Empirical reanalysis of crown fire initiation:
Working Paper

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Abstract
Crown fires are a dangerous, albeit natural phenomenon in conifer forests, and represent a major concern for fire management personnel and public safety. Operational prediction of crown fire behaviour in Canada has largely depended on the Canadian Fire Behaviour Prediction (FBP) System, in which crown fire involvement is estimated for discrete fuel types using simple physical principles and generalized indices of fuel moisture content (mc) based on the Fire Weather Index (FWI) System. The Crown Fire Initiation and Spread (CFIS) system presented an alternative suite of crown fire models based on empirical analysis of part of the FBP System dataset. Using an expanded database of 20th century observations from conifer experiments across Canada (1960–2000; N=108), we expanded on the CFIS approach, fitting crown fire initiation models based on fire environment predictors to complement existing decision support tools. We tested a stand-adjusted model of mc based on stand condition variables in addition to FWI components, and estimated crown fuel structure using detailed reconstructions of Fuel Strata Gap (FSG). We also tested a novel approach for estimating heat flux contributions from ladder fuels and mid-story crown cohorts using simple physical principles, adopting a modified definition of crown fire that includes a general fire transition from a lower fuel stratum to a higher one. Other predictor variables included surface fuel consumption (measured in experimental burns; estimated for prediction purposes); and 10-m wind speed. Logistic regression modelling with Monte Carlo cross-validation was used to select the final model forms, and the resulting models were tested on an independent validation dataset from some recent experimental fires as well as crowning of upper canopy cohorts from select training fires (n=31). Final models were highly significant ($\alpha = 0.01$ for all predictors) and correctly predicted 91–94% of crowning events correctly in the training data and up to 87% from the test data. Based on these results, the new models provide a small accuracy improvement over previously published crown fire prediction models, but a significantly more flexible formulation for characterizing various interactions between fuel structure and moisture elements. This will help managers understand the influence of various fire environment factors, particularly for regions where detailed fuels data exists or when planning hazard reduction treatments to reduce the probability of future crown fires.

Introduction

High intensity crown fires in conifer forests continue to endanger communities in Canada and worldwide, despite being recognized as natural ecological phenomena (Coogan et al. 2020, Tymstra et al. 2020). At the scale of an individual forest stand, a primary management question of concern is 'does this stand support crown fire behaviour?' Crown fire behaviour in conifer stands has often been observed to result in a 2 to 10-fold increase in rate of spread (ROS) compared with surface fires under comparable conditions immediately prior to crowning (Alexander and Cruz 2016, Cruz and Alexander 2017). Since most conifer forests will support crown fire under extreme fire weather conditions (Beverly et al. 2020), the more precise challenge involves identifying threshold fire environment conditions for crown fire initiation and overall crown fire activity.

Canadian Empirical and Semi-Empirical Crown Fire Models

Since its draft release in the 1980's, Canadian managers and operational researchers have primarily used the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992, FCFDG 1992 hereafter) to forecast fire behaviour (e.g. Pelletier et al. 2009, Perrakis et al. 2018, Stockdale et al. 2019). The FBP System is a sub-system of the larger Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al. 1989), used broadly for operational fire management decision support across the country (Taylor and Alexander 2006). The present-day system is currently being renewed to address various limitations and enable more detailed fire environment inputs; a new complete system is expected to be released within a few years (CFS Fire Danger Group 2021). The current FBP System uses discrete fuel types representing common fire-prone vegetation types across Canada. Conifer fuel types each have empirical functions representing rate of spread (ROS) and surface fuel consumption (SFC) that allow users to predict these outputs using components of the Fire Weather Index (FWI; Van Wagner 1987) as inputs (FCFDG 1992). Empirical ROS and SFC functions are credible but inflexible by nature; deviations from standard fuel conditions defined by the fixed fuel types cannot easily be handled, with some exceptions. The Van Wagner (1977) crown fire initiation model underpins the system and is used to predict surface or crown fire behaviour, based on a combination of physical theory and empirical evidence from the field and laboratory (Van Wagner 1968). Crown fire behaviour is predicted when the surface fire intensity (I) surpasses a critical threshold (I_0) according to the following well-known equation (Van Wagner 1977):

$$I_0 = [0.01z(460 + 25.9m)]^{1.5} \qquad [1],$$

where z is the live canopy base height (LCBH, m) and m is the live conifer foliar moisture content (FMC, % of dry mass). The I_0 value is converted to a critical ROS using Byram's (1959) fireline intensity equation and fuel consumption is estimated for this purpose with the fuel type-specific SFC functions. At its simplest, predicting conifer crown fire involvement with the FBP System therefore involves using Equation 1 as well as the relevant empirically-based ROS and SFC functions.

Within this scheme, LCBH is the critical forest structure variable influencing crown fire initiation. In the FBP System, LCBH values are constants assigned to the conifer and mixedwood fuel types, from 2 m to 18 m, although assigned LCBH values do not consistently represent measured values in experimental stands. Rather, LCBH values were adjusted somewhat to match observed fire behaviour and model outputs while still reflecting actual forest structure "as well as possible" (FCFDG 1992), and vary within a few metres in some cases from actual measured LCBH values. Assigned LCBH values in the FBP System are therefore not intended to be modified by users nor can they be readily verified in the field (Wotton et al. 2009). Additional confusion regarding LCBH values stem from various interpretations of the appropriate spatial scale, including the role of ladder fuels (Keane 2015). Outside the FBP System, users have long used Equation 1 to identify variations in I_0

under varying levels of LCBH (e.g. Alexander 1988, Hirsch and Pengelly 1999, Agee et al. 2000, Scott and Reinhardt 2001). However, this method requires a separate estimate of surface ROS to generate *I* estimates using Byram's equation. Alternative methods for estimating LCBH have contributed to significant problems with underprediction bias (Cruz and Alexander 2010).

Seeking empirical solutions: CFIS

A previous effort to reanalyze the Canadian fire database with a focus on crown fires resulted in CFIS: a system of empirical models for characterizing crown fire probability based on a small number of fire environment predictors (Alexander et al. 2006). The CFIS studies offered an alternative to Van Wagner's simple physically conceived model (Equation 1) with statistical models using various common inputs based on 63-71 fire observations from the FBP experiments. Separate models require inputs from FWI system components and LCBH (Cruz et al. 2003b) or a blend of alternative fire environment inputs and estimates (Cruz et al. 2004), while a related empirical analysis predicts crown fire type and spread rate from 37 crown fire observations (Cruz et al. 2005, Alexander and Cruz 2006). The authors also introduced the term 'fuel strata gap' (FSG) as an alternative to LCBH, representing a more generic notion of vertical separation between discrete fuel layers; we presently use that term hereafter for representing vertical separation between conifer fuel strata. While the existing CFIS models provide highly usable tools for certain applications and an empirically based alternative to the Van Wagner CFI model, they were never fully integrated with other CFFDRS components such as surface fire behaviour models or fuel moisture research. Nevertheless, the CFIS studies provide an excellent starting point for additional refinements, particularly with the addition of new data and additional tools published since their development. We used the CFIS approach and data as a starting point for the present reanalysis.

Objective: reanalysis of experimental surface and crown fire data

The objective of this study was to produce a set of empirical models of crown fire initiation suitable for situations when fairly detailed fuel structure and fire environment inputs are available. We expanded on the FBP and CFIS datasets with additional experimental observations to create a database of > 100 observations for fitting operationally usable models sensitive to a range of fire environment variables. The overall goal was to harness the findings from over four decades of systematic experimental burning in Canada to inform an empirical crown fire initiation modelling system, continuing the approach of data-driven modelling informed by simple physical principles. We also aimed to clarify the data flow from field surveys through to quantitative or categorical crown fuel characteristics, an often-skipped step (e.g. Affleck et al. 2012). To address the challenge of ladder fuel influence, we propose a novel but simple solution based on a reworking of Van Wagner's (1977) crown fire equation to solve for critical fuel consumption. Compared to the FBP System and CFIS models (Cruz et al. 2003b, Cruz et al. 2004), the present analysis involved a larger dataset of observations; tested a stand- and season-adjusted model of mc; and included explicit and continuous variables for wind speed, SFC and mc rather than FWI indices alone or coarse categorical variables.

The present document is presented as a working paper to indicate that it represents work in progress. This should not prevent operational use of the final models but suggests that model parameters will be revised as more data becomes available and additional research is used to refine the formulation.

