs versus observed results at the 1997 Magitchlie Creek Experimental Fire study area, Innoko National Wildlife Refuge, Alaska, USA. Two-meter winds were adjusted to 11.8 km h^{-1} at 10 m above ground using the inverse of the 0.7 WAF. N/A refers to data that is not produced by the fire behavior modeling system tested

	Observed	BehavePlus6 (TU4)	BehavePlus6 (SH5)	REDapp	CanFIRE	CFIS[a]
Rate of spread (m min^{-1})	8.8	1.1	6.6	10.6	10.6	13.6
Head fire intensity (kW m^{-1})	9489	196	1740	11 953	10 530	N/A
Flame length (m)	10 to 30	0.9	4.5	N/A	N/A	N/A
Surface fuel consumption (kg m^{-2})	2.6	N/A	N/A	3.2	10.4	N/A
Crown fuel consumption (kg m^{-2})	0.9	N/A	N/A	0.7	0.7	N/A
Total fuel consumption (kg m^{-2})	3.5	N/A	N/A	3.9	11.1	N/A
Crown fraction burned (%)	100	0	28	89	N/A	N/A
Fire type	Active crown	Surface	Torching	Active crown	Active crown	Active crown

[a] CFIS does predict the probability of crown fire initiation, which was 100% for this study

rates of spread and head fire intensities (Table 4) using the C-2 (boreal spruce) fuel type (De Groot 1993; Taylor and Alexander 2018) and the CanFIRE black spruce forest type (Viereck 1973), respectively. BehavePlus produced the lowest predicted rates of spread among the four fire behavior modeling systems when vegetation was input using the standard dwarf conifer black spruce fire behavior fuel model TU4 (Scott and Burgan 2005). Modeling fire behavior with TU4 dramatically underestimated rate of spread, flame length, and fireline intensity (Table 4). When the shrub fire behavior fuel model SH5 (Scott and Burgan 2005) was applied in BehavePlus, agreement among modeled and observed rates of spread were improved, but rate of spread, head fire intensity, and flame length were still underestimated (Table 4). The poorest agreement with the observed rate of spread was provide by CFIS, which overestimated rate of spread across the experimental fire area by a factor of 1.5 (Table 4). CFIS does not predict flame length nor head fire intensity.

Discussion

Direct comparisons of my fire behavior observations with those recorded by Norum (1982) near Hughes, Alaska, in the summer of 1977, suggest that fire behavior during the Magitchlie Creek Fire was on the high end of the normal range of fire behavior for Alaskan black spruce ecosystems. My observed rate of spread of 8.8 m min^{-1} (26.2 chains hr^{-1}) fell within the upper range of 31 rate-of-spread observations reported by Norum (1982). Of Norum's (1982) 31 rate-of-spread observations, 11 were above 7 m min^{-1} and three were slightly greater than my observed 8.8 m min^{-1} (9.0, 9.4, 10.1 m min^{-1}, respectively). Interestingly Norum's (1982) flame length observations of 1 to 2 m were roughly a factor of 10 lower than those observed at Magitchlie Creek. Norum (1982) reported mid-flame wind speeds for the faster rates of spread ranging from 11 to 16 km h^{-1}. Assuming Norum's mid-flame wind speed observations were taken at eye level (2 m high), my field-measured wind speeds at Magitchlie Creek were lower than those observed by Norum (1982) by a factor of 2. Norum (1982) reported fuel moistures similar to those at Magitchlie Creek.

The short, intense period of fire behavior when rates of spread of 40 m min^{-1} and flame lengths up to 30 m were observed at Magitchlie Creek was also consistent with a study conducted by Butler et al. (2013). Butler et al. (2013) recorded a rate of spread of 40 m min^{-1} and flame lengths of 8 to 45 m for a short time span in a black spruce stand near Nenana, Alaska. All evidence suggests that the fire behavior observed at Magitchlie Creek was well within the range of possibilities for fire behavior in Alaskan black spruce.