Figure 1. Photographs of experimental burns across Canadian boreal and sub-boreal conifer forests, 1960s-2019. a: Vigorous surface fire near the crown fire threshold in red pine at the Petawawa National Forestry Institute, ON; b-c: Ignition in overstocked immature jack pine at Sharpsand Creek, ON, showing fuel structure and rapid crowning; d: Surface fire at Darwin Lake, AB; e: Active crown fire in boreal lowland black spruce at Bigfish Lake, AB; f: Mid-story black spruce under mature jack pine overstory at Kenshoe Lake, ON; g: Active crown fire at the International Crown Fire Modeling Experiment (ICFME) site, NWT; h: Active crown fire behaviour in thinned and unthinned black spruce, Pelican Mtn, Alberta; i: Surface fire in mature lodgepole pine at Summit Lake (near Prince George), BC; j: Simultaneous ignition of 'simulated pine beetle' treated stands (left) and untreated 'controls' (right) at Archer Lake, AB (Photos from CFS archives except 'j', courtesy of Dave Schroeder, Alberta Environment and Natural Resources).

Methods

Training data and study areas: 20th century experimental burn projects in Canada
Most of the main FBP System-era burn experiments have been documented in previous reports and analyses. Briefly, fire behaviour experiments in various conifer fuel types took place across Canada between 1960 and 1986, gradually coalescing from isolated studies into a national fire behaviour research program with common methods and goals (Alexander and Quintilio 1990, Van Wagner 1990, Taylor and Alexander 2006); Figure 1. Following completion of the formal FBP System (FCFDG 1992), the experimental burning program continued at a reduced pace until about 2000, with two notable projects: the later experiments on ignition and acceleration at Sharpsand Creek, Ontario (early 1990s; McRae et al. 2017), and the International Crown Fire Modelling Experiment, Northwest Territories (ICFME: late 1990s-2000; Stocks et al. 2004). The assortment of burn experiment sites was heavily weighted to boreal and sub-boreal regions (Ecological Stratification Working Group 1996), with most observations (58%) from 3 sites in the Boreal Shield of central and eastern Ontario. Another 18% of observations occurred in the Boreal Plains of northern Alberta, and another 17% of plots were in the central Northwest Territories, including about 10% and 6% in the Taiga Plains and Taiga Shield, respectively. The remaining 7% of observations were from one site in the Montane Cordillera of central British Columbia (Table 1).[1]

Most burns consisted of square or rectangular plots[2] in flat terrain subject to line ignition along an exposed windward edge under varying weather conditions (generally dry), in order to associate fire behaviour with a range of low to high ambient fire danger values. Fuel loading and structure, fire danger and weather conditions and resulting fire behaviour observations were assessed and monitored before and during fires to develop empirical models and relationships. Pre-burn sampling efforts varied somewhat between studies and are sparsely described in some cases, particularly the earliest work. By the mid-1970s, a 10% overstory plot cruise and well-replicated sub-sampling grids for surface fuel attributes had become established as standard (e.g. Walker and Stocks 1975, Alexander et al. 2004).

For the present analysis, we included the majority of standing conifer experimental burns between 1960 and 2000, with jack pine and black spruce forest types heavily represented (Table 1). For most experiments, assignments of crown fire or surface fire to each observation as well as fire weather and forest structure inputs were taken directly from primary sources. Where original studies or reports were absent, the source was the experimental burn data in the FBP database, previously summarily published by Cruz (1999). There is a small degree of pseudoreplication in the dataset due to certain inputs being double-counted. These are mostly due to weather shifts (particularly wind speed) in the middle of a burn plot, causing divergent fire behaviour on either side of the change, leading investigators to consider the two sides distinct (e.g. Quintilio et al. 1977, Stocks et al. 2004). A similar issue exists with respect to weather observations, when certain plots were ignited simultaneously or within a short time (< 1 hour) on a given day (e.g., the escaped burn at Porter Lake; Alexander et al. 1991). These issues affected only a small portion of the data (< 10 observations) but are noted for completeness. Along with the experimental data, three

[1] The 'C-7' fuel type experiments in Douglas-fir - ponderosa pine stands in southern interior BC, conducted by researchers from the University of British Columbia, were not included in this analysis due to significant fuel structure uncertainties and incomplete documentation.
[2] 'Plot' is used in the present study to denote individual burn units, with one plot representing a single independent observation. In primary sources these are characterized in various ways: plots, experimental units, burn blocks, stands, etc.

wildfire observations were also included in the main dataset: the Porter Lake CR-6-82 wildfire noted above as well as two observations from the Gwatkin Lake, ON wildfire (Van Wagner 1965). The latter report is a detailed fire behaviour reconstruction with high quality weather and fuels data in very familiar terrain to its author. The overall list of observations and mean characteristics are summarized in Table 1 A, with further details described in the text and Appendix A.

Test data: additional observations

Data from three additional and more recent burn experiments were combined to form an independent dataset for model testing purposes (Table 1 B#): (1) ten fires in 'control' stands burned as part of fire behaviour experiments in simulated mountain pine beetle-killed stands near Archer Lake, AB (Schroeder and Mooney 2012); (2) four plots burned in natural and thinned stands adjacent to the ICFME experiment site near Fort Providence, NWT (Schroeder 2010); and (3) two plots burned in thinned and unthinned black spruce stands near Pelican Mountain, Alberta (Thompson et al. 2020).

Some fire environment characteristics in the Archer Lake and Fort Providence experiments were not directly measured and required post-hoc estimation in order to create the inputs needed for testing CFI models. For Archer Lake, we obtained raw data to calculate FSG values at the level of forest stands, each stand containing one or more plots (D. Schroeder, personal communication Nov. 2021); however, no surface fuel consumption (SFC) data were available. In the Fort Providence experiments, neither FSG nor SFC were available for control plots, although FSG was reported for the 'thinned' treatment plots, and pre-burn structure in controls was described as similar to that of the ICFME experiments. We therefore used the mean FSG from the ICFME plots (black spruce cohorts: 2.71 m; Alexander et al. 2004) [3] as an estimate for the control plots. To estimate SFC at both sites (Archer Lake and Fort Providence), we used DeGroot et al.'s (2009) model of forest floor consumption based on surface fuel load and the buildup index (BUI). Mean surface fuel loading values were taken from Schroeder et al. (2012) for Archer Lake and from the mean of plot values at ICFME (Alexander et al. 2004) for the Fort Providence plots.

In the Pelican Mountain experiment, most of the needed inputs were documented and reported (Thompson et al. 2020), with the exception of FSG. Mean overstory FSG values were obtained from the authors for control and thinned plots (G. Marshall, personal communication April 2022: control: 2.08 m; thinned: 4.15 m). In addition to these independent observations, involvement of upper canopy pine cohorts was considered separately, discussed further below.

Finally, a few exceptions should be noted regarding ignition type. All independent plot ignitions were completed by lighting surface fires at the windward edge by hand (e.g. Figure 1b) or high-volume gel-torch (e.g. Stocks et al. 2004). In a small number of cases, ignition actually occurred from an adjacent plot with no separation or clearing; these include ignition by crown fire in the case of the Porter Lake wildfire escape noted above as well as the Fort Providence and Pelican Mountain experiments. In the case of the Gwatkin Lake wildfire, the downwind crown fire portion ignited via a high intensity surface fire (under mature jack pine) spreading into a different stand type (mix of jack pine and red pine; Van Wagner 1965). These discrepancies are again noted for completeness.

[3] Note: Alexander et al. (2004), Table 12 contains an unreported error in the black spruce overstory LCBH. The value for Plot 5 should be 0.7 m (not 10.0 m as shown); the mean for all plots (2.7 m) is shown correctly.

Table 1. Database of experimental observations and input data. See Appendix A for additional details of experimental burn projects. Columns represent input ranges as follows: N: S/C: number of surface fire / crown fire observations; ws: 10-m wind speed; FFMC, DMC: Fine Fuel Moisture Code and Duff Moisture Code from the Canadian Fire Weather Index System; FMC: foliar moisture content; SFC: surface fuel consumption; mcFFMC: estimated litter moisture content from the FFMC model; mcSA: estimated litter moisture content from the stand-adjusted model; mcSA Stand: forest stand type for the mcSA; mcSA Season Sp/Tr/Sum: Spring / Transition / Summer seasons for mc_{SA} model; mcSA Density Li/Mod/Den: Light/Moderate/Dense stand closure category for mc_{SA} model; FSG: fuel strata gap; SFC, scaled snag LF: scaled SFC-equivalent based on small diameter ladder fuel loading. Details described in text.

A.

Experimental Project: Training data [a]	**Years**	**N: SF/CF**	**ws km/h**	**FFMC**	**DMC**	**FMC %**	**SFC kg m^{-2}**	**Sources**
1. PNFI, ON (WRP)	1960 - 1964	8 / 0	10.9 (5.0-23.0)	90.8 (87.8-92.8)	59 (42-76)	113.7 (100.5-120.0)[b]	2.1 (0.9-3.1)	Van Wagner 1963, unpublished files
2. PNFI, ON (JP) †	1962 - 1965	5 / 2	12.6 (5.0-23.0)	90.6 (88.5-92.8)	56 (28-77)	107.3 (100.0-118.0)[b]	1.5 (0.4-2.7)	Van Wagner 1977, Hummel 1979, Weber et al. 1987
3. PNFI, ON (RP) †	1962 - 1967	5 / 4	14.9 (6.0-23.0)	91 (88.5-92.9)	50 (21-89)	97.8 (91.0-108.0)[b]	1.4 (1.0-1.9)	Van Wagner 1968, Van Wagner 1986
4. Prince George, BC (LP)	1970	8 / 0	8.2 (6.4-12.9)	91.6 (90.5-93.0)	61 (33-77)	102.8 (90.5-116.6)[c]	0.6 (0.2-1.2)	Lawson 1972
5. Bigfish Lk and others, AB (BS)	1972 - 1986	3 / 9	11.6 (5.0-18.7)	87.7 (80.0-91.2)	21 (9-44)	102.3 (79.0-120.0)[d]	1.5 (0.8-2.3)	Kiil 1975, Newstead and Alexander 1983, Cruz 1999, unpub. files
6. Kenshoe Lk, ON (JP/BS)	1973 - 1983	6 / 6	12.3 (3.0-29.0)	89.6 (87.2-91.4)	32 (19-42)	89.4 (85.0-106.1)[c]	0.9 (0.4-1.5)	Stocks 1989, Walker and Stocks 1975, unpublished files
7. Darwin Lake, AB (JP)	1974	5 / 2	10.3 (6.3-16.9)	91 (88.7-93.7)	30 (15-43)	116.3 (109.7-120.0)[c]	2 (1.0-3.2)	Quintilio et al. 1977, Alexander et al. 1991
8. Sharpsand TH, ON (JP)	1974 - 1981	3 / 3	11.8 (8.0-15.0)	91.3 (87.9-94.1)	41 (29-47)	109.3 (99.8-116.0)[c]	1.1 (0.8-1.5)	Cruz 1999, unpublished files
9. Sharpsand IM, ON (JP)	1975 - 1981	2 / 11	12.6 (6.0-21.0)	90.7 (89.4-93.3)	43 (25-57)	107.3 (85.7-117.8)[c]	1.4 (0.7-2.4)	Stocks 1987, Walker and Stocks 1975, unpublished files
10. Porter Lake, NWT (BS) ††	1982	0 / 7	23.5 (14.5-34.6)	91.5 (89.4-92.8)	59 (51-66)	86 (85.1-86.5)[c]	1.3 (1.1-1.6)	Alexander et al. 1991
11. Sharpsand SM, ON (JP)	1988 - 1991	3 / 5	12 (9.0-19.0)	90.8 (88.6-93.4)	48 (32-70)	86.8 (85.1-92.6)[c]	2.7 (1.4-4.0)[f]	McRae et al. 2017
12. ICFME, NWT (JP/BS)	1997 - 2000	0 / 11	14.2 (7.9-25.0)	91.8 (89.4-94.2)	54 (35-84)	82.2 (74.2-92.1)[e]	2.6 (1.5-3.8)	Alexander et al. 2004, Stocks et al. 2004
Overall: Training data	1960 - 2000	48 / 60	3.0 - 34.6	80.0 - 94.2	9 - 89	74.2 - 120.0	0.2 - 4.0	

B.

Test data								
1. Ft Providence FT, NWT (JP/BS)	2005 - 2007	2 / 2	12.5 (12.0-13.0)	92 (91.0-93.0)	97 (62-132)	83.9 (80.0-87.7)	3 (2.7-3.3)	Schroeder 2010
2. Archer Lk, AB (JP)	2008 - 2009	4 / 6	8.7 (5.0-12.0)	88.2 (85.6-92.0)	43.3 (36-65)	113.8 (106.2-116.0)	1.9 (1.8-2.5)	Schroeder and Mooney 2012
3. Pelican Mt, AB (BS)	2019	0 / 2	12.0	93.6	46	79	1.6 (1.5-1.7)	Thompson et al. 2020
Overall: Test data	2005 - 2019	6 / 10	5.0 - 13.0	85.6 - 93.6	36 - 132	80.0 - 116.0	1.5 - 3.3	

A (continued). Project: Training	mc_{FFMC}	mc_{SA}	mc_{SA} Stand:	mc_{SA} Season: Sp/Tr/Su	mc_{SA} Density: Li/Mo/De	FSG m	SFC_L from fine dead snags kg m^{-2} †††	Notes
1.	10.0 (7.9-13.2)	9.5 (6.9-11.7)	Pine	0 / 0 / 8	2 / 6 / 0	11.7 (7.4-13.3)[g]	-	
2.	10.2 (7.9-12.4)	9.3 (7.2-11.9)	Pine	1 / 2 / 4	1 / 6 / 0	8.4 (6.0-12.0)[h]	-	
3.	9.8 (7.8-12.4)	10.5 (7.4-17.2)	Pine	2 / 1 / 6	0 / 1 / 8	7.1 (6.0-8.0)[h]	-	
4.	9.1 (7.7-10.3)	8.2 (7.3-9.7)	Pine	0 / 0 / 8	4 / 4 / 0	8.2 (6.7-9.8)[h]	-	
5.	13.4 (9.6-22.2)	13.9 (10.9-19.8)	Spruce	0 / 0 / 12	9 / 3 / 0	1.1 (0.4-1.9)[i]	-	
6.	11.2 (9.4-13.8)	12.0 (10.9-14.1)	Pi/Sp	7 / 1 / 4	0 / 0 / 12	2.0[h,j]	-	Mid-storey conifer cohort present; upper crowning modelled separately
7.	9.8 (7.0-12.2)	10.3 (7.0-14.5)	Pine	0 / 0 / 7	4 / 3 / 0	5.6 (4.8-6.3)[i]	-	
8.	9.5 (6.6-13.1)	9.9 (7.3-12.9)	Pine	0 / 0 / 6	0 / 6 / 0	4.4 (4.3-4.8)[i]	0.1 (0-0.4)	Moderate density small diam. snags
9.	10.1 (7.4-11.5)	11.5 (7.9-15.0)	Pine	0 / 1 / 12	0 / 2 / 11	4.4 (4.1-4.9)[i]	0.6 (0.3-1.3)	High density small diam. snags
10.	9.3 (7.9-11.5)	8.0 (6.9-9.7)	Spruce	0 / 0 / 7	7 / 0 / 0	1.0 (0.8-1.1)[i]	-	
11.	10.0 (7.3-12.3)	9.0 (7.3-10.4)	Pine	2 / 5 / 1	0 / 8 / 0	5.3[h]	0.2 (0-0.4)	High dens. small diam. snags
12.	9.0 (6.5-11.5)	9.1 (6.3-11.9)	Pi/Sp	0 / 0 / 11	0 / 11 / 0	2.6 (0.7-8.2)[i,]	0.1 (0-0.4)	Mid-storey conifer cohort present; upper crowning modelled separately. Moderate density small diam. snags.
Overall: Train	6.5 - 22.2	6.3 - 19.8		12 / 10 / 86	27 / 50 / 31	0.4 - 13.3	0 - 1.3	
B (continued). Test								
1.	8.8 (7.7-9.8)	7.6 (6.1-9.4)	Pi/Sp	0 / 0 / 4	2 / 2 / 0	5.7 (1.5-9.8)[g-i]	0.05 (0.0-0.1)	Moderate density small diam. Snags (estimated).
2.	12.8 (8.7-15.6)	10.6 (7.4-12.5)	Pine	0 / 0 / 10	10 / 0 / 0	4.7 (3.9-5.1)[i]	-	
3.	7.1	6.6 (6.3-6.9)	Spruce	2 / 0 / 0	1 / 1 / 0	3.1 (2.1-4.2)[i]	-	
Overall: Test	7.1 - 15.6	6.1 - 12.5		2 / 0 14	11 / 3 / 0	1.5 - 9.8	0 - 0.1	