In general, REDapp and CanFIRE outperformed both BehavePlus and CFIS when direct observations during the Magitchlie Creek Experimental Fire were compared with modeled fire behavior predictions. All of the Canadian systems over-predicted rates of spread, but the predicted values from REDapp and CanFIRE were closer than those from CFIS (1.8 m min^{-1} over versus 4.8 m min^{-1} over). In addition, REDapp and CanFIRE produced reasonable, albeit higher, predictions of head fire intensity. While results from a single case study should be viewed with caution, these results suggest that the Canadian FBP system could be used with confidence when predicting fire behavior in interior Alaska.

The 2018 Fuel Model Guide to Alaska (Saperstein et al. 2018) suggests using TU4 in open black spruce forests for most cases when modeling fire behavior with BehavePlus, but recommends using SH5 when conditions are dry, such as during the Magitchlie Creek Fire. Although this is only one case study, my results support using the SH5 fire behavior fuel model to predict fire behavior with BehavePlus during dry conditions with Rh values in the low 30s (Saperstein et al. 2018). BehavePlus under-predicted fire behavior using either the TU4 or the SH5 fuel model under the observed conditions, but the modeled rate of spread was much closer when SH5 was applied. More supporting evidence for using SH5 in this case come from my observations of the simultaneous burning of all fuel strata (surface, shrubs, overstory), even at the low wind speeds observed during the experimental fire. The simultaneous burning of all fuel strata suggest that black spruce forests burn more like shrub systems than the forest types commonly found in the contiguous United States. While a good start, this study provides information to suggest more studies that compare fire behavior observations with modeled fire behavior are needed to determine which fuel model should be used when modeling with BehavePlus in Alaskan black spruce ecosystems.

One approach for future evaluations is to follow Norum's (1982) lead and use multiple fuel models to predict the suite of fire behavior characteristics needed. For example, Norum (1982) recommended using the timber fuel model 9 (Anderson 1982) for predicting rates of spread and the shrub fuel model 5 (Anderson 1982) for predicting flame length (Norum 1982). Devising alternative ways of using existing operational fire behavior modeling systems to more effectively and accurately represent fire behavior in real world situations was beyond the scope of this study due to the lack of replication. However, this study could potentially serve as a template for obtaining the needed observational data for a more detailed, data-driven evaluation for how to more precisely apply fire behavior and fuel models in Alaska.

Conclusions

Although one should use the results of a single experimental fire case study with caution, this study provides information supporting the use of Canadian fire behavior modeling systems in Alaskan black spruce ecosystems over the use of US fire behavior modeling systems. The slight over-prediction of rate of spread and head fire intensity produced by REDapp and CanFIRE suggests that these systems provide a conservative approach that avoid under-prediction of potential fire movement across the landscape. With the same data, BehavePlus under-predicted fire movement. When modeling fire behavior, it is preferable to over-predict rather than under-predict as fire behavior modeling is primarily conducted to assess the potential hazard and risk of an area burning, with the goal of ensuring the safety of human life and property. In that context, a slight over-prediction of potential fire movement would be preferable to under-predicting how rapidly a fire might move across the landscape and the subsequent hazard and risk of fire to communities and resources in the fire's path.

In closing, deciding which fire behavior modeling system to use in Alaskan black spruce ecosystems is a difficult decision that requires a series of real world observations to compare with model predictions. Comparing model predictions with observed fire behavior characteristics allows end users to select a modeling system based on the model's ability to produce predictions that most closely represent reality. For example, a specific modeling system 1 might be chosen over modeling system 2 because the modeled rate of spread from system 1 was consistently closest to a documented set of rate-of-spread observations. To effectively evaluate fire behavior fuel modeling systems currently in operation, or to evaluate new fire behavior modeling systems when they are released, more fire behavior case studies for which direct observations of fire behavior are coupled with onsite sampled weather data and field-sampled tree demographic data are needed. Hand in hand with model development comes evaluation (Alexander and Cruz 2006), which should be an ongoing activity (Cruz et al. 2018). Future data sets that look to couple fire behavior observations with field observations should collect atmosphere, landscape, and vegetation data that serve as input to fire behavior modeling systems. The current study could provide a template for how fire managers could collect and assemble fire behavior observations needed to choose the most appropriate fire behavior modeling system for their use.