† Includes 1 observation from the Gwatkin Lake wildfire (Van Wagner 1965, Van Wagner 1977)
†† Includes 1 observation from the CR-6-82 wildfire (Alexander et al. 1991)
††† Estimated surface fuel consumption contribution from small diameter dead ladder fuels, for plots with high densities (> 250 ha^{-1}) of small diameter (< ~5 cm) standing snags
[a] Dominant overstory species as follows: WRP- white and red pine; JP- jack pine; RP- red pine; LP- lodgepole pine; BS- black spruce
[b] Foliar moisture content (FMC) interpreted from tables (Van Wagner 1967)
[c] FMC estimated from FBP System equation (FCFDG 1992)
[d] FMC from Kiil (1975, 1 observation), Newstead and Alexander (1983, 2 observations), and estimated from FBP System equation (FCFDG 1992; 9 obs.)
[e] Calculated from Stocks et al. (2004) based on stand composition and measured FMC
[f] Calculated from McRae et al. (2017) based on depth of burn and forest floor bulk density.
[g] Estimated using crown ratio models with site-level stand attribute inputs (DBH, basal area), averaged over several plots (highest uncertainty FSG)
[h] Estimated site value (multiple plots), as reported in primary literature (medium uncertainty FSG)
[i] Plot-level values reported in primary sources or calculated independently from raw data (least uncertain FSG)
[j] FSG values in table refer to mid-story conifer stratum (mid-story black spruce); crowning into upper stratum (jack pine) modelled separately; see text for details.

Fuel Strata Gap and LCBH
The previously-discussed approaches to crown fire initiation (Van Wagner 1977, Cruz et al. 2003b) presume a notionally simple conifer structure, with a meaningful gap between crown and surface fuels (FSG) and a relatively uniform live conifer canopy. Most published sources for the burns in our database reported measured or estimated values for FSG or LCBH. Definitions and sampling methods were not always explicitly defined in these studies, but LCBH was generally considered the average height of the live conifer crown base, as measured on individual trees in a small biomass tree sample (~10-30 trees). Height-diameter and height-LCBH relationships were then used to estimate stand-level LCBH at the plot level of whole site level (e.g. Walker and Stocks 1975, Alexander et al. 1991). At other sites, LCBH was sampled or estimated directly, in individual plots or groups of plots (e.g. Van Wagner 1968, Lawson 1972, Hummel 1979). A few studies reported only site averages across all plots (e.g. McRae et al. 2017); in other cases the source appeared to be from a third party (e.g. coarse categorical values from a forest cover map; Quintilio 1977). When previously published LCBH information appeared suspect or imprecise, we sought to produce new estimates of FSG based on available forest stand information and using various independent models and datasets; see Table 1 notes and Appendix A for details.

For the Kenshoe Lake and Sharpsand Creek (IM and TH) sites, raw stand survey data were available (Walker and Stocks 1975) and allowed for a more thorough effort to properly characterize the complex crown fuels at these sites. We used local tree biomass data to calibrate an Ontario-based mixed-effects model (Sharma and Parton 2007) for describing tree heights and crown ratios, ultimately resulting in plot-based estimates of jack pine height for live and dead cohorts (Sharpsand Creek), and black spruce height and the spruce-pine FSG at Kenshoe Lake. Unfortunately, no measurements of spruce LCBH were collected from Kenshoe Lake; following prior studies (Van Wagner 1993, Cruz 1999), we assigned FSG of 2 m to the mid-story spruce. At Bigfish Lake, unpublished plot-level LCBH measurements were found and used for the analysis. Sites with new plot-level FSG measures were Sharpsand Creek (immature and thinned), Kenshoe Lake (upper canopy), ICFME (upper canopy), Darwin Lake, PNFI (jack pine), and Bigfish Lake. See Appendix A for further details and figures.

Complex crown fuels: ladder fuels and mid-canopy conifer strata
A number of sites stood out for having more complex crown fuel structure than suggested by the simple LCBH concept, whether due to dense fine dead ladder fuels or bimodal live crown fuel distributions. The Sharpsand Creek (IM) experiments provide an example of extreme ladder fuel density, with a very high abundance (mean density: 10,229 ha^{-1}) of small diameter (mean DBH: 1.7 cm) dead trees (Stocks 1987), and a clear fire behaviour influence due to their presence (Stocks and Hartley 1995). A subset of plots had been previously thinned 15 years prior to burning (Sharpsand –TH) and had much lower overstory density of both dead and live stems (Stocks 1987). Later experiments at this site noted that the ladder fuels declined rapidly over time, with over 50% reduction in dead stem density over 10 years between measurements (McRae et al. 2017). Previous analyses using these sites have either considered thinned and unthinned plots as separate fuel types (the FBP System approach; FCFDG 1992)[1], ignored the ladder fuel influence in the Sharpsand-IM plots (Cruz et al. 2003), reduced the overall crown fuel moisture to account for the snag ladder fuels (Van Wagner 1993) or simply estimated the FSG to be 2 m lower on account of them (Cruz et al.

[1] Although it is not explained in detail in the STX-3 report, the FBP System ‘C-3’ fuel type includes the observations presently identified as ‘Sharpsand-TH’, while the ‘C-4’ fuel type includes the ‘Sharpsand-IM’ observations.

2004, Cruz et al. 2006). We explored four separate options regarding quantifying the ladder fuel influence, discussed below.

Two other sites, Kenshoe Lake and ICFME, were notable for having crown structure with bimodal vertical distributions in most plots: variable mid-story black spruce underneath upper canopy jack pine (Alexander et al. 2004, Stocks 1989). Rather than using a combined value for these distinct fuel strata, we treated crown fire activity in each layer as separate ‘crowning events’. The stem densities, tree heights, and even descriptions of these strata differed considerably between these two sites (‘overstory black spruce’ at ICFME, which also had a separately-described ‘understory black spruce’ layer; and ‘understory black spruce’ at Kenshoe Lake). However, it is apparent that relative proportions of pine and spruce in the overstory were otherwise quite similar, with the spruce comprising about 11 % of live basal area and 30-35 % of live tree density at both sites (see Alexander et al. 2004, Table 2). At both sites, only crown fire initiation into the mid-story spruce cohorts near the ground (LCBH ≤ 2.5 m) was tested in the main database. This required treating crown fire ‘success’ differently than previous studies, particularly for the Kenshoe Lake fires.

In the Kenshoe Lake study, 12 fire observations were grouped into 3 classes: (1) surface fires; (2) vigorous surface fires with ‘various degrees of torching or intermittent crowning’ (Stocks 1989) and measurable crown fuel consumption; and (3) fully developed passive crown fires with involvement of the upper crown fuel stratum (Stocks 1989, Van Wagner 1993). Following the classification from previous studies, bolstered by photographs (Stocks and Hartley 1995), crowning into the spruce stratum was assumed to have occurred for plots in groups 2 and 3 (see also Figure 1 f.). Involvement of the mid-story spruce alone could also be considered an understory crown fire, a distinct type of fire behaviour from a full canopy fire involving the entire crown fuel complex, including the jack pine crowns several metres higher (Walker and Stocks 1975). Therefore, for present purposes, crowning into the mid-story spruce layer occurred successfully in 6 of the 12 plots. Three of the 6 spruce crown fires also appeared to involve the jack pine layer (including plot 9, as per Cruz 1999), and evaluating these upper crowning events was viewed as a separate step tested using the final fitted models (see ‘Data analysis’ below). The remaining 6 observations were unambiguously surface fires.

At ICFME, in addition to an overstory structure with separate spruce and pine layers, most plots also contained moderately high densities of small snags, which needed to be considered in crown fire initiation (described below). As with the Kenshoe Lake fires, crowning into the upper canopy pine layer at ICFME was evaluated as an extension to the test dataset (below) after model-fitting based on the main database inputs. Unlike Kenshoe Lake, however, all 11 ICFME fires in our database were full canopy fires engaging with the entire crown fuel complex (Stocks et al. 2004). Thus, the upper canopy tests also involved 9 ICFME fires with overstory spruce and pine. Plots 3 and 4, with no overstory spruce, were excluded (Alexander et al. 2004).

In addition to overstory conifer fuels, some sites also clearly had significant densities of understory conifer seedlings and saplings, generally defined as < 1.3 m height. Information on understory conifer cohorts is thorough at some sites (e.g., Alexander et al. 2004, Lawson et al. 1972) but missing or marginal at other sites. While understory conifer cohorts may have contributed to crowning in some stands, the lack of consistent data made further calculations across our test database impossible on understory conifer layers.

Scaling ladder fuels to augment SFC

We tested versions of the database that ignored dead ladder fuels as well as a version that reduced FSG at Sharpsand-IM (LCBH-2 m) to account for the dead ladder fuels at that site (as per Cruz et al. 2004); no other sites' inputs were adjusted in these analyses (see 'Data analysis', below). We then explored an alternative approach for quantifying ladder fuel influence on crown fire initiation based on rescaling the ladder fuel consumption into an equivalent surface fuel contribution. This rescaling is based on the Van Wagner (1977) CFI model and relies on an implied equivalency between SFC and the inverse of *z* (LCBH) in Van Wagner's model.

When we replace $SFI_{critical}$ (Equation 1) with Byram's (1959) fireline intensity, we get the following well-known equation (e.g. FCFDG 1992, Scott and Reinhardt 2001; units omitted for simplicity):

$$h \cdot SFC \cdot ROS = (ch)^{1.5} \cdot z^{1.5} \qquad [2],$$

where *h* is the heat of combustion, *SFC* is surface fuel consumption, *ROS* is rate of forward spread, *c* is a complex dimensional constant (empirically derived), and *z* is the LCBH.

This relationship has previously been evaluated in terms of identifying critical ROS for crown fire initiation (Van Wagner 1977, Alexander 1988). However, if we assume that surface ROS is insensitive to moderate variations in LCBH, it should also hold for comparing a range of SFC values. Under surface fire conditions near the crown fire initiation threshold, critical SFC could then be defined as follows:

$$SFC_0 = \frac{(ch)^{1.5} \cdot z^{1.5}}{h \cdot ROS} \qquad [3].$$

Critical SFC can then be compared between two LCBH levels, z_1 and z_2.

$$\frac{SFC_2}{SFC_1} = \frac{\left[\frac{(ch)^{1.5} \cdot z_2^{1.5}}{h \cdot ROS}\right]}{\left[\frac{(ch)^{1.5} \cdot z_1^{1.5}}{h \cdot ROS}\right]} \qquad [4]$$

This assumes no change in ROS with varying LCBH. When holding all other terms constant, we can simplify this to yield a basic relationship between SFC and LCBH:

$$SFC_2 = \left[\frac{z_2}{z_1}\right]^{1.5} \cdot SFC_1 \qquad [5].$$

The theoretical relationship can be examined by comparing the SFC_0 in Equation 3 at two different *z* values. For example, at 90% FMC and LCBH=2m, Equation 1 suggests I_0 of about 417 kW/m, the intensity of a low to moderate intensity surface fire. At some moderate surface ROS value, e.g. 3 m/min, Equation 3 gives SFC_0 of 0.463 kg m^{-2}. Using Equation 5, increasing LCBH to 5 m (without altering other inputs) would therefore raise SFC_0 to 1.83 kg m^{-2}, thus suggesting that a 67 % increase in LCBH would result in a fourfold increase in fuel consumption needed to generate the greater surface fire intensity for crowning at the higher *z*. In this manner, it should be possible to scale the contribution of parts of the fuel complex based on their vertical position in the crown, as if they were part of the surface fuel complex. It is important to note that this theoretical relationship does not account for the critical differences between the surface and crown fuel complexes; in particular, surface fuelbeds are much more compact (higher bulk density and packing ratio) than crown fuel complexes, with a much more aeration-limited combustion environment (Keane 2015, Schwilk 2015). The general FBP System approach to SFC, where all consumed surface and ground fuels are assumed to contribute to surface fire intensity, may overemphasize dense fuels that burn in post-frontal combustion. In contrast, fine crown and ladder fuels are much better aerated (more porous) but also vertically and horizontally discontinuous (refs and explanation#).

In sum, ladder fuel influence was incorporated into certain models using Equation 5 to scale the fine dead ladder fuels (snags and dead crown fuel < 1 cm; Stocks 1987) into an equivalent SFC contribution value, SFC_L. The vertical position of fine standing ladder fuels was assumed to be the centroid of the mean dead snag height (height/2) in an experimental plot (Figure 2). To recognize that some small percentage of snags exist in all natural stands and cause negligible influence, we only added the contributions from plots with more than 250 stems/ha of fine dead snags, a baseline value that could be readily tested or changed as needed in future reanalyses. SFC_L was then added to the actual (measured) SFC for modelling. An additional version was tested where the elevated fuel contribution was increased using a multiplier, discussed further below.

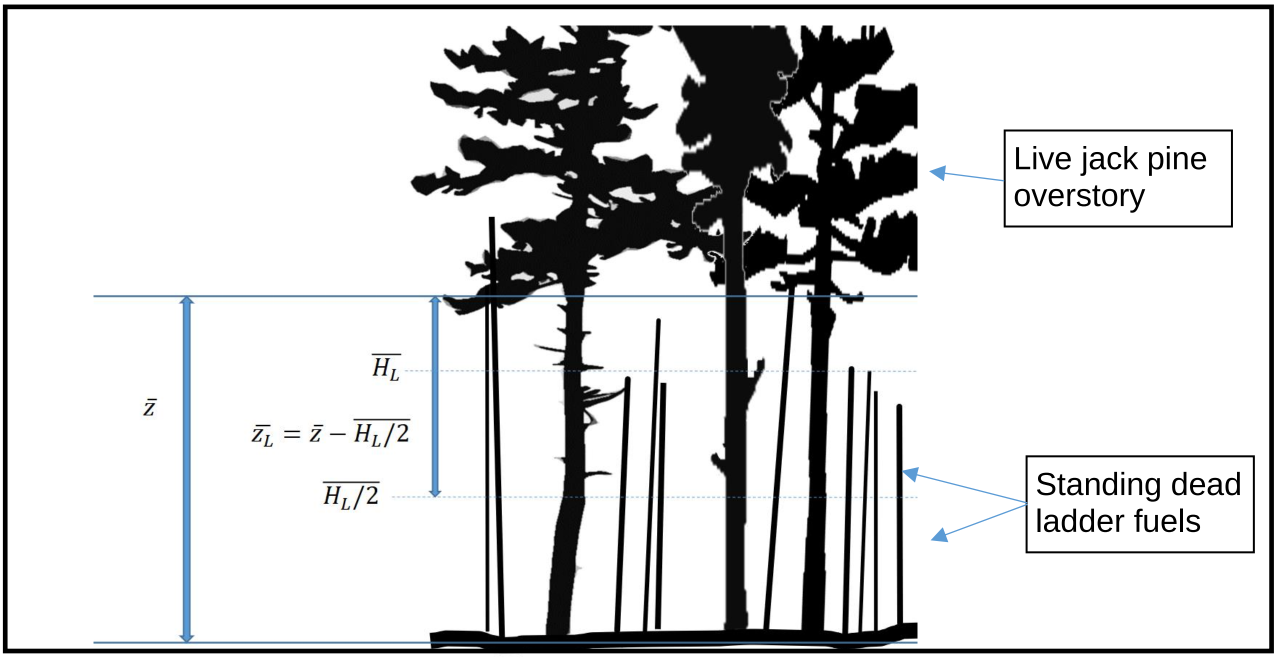

Figure 2. Illustration (not to scale) of a conifer overstory with high density of small diameter snag ladder fuels. The live canopy base height is *z*, while the mean ladder fuel height is H_L. The heat flux contribution to crown fire initiation is hypothesized to originate from the centroid of the snag height layer, $H_L/2$, and the relevant fuel strata gap between ladder fuels and canopy, z_L, is therefore z-$H_L/2$.

Crowning into the upper canopy stratum: Kenshoe Lake and ICFME

As an exploratory test of the vertical scaling assumptions, we tested the final models with the upper canopy crowning data and crown structure from the Kenshoe Lake and ICFME plots. This demanded some significant assumptions, including using the upper gap between fuel strata (spruce-pine) as FSG (Figure 3), estimating the black spruce crown fuel consumption values at Kenshoe Lake, and duplicating the weather and estimated mc inputs from the original training dataset records. In additional to evaluating the FSG and any contributions from ladder fuels, two additional data processing steps were needed: incorporating the (reduced) contribution from the actual surface fire at height zero (SFC_G) to the higher position (spruce crown centroid, C_{BS}), and estimating the appropriate fuel consumption for the spruce layer. To incorporate the surface fire contributions, we needed to do the reverse of the previous snag scaling step, where fuel consumption was boosted to account for a higher vertical position; in this case, the actual SFC was reduced (using Equation 5) to scale SFC down by a distance equal to C_{BS}.