Additional files

Additional file 1: Plot layout for biomass (fuels available to burn) plots on the 1997 Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA. (PDF 949 kb)

Additional file 2: Magitchlie Creek Fire, Innoko National Wildlife Refuge, Alaska, USA, on 26 June 1997. Fire was concentrated in slightly raised black spruce islands within a matrix of low-lying sphagnum moss. Note the lack of consumption of the sphagnum moss "sea," which is normally covered by standing water. Photo credit: S. Drury. (PDF 119 kb)

Additional file 3: Cover, frequency, and importance values for low shrubs and forest floor materials on 12 0.25 m^2 plots within the Magitchlie Creek Experimental Fire study area, Innoko National Wildlife Refuge, Alaska, USA. Importance value is the sum of cover and frequency values divided by two. (PDF 168 kb)

Additional file 4: Low shrub layer on the Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA, on 27 June 1997. Photo credit: S. Drury. (PDF 929 kb)

Additional file 5: Preburn biomass, preburn fuel moistures, biomass consumed, and postburn biomass estimates (± SE) for the 28 June 1997 Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA. Standing trees are all stems taller than 1.37 m. Seedlings are all stems less than 1.37 m tall. Duff includes both upper and lower duff. Woody fuels added to the forest floor by the fire are quantified in the postburn standing-stem estimate. Total biomass estimates may not equal sum of individual biomass estimates due to rounding. (PDF 143 kb)

Additional file 6: Most intense portion of the 28 June 1997 Magitchlie Creek Experimental Fire, Innoko National Wildlife Refuge, Alaska, USA, when rates of spread approached 40 m min^{-1} and flame lengths ranges from 15 to 30 m. Photo credit: S. Drury. (PDF 663 kb)

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Author's contributions

SD conceived of the project, collected the field data, analyzed the data, and wrote the manuscript.

Author's information

Stacy Drury is currently a research fire ecologist with the USDA Forest Service Pacific Southwest Research Station. Data used in this paper was collected while he was an employee of the USDA Pacific Northwest Research station on a detail to the Alaska Fire Service in 1997.

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Availability of data and materials

The datasets used or analyzed during the current study are available from the author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declares that he has no competing interests.

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References

Albini, F.A. 1976. *Estimating wildland fire behavior and effects. USDA Forest Service General Technical Report INT-30*. Ogden: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Alexander, M.E., and F.V. Cole. 1995. Predicting and interpreting fire intensities in Alaskan black spruce forests using the Canadian system of fire danger rating. In *Managing forests to meet people's needs: proceedings of 1994 Society of American Foresters/Canadian Institute of Forestry convention, September 18–22, 1994. Publication 95-02*, 185–192. Bethesda: Society of American Foresters.

Alexander, M.E., and M.G. Cruz. 2006. Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Canadian Journal of Forest Research* 36: 3015–3028 https://doi.org/10.1139/x06-174.

Alexander, M.E., M.G. Cruz, and A.M.G. Lopes. 2006. CFIS: a software tool for simulating crown fire initiation and spread. *Forest Ecology and Management* 234 (Supplement): S133 https://doi.org/10.1016/j.foreco.2006.08.174.

Anderson, H.E. 1982. *Aids to determining fuel models for estimating fire behavior. USDA Forest Service General Technical Report INT-122*. Ogden: USDA Forest Service, Intermountain Forest and Range Experiment Station https://doi.org/10.2737/INT-GTR-122.

Andrews, P.L. 2012. Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model. USDA Forest Service General Technical Report RMRS-GTR-266. Fort Collins: USDA Forest Service, Rocky Mountain Research Station https://doi.org/10.2737/RMRS-GTR-266.