The spruce crown fuel consumption (CFC_S), which was used as the equivalent SFC input for the upper crowning test, was measured at ICFME, with a mean value as follows: $CFC_S = 2.08 * CFL_N$ [6], with CFL_N the spruce needle fuel load (calculated from Stocks et al. 2004). At Kenshoe Lake, we assumed a similar crown fuel proportion burned, and used Equation 6 to estimate CFC_S for crown fire successes at that site based on published spruce CFL_N values in each plot (Stocks 1989). Since the degree of crown involvement at ICFME was much higher than in most Kenshoe Lake plots, this assumption was likely to overestimate CFC_S for Kenshoe Lake (and consequently probability of crown fire). This probable overestimate of CFC_S was compensated by the overall low values of crown consumption compared to SFC. Given their different (vertical) orientation and much lower bulk density compared with surface fuel loads, we tested the use of a multiplier *M* in order to boost both ladder fuel contributions, noted above, and CFC_S values at both ICFME and Kenshoe Lake (further described in 'Data analysis', below). One additional transformation was needed: in order to convert live crown fuel consumption values (needles and small roundwood) to the much lower moisture dead fuel equivalents, to match the character of the remaining SFC and dead ladder fuels, we used Babrauskas' (2006) empirical relationship between FMC and effective heat of combustion to transform the crown fuel consumption values: $\Delta h = 16.52 - 0.057 \cdot FMC$ [7]. This required an estimate of black spruce foliar moisture content; we used 82% at Kenshoe Lake (Van Wagner 1993), and the measured values at ICFME, between 69.1 % and 93.5 %, in the 9 upper crowning test plots (Stocks et al. 2004).

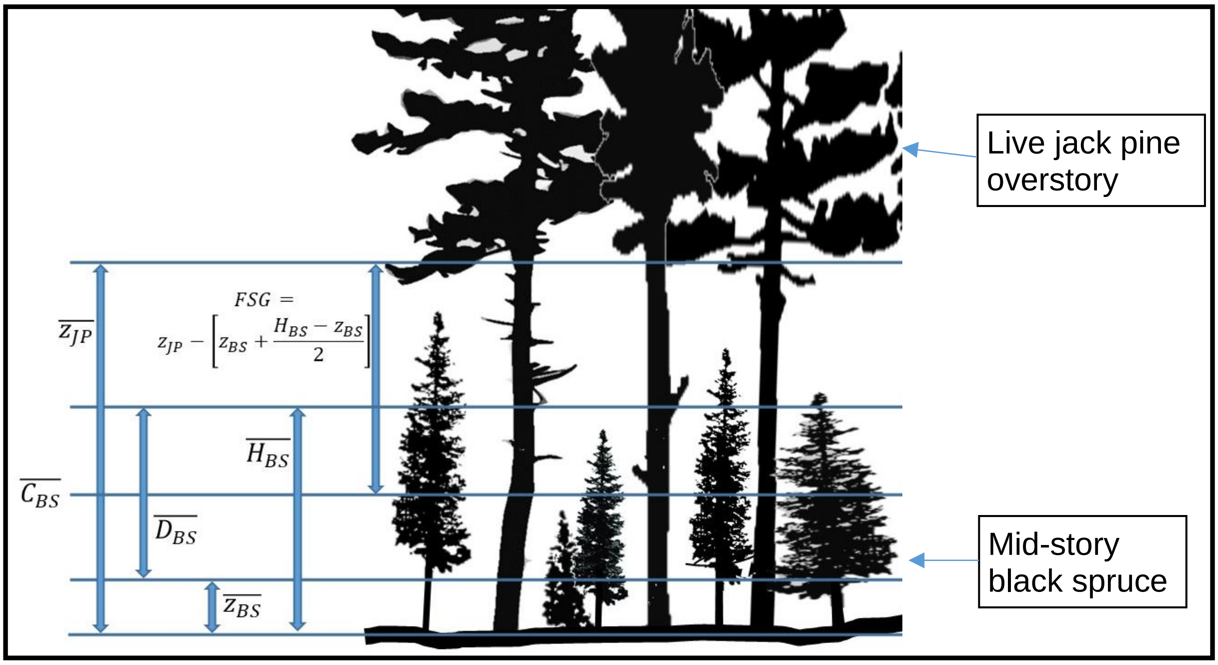

Figure 3. Illustration (not to scale) of suggested fuel metrics influencing upper canopy crown initiation in a jack pine-black spruce stand, such as at Kenshoe Lake, Ontario. Live crown

base heights are z_{JP} and z_{BS} for jack pine and black spruce strata, respectively. Spruce crown depth is D_{BS}, and fuel consumption of the spruce layer originates from the spruce crown centroid, C_{BS}, at a height of $z_{BS} + D_{BS}/2$; this height is also used for adding the scaled heat flux contribution from actual surface fuels. The relevant fuel strata gap (FSG) between the spruce and pine layers is assumed to be the distance from the spruce crown centroid to z_{JP}.

Stand-adjusted moisture content model (mc_{SA})

To test for the influence of litter and fine surface fuel moisture (mc), we tested two estimates: the first was the standard Fine Fuel Moisture Code (FFMC; Van Wagner 1987), an empirical index based on weather observations alone calibrated to predict mc in fully-stocked conifer forests (Van Wagner 1974b). The second method was a more recently published stand-adjusted moisture content (mc_{SA}) model (Wotton and Beverly 2007) that incorporated stand structure and season influences on mc in addition to FFMC. The Wotton & Beverly (2007) model (WB07 hereafter) was empirically derived from several thousand fuel moisture measurements across western Canada on days with daily FFMC from 75 to 96 (i.e. somewhat dry to extremely dry conditions; Wotton 2009). Calculating the mc_{SA} for the fires in our database required assigning the required input variables specified by WB07: diurnal or hourly FFMC and DMC from the FWI System; stand type ('deciduous', 'interior Douglas-fir', 'mixedwood', 'pine', or 'spruce'); and density class and season categorical variables, discussed below. We contacted the authors in order to clarify uncertainties associated with assigning appropriate attributes (J. Beverly, personal communication 2019; B. M. Wotton, personal communication 2020). The FWI components (FFMC and DMC) were left unchanged from their original coding in primary sources or in the Canadian experimental burn database, as they had already been adjusted as needed to account for diurnal variations due to ignition timing. Stand type for our dataset was either 'pine' or 'spruce' (or the mean of both) based on dominant overstory species (Table 1).

Assigning stand density and season for mc_{SA} calculations required some interpretation. Density in the WB07 study was a categorical variable with three classes ('light', 'moderate', 'dense') based on site descriptions, relative shading and photographic evidence. We assumed that stand density affected mc primarily due to variable solar radiation at the forest floor and the influence of in-stand wind and turbulence (Whitehead et al. 2008, Ma et al. 2010, Moon et al. 2016). The majority of observations in our database were ultimately assigned to the 'moderate' density class, reflecting the dominance of moderately closed (~ 50 - 65% canopy closure) unmanaged boreal conifer stands among both the WB07 litter moisture data and the experimental burn studies. Assigning 'light' and 'dense' classes was justified for a few stands using stand structure data from published records and site notes, along with calculated crown fuel load values (FCFDG 1992, Cruz 1999). Plots at Porter Lake, Darwin Lake, Bigfish Lake and Prince George ('dry pine') sites contained the bulk of 'Light' density stands, while stands at Kenshoe Lake, Sharpsand Creek (immature) and PNFI-Red Pine were classed as 'Dense' on the basis of very high canopy closure and estimated crown fuel loading values. Individual plots among the PNFI experiments that were described as 'half-stocked' or described as thinned to allow direct sun on the forest floor were also assigned to 'Light' density (Van Wagner 1968, Hummel 1979).

The season factor in the WB07 model was intended to represent the influence of greenup and leaf-fall of surrounding overstory vegetation, particularly deciduous trees: spring (SP; pre-bud flush), summer (SU; post-greenup), and fall (senescence; Paul 1969, Wotton and Beverly 2007). Dates of these phenological events were intended to be identified locally. Due to the difficulty of identifying these dates retrospectively for all burns, we resorted to using simple calendar dates for the fires in our database. Following guidance in Wotton and Beverly (2007), the SP and SU seasons were first assigned to obvious early season (May) and late season (July and August) fires. Fires in June were heavily represented in our dataset, due to the experimenters' intentions to conduct experiments that included boreal crown fires, i.e., temporally close to the 'spring dip'. To avoid an artificially abrupt effect on moisture estimates and to approximate a reasonable greenup transition (Chrosziewicz 1986), we added a 'spring-summer transition' (TR) season from 01-15 June, simply the mean of SP and SU estimates according to the mc_{SA} model. Summer fires, starting from 16 June onward, represented the remainder of the dataset and majority of observations (Table 1).

As a test of the value of the mc_{SA}, including assumptions regarding seasonality and stand density and how they might affect fuel moisture, we also fitted versions of the model using the predicted mc based on the FFMC alone (Van Wagner 1987) instead of mc_{SA}. This would help evaluate whether the additional complexity and assumptions associated with the mc_{SA} provided predictive skill compared to the standard FFMC approach.

Surface fuel consumption

Recognized as a key component of surface fire intensity (Van Wagner 1977, Agee et al. 2000), surface fuel consumption (SFC) was measured carefully in most studies in our dataset. As has been described previously, surface fuels in experimental burns were measured before and after burning to identify fuel consumption per unit area. The sum of all forest floor and downed woody fuels were included as the analyzed SFC value, since several studies did not report the portion of SFC between litter and duff or woody debris. In most experiments (e.g. Stocks 1989, Alexander et al. 1991) the SFC values were dominated by forest floor consumption, with relatively lower (1/3 or less) contributions from downed woody fuels. Due to the strong influence of these high duff consumption values in regression equations, most model forms included log-transformations of SFC values during the model building phase.

Data Analysis

The assembled database consisted of 108 fire observations that included measurements or estimates of fuel structure and consumption, weather and FWI components from a nearby representative station (usually on-site, < 1 km from the burns), and a fire behaviour description (Table 1). Crown fire initiation (CFI=1) was considered to have occurred when reported as such in primary sources, in cases of passive or active crown fire (Van Wagner 1977), or if significant torching (> 10 % of stand) was reported by experimental leaders, as per FBP System convention regarding crown fraction burned thresholds (FCFDG 1992). Following Cruz (1999) and Cruz et al. (2003b, 2004) crown fire initiation was modelled as the response variable in a generalized linear model (logistic regression).

The initial set of explanatory variables was suggested from previous efforts (Cruz et al. 2004, Perrakis et al. 2020). A backwards stepwise regression approach was used starting with all interaction effects between predictor variables: mc_{SA}, ws, SFC, FSG, FMC, with terms tested at the α=0.05 level. For FSG, linear, quadratic and 1.5 power exponents were tested, with the latter following from Equation 1. Linear, log-transformed and square root-transformed SFC terms were tested, to reduce undue influence from compact, heavy fuel loads less likely to affect flaming combustion (#ref.). A categorical SFC model (0-1, 1-2, > 2 kg m^{-2}) was also tested, similar to Cruz et al. (2004). As we simplified and approached the final model form, we compared several competing models using a Monte Carlo implementation of 4-fold cross validation (MCCV). This evaluation method, also known as the repeated learning-testing criterion, is statistically efficient and superior to simpler forms of cross-validation (Zhang 1993), while still allowing for retention of all degrees of freedom in the final model. Cross-validation was performed in R v.4.0.5, using the 'vtreat' data package (Mount and Zumel 2018). The training and testing selections were iterated 1000 times for each model form and compared using Akaike's Information Criterion (AIC) and Matthews' Correlation Coefficient (MCC; Chicco and Jurman 2020); the MCC is a ratio of correct model outputs that gives highest scores for good results among all four categories of a binary confusion matrix.

Initial model runs used the base input dataset. We then tested the most promising model forms on three modified versions of the dataset with adjusted FSG and SFC values to account for the most significant ladder fuel influences, as described above (Table 2). We first reduced the Sharpsand-IM FSG by 2 m, following the observations and assumption noted by Cruz et al. (2004) that crown fuel structure of the IM plots suggested a significantly lower effective LCBH compared with the TH plots. We then scaled the fine dead ladder fuels to produce SFC_L values (Equation 5) for plots with higher densities of fine dead ladder fuels: Sharpsand Creek (all plots: IM, TH, and SM) and ICFME. Finally, we increased the influence of the ladder fuels with a multiplier based on the estimated difference between the 'effective' FSG values in the Sharpsand-IM (4.36 m – 2 m = 2.36 m) and Sharpsand-TH (4.45 m) plots. The reasoning was as follows: if the difference in fire behaviour between the IM and TH plots was in fact caused by the excess standing dead ladder fuels in the IM plots, and the difference is reasonably represented by a ~2 m difference in LCBH (estimated by authors BJS and MEA, who observed the burns), then this difference could be used to estimate a multiplier (M) for adjusting the SFC_L value to equilibrate the vertical heat flux contributions to crown fire initiation between ladder fuel consumption and surface consumption. This value would approximately compensate for differences in the combustion environment between ladder fuels and surface fuels, including compactness and other differences. Based on Equation 5, this resulted in $M = [4.45/2.36]^{1.5} = 2.59$ [8].

The best-performing models were tested on the 16 test observations along with the 15 upper canopy crowning observations. The models from this study were compared alongside outputs from previously-published CFIS models using FWI and LCBH inputs (Logit 1 and 2 from Cruz et al. 2003b) for comparison purposes.

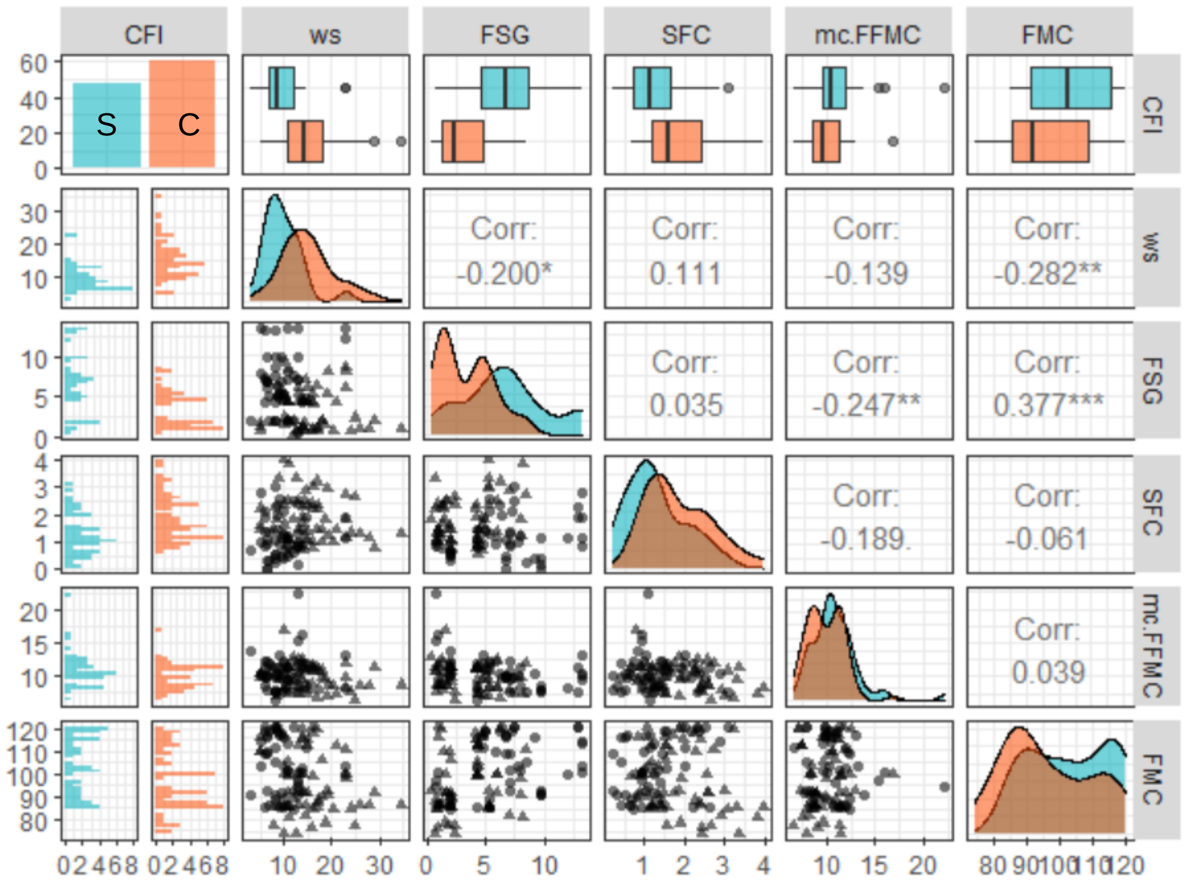

Figure 4. Pairwise plots and correlations. Abbreviations for CFI, ws, FSG, SFC, mc.FFMC, and FMC represent crown fire initiation, wind speed, fuel strata gap, surface fuel consumption, estimated dead moisture content (from the fine fuel moisture code), and foliar moisture content, respectively. S (blue) and C (red) represent surface fires (circles) and crown fires (triangles), respectively. Corr. Indicates Spearman's correlation, at the indicated significance level: 0.1 (.), 0.05 (*), 0.01 (**), 0.001 (***). See text for units and additional details.