Andrews, P.L., C.D. Bevins, and R.C. Seli. 2008. BehavePlus fire modeling system, version 4.0: user's guide. USDA Forest Service General Technical Report RMRS-GTR-106WWW. Fort Collins: USDA Forest Service, Rocky Mountain Research Station https://doi.org/10.2737/RMRS-GTR-106.

Barney, R.J., K. Van Cleve, and R. Schlentner. 1978. Biomass distribution and crown characteristics of two Alaskan *Picea mariana* ecosystems. *Canadian Journal of Forest Research* 8: 36–41 https://doi.org/10.1139/x78-007.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service General Technical Report INT-16. Ogden: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Butler, B.W., R.D. Ottmar, T.S. Rupp, R.R. Jandt, E.A. Miller, K. Howard, R. Schmoll, S. Theisen, R.E. Vihnanek, and D. Jimenez. 2013. Quantifying the effect of fuel reduction treatments on fire behavior in boreal forests. *Canadian Journal of Forest Research* 43: 97–102 https://doi.org/10.1139/cjfr-2012-0234.

Byram, G.M. 1959. Combustion of forest fuels. In *Forest fire control and use*, ed. K. P. Davis, 6–89. New York: McGraw-Hill Book Company.

Cruz, M.G., M.E. Alexander, A.L. Sullivan, J.S. Gould, and M. Kilinc. 2018. Assessing model improvements in predicting wildland fire rates of spread. *Environmental Modelling & Software* 105: 54–63 https://doi.org/10.1016/j.envsoft.2018.03.027.

Daubenmire, R. 1959. A canopy-coverage method of vegetation analysis. *Northwest Science* 33 (1): 43–63.

De Groot, W.J. 1993. Examples of fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System, Forestry Canada. Poster (with text). Edmonton: Northern Forestry Centre http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/11038.pdf. Accessed 12 Apr 2018.

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

Gallant, A.L., E.M. Binnian, J.M. Omernik, and M.B. Shasby. 1995. Ecoregions of Alaska. US Geological Survey Professional Paper 1567. Denver: USDI, US Geological Survey https://doi.org/10.3133/pp1567.

ISFFAOG [Interagency Standards for Fire and Fire Aviation Operations Group]. 2018. Interagency standards for fire and fire aviation operations. (Redbook). Boise: National Interagency Fire Center https://www.nifc.gov/PUBLICATIONS/redbook/2018/RedBookAll.pdf.

Lawson, B.D., and O.B. Armitage. 2008. Weather guide for the Canadian Forest Fire Danger Rating System. Edmonton: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre.

Lawson, B.D., and G.N. Dalrymple. 1996. Ground-truthing the Drought Code: field verification of overwinter recharge of forest floor moisture. FDRA Report 268. Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II. Victoria: Canadian Forest Service, Pacific Forestry Centre and British Columbia Ministry of Forests, Research Branch.

Little J., R. Jandt, S.A. Drury, A. Molina, and L. Brock. 2018. Final report to the Joint Fire Science Program Project #14-5-01-27: evaluating the effectiveness of fuel treatments in Alaska. https://www.firescience.gov/projects/14-5-01-27/project/14-5-01-27_final_report.pdf. Accessed 9 Aug 2019.

McAlpine, R.S., and P.L. Andrews. 1998. Cooperative wildland fire research: Canada and the US. In *Fire management under fire—proceedings of the 1994 Interior West Fire Council meeting and symposium, 1–4 November, 1994, Coeur d'Alene, Idaho*, ed. K. Close and R.A. Bartlett, 247–251. Fairfield: International Association of Wildland Fire.

McLoughlin, N.R. 2016. *REDapp—the universal fire behavior calculator. Version 1.0 user guide*. Edmonton: Government of Alberta.

Noonan-Wright, E.K., T.S. Opperman, M.A. Finney, G.T. Zimmerman, R.C. Seli, L.M. Elenz, D.E. Calkin, and J.R. Fieldler. 2011. Developing the US Wildland Fire Decision Support System. *Journal of Combustion* 2011: Article 168473 https://doi.org/10.1155/2011/168473.

Norum, R.A. 1982. Predicting wildlife behavior in black spruce in Alaska. USDA Forest Service Research Note PNW-401. Portland: USDA Forest Service, Pacific Northwest Forest and Range Experimental Station https://doi.org/10.2737/PNW-RN-401.

Norum, R.A., and M. Miller. 1984. Measuring fuel moisture content in Alaska: standard methods and procedures. USDA Forest Service General Technical Report PNW-171. Portland: USDA Forest Service, Pacific Northwest Forest and Range Experimental Station https://doi.org/10.2737/PNW-GTR-171.

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 Fire Equipment System Publication NFES 2581. Boise: National Interagency Fire Center.

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

Rothermel, R.C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. USDA Research Paper INT-438. Ogden: USDA Forest Service, Intermountain Research Station https://doi.org/10.2737/INT-RP-438.

Saperstein, L., J. Barnes, P. Butteri, R. DeVelice, K. Howard, J. Hrobak, R. Loehman, N. Lojewski, C. Martin, E. Miller, B. Rowe, T. St. Clair, B. Schultz, B. Sorbel, W.

Wahrenbrock, L. Weddle, A. York, and R. Ziel. 2018. Fuel model guide to Alaska vegetation. Alaska Wildland Fire Coordinating Group. https://fire.ak.blm.gov/content/admin/awfcg_committees/Fire%20Research%20Development%20and%20Application/e.%20AK%20Revised%20Fuel%20Model%20Guide%20May%202018.pdf. Accessed 13 May 2019.

Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service General Technical Report RMRS-GTR-153. Fort Collins: Rocky Mountain Research Station https://doi.org/10.2737/RMRS-GTR-153.

Stocks, B.J., B.D. Lawson, M.E. Alexander, C.E. Van Wagner, R.S. McAlpine, T.J. Lynham, and D.E. Dube. 1989. The Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle* 65: 450–457 https://doi.org/10.5558/tfc65450-6.

Taylor, S.W., and M.E. Alexander. 2018. Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Third edition. Special Report 11. Edmonton: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre.

Van Wagner, C.E. 1973. Rough prediction of fire spread rates by fuel type. Environment Canada, Canadian Forestry Service, Information Report PS-X-42. Chalk River: Petawawa Forest Experiment Station http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/23606.pdf.

Van Wagner, C.E. 1983. Fire behaviour in northern conifer forests and shrublands. In *The role of fire in northern circumpolar ecosystems. SCOPE 18*, ed. R.W. Wein and D.A. MacLean, 65–80. Chichester: Wiley.

Van Wagner, C.E. 1985. Fire behavior modelling—how to blend art and science. In *Proceedings of the eighth conference on fire and forest meteorology. SAF Publication 85-04*, ed. L.R. Donoghue and R.E. Martin, 3–5. Bethesda: Society of American Foresters.

Van Wagner, C.E. 1987. *Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service Forestry Technology Report 35*. Ottawa: Government of Canada.

Viereck, L.A. 1973. Wildfire in the taiga of Alaska. *Quaternary Research* 3: 465–495 https://doi.org/10.1016/0033-5894(73)90009-4.

Viereck, L.A. 1983. The effects of fire in black spruce ecosystems of Alaska and northern Canada. In *The role of fire in northern circumpolar ecosystems*, ed. R. W. Wein and D.A. MacLean, 201–220. New York: Wiley.

Wotton, B.M., M.E. Alexander, and S.W. Taylor. 2009. Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System. Information Report GLC-X-10. Sault Ste. Marie: Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/31414.pdf.

Zar, J.H. 1984. *Biostatistical analysis*. 2nd ed. Englewood Cliffs: Prentice Hall.

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