Results

The overall range of measured and estimated variables in the database were as follows: wind speed from 3.0–34.6 km h^{-1}; estimated FMC from 74.2–120 %; FSG from 0.4–13.3 m; SFC from 0.2–4.0 kg m^{-2}; FFMC from 80.0–94.2; and mc_{SA} of 6.4–19.8 %. Our initial model-building suggested adequate independence between predictor variables, with no 2-way correlations > 0.35. Bivariate relationships between predictors and CFI were mostly as expected: successful crown fire initiation was clearly associated with low FSG, mc.FFMC and FMC, and high ws and SFC values (Figure 4). Estimated FMC values had the only bivariate correlation > 0.3 (with FSG), although this was believed to be coincidental.

During model building, complex high-level interactions failed to converge and there was no evidence that any 3-way or greater interactions were significant. Some model forms with multiple 2-way interaction terms appeared significant, but further testing revealed illogical behaviour interaction variables and evidence of overfitting, and these were not explored further. The next best model forms involved dropping the FMC term, it being non-significant (P > 0.2) in any of the subsequent tests. Final model forms included ws, FSG, SFC, and mc_{SA}

terms with various transformations and interactions. Alternative models were tested that included the ws × mc_{SA} interaction, linear and non-linear transformations of FSG and SFC, and the predicted mc from the FFMC alone as well as mc_{SA}. For the fuel moisture terms, mc_{SA} or mc_{FFMC}, either the main effect or the interaction term with wind speed (ws × mc_{SA} or ws × mc_{FFMC}) was significant when included, but not both; in these cases, the interaction terms all produced better results (greater accuracy, lower AIC) than main effects alone.

Table 2. Model comparison, based on Monte Carlo cross-validation, comparing alternate forms for predictors. MCC and AIC represent the Matthews Correlation Coefficient and Akaike's Information Criterion, respectively. 'Dataset' refers to original data (Base), reduction of Sharpsand-IM FSG by 2 m ('Sharp FSG - 2'), or addition of scaled ladder fuels ('Scaled LF') to actual surface fuel consumption (SFC) to give a modified SFC (SFC2 or SFC3), with or without the multiplier ('M'). Model 9 includes a categorical term for SFC; all other inputs are continuous. See Table 1 for input abbreviations.

Model	Form	Accuracy	MCC	AIC	Dataset	MCC Rank	AIC Rank
1	ws + FSG + SFC + mc_{SA}	0.833	0.662	53.2	1.Base	12	13
2	ws + FSG + SFC + mc_{SA} x ws	0.830	0.654	52.3	1.Base	13	12
3	ws + $FSG^{1.5}$ + ln(SFC) + mc_{SA}	0.848	0.692	51.1	1.Base	11	11
4	ws + $FSG^{1.5}$ + ln(SFC) + mc_{SA} x ws	0.856	0.707	49.0	1.Base	10	10
5	ws + FSG + SFC + mc_{FFMC}	0.861	0.718	47.9	1.Base	9	9
6	ws + $FSG^{1.5}$ + ln(SFC) + mc_{FFMC} x ws	0.888	0.773	44.0	1.Base	6	8
7	ws + $FSG.2^{1.5}$ + ln(SFC) + mc_{SA} x ws	0.868	0.733	43.4	2.Sharp FSG-2	8	7
8	ws + $FSG.2^{1.5}$ + ln(SFC) + mc_{FFMC} x ws	0.902	0.802	39.2	2.Sharp FSG-2	4	5
9	ws + $FSG^{1.5}$ + SFC.CLS + mc_{FFMC} x ws	0.908	0.815	38.1	2.Sharp FSG-2	3	3
10	ws + $FSG^{1.5}$ + ln(SFC2) + mc_{SA} x ws	0.881	0.758	41.3	3.Scaled LF	7	6
11	ws + $FSG^{1.5}$ + ln(SFC2) + mc_{FFMC} x ws	0.912	0.821	38.5	3.Scaled LF	1	4
12	ws + $FSG^{1.5}$ + ln(SFC3) + mc_{SA} x ws	0.889	0.775	37.4	4.Scaled LF * M	5	1
13	ws + $FSG^{1.5}$ + ln(SFC3) + mc_{FFMC} x ws	0.910	0.817	38.0	4.Scaled LF * M	2	2

Results of the cross-validation comparing model forms and various interactions and transformations are shown in Table 2. Accuracy and MCC score improved, and AIC decreased, as we progressed from simple main-effects models on the base data (Model 1) to log-transformed SFC, ws × mc interactions, and incorporating the ladder fuels into the inputs, as previously described. Overall, model forms using the mc_{FFMC} had slightly better performance (higher accuracy and MCC, and lower AIC) than comparable forms using the mc_{SA}, particularly using the base dataset. Among best-performing models, however, the comparison was more equivocal: models 12 and 13, using the scaled ladder fuels boosted with the multiplier, had slightly higher accuracy and MCC using the mc_{FFMC} model, but slightly lower AIC using the mc_{SA} model (Table 2). Based on these results, we moved ahead with final analysis and validation using model forms 7 - 13. Table 3 shows the fitted coefficients and performance of these final models based on the full set of training data. Model 9, with a categorical variable for SFC and subjectively reduced FSG for the Sharpsand-IM plots, predicted fire type (surface or crown fire) correctly for 90.7 of observations (98/108), as shown; the remaining models all predicted 94.4 % of observations correctly (102/108). The mc_{SA}-based Model 12, with the scaled and multiplier-boosted ladder fuel influence on SFC, had the lowest AIC, while the second lowest AIC was from the FFMC-based model with the similar boosted ladder fuels influence.

Table 3. Fitted coefficients and performance metrics of best crown fire initiation logistic regression models based on Training data. β_0 represents the model intercept coefficients, while $\beta_{1\text{-}5}$ represent coefficients for the various predictor terms (Pred.): wind speed (ws), Fuel Strata Gap (FSG), the fine dead moisture content (mc) and wind speed interaction, and Surface Fuel Consumption (SFC), respectively. For Model 9, SFC classes 2 and 3 (SFC.C2, SFC.C3) represents 1 - 2 kg m^{-2} and > 2 kg m^{-2} consumption classes, respectively (default is 0–1 kg m^{-2}). Degrees of freedom was 103 for all models except 102 for Model 9. True SF and CF represent numbers of correct surface fire and crown fire predictions, respectively, out of database totals; AIC is Akaike's Information Criterion. Input types and modifications show the type of mc estimate – stand-adjusted (mc_{SA}), or based on the Fine Fuel Moisture Code (mc_{FFMC}); FSG used is either actual measured FSG (Measured) or adjusted 'effective' FSG (Adjusted) to account for ladder fuel effects; SFC in model is either consumption of surface fuels (SF) alone or surface fuels plus scaled ladder fuels times the multiplier (LF·M).

Pred.:	-	ws	$FSG^{1.5}$	ws X mc	ln(SFC)		True	True			Input modifications		
Model	*β₀*	*β₁*	*β₂*	*β₃*	*β₄*		SF (/48)	CF (/60)	AIC	*N.R²*	mc	FSG	SFC
7	-3.5156*	1.5332***	-0.57561***	-0.075519***	3.6165**		45	57	50.9	0.844	mc_{SA}	Adjusted	SF only
8	-4.0867**	1.5393***	-0.50826***	-0.08096**	4.3894**		45	57	50.2	0.847	mc_{FFMC}	Adjusted	SF only
11	-3.8457**	1.4556***	-0.5004***	-0.076179**	4.603***		45	57	50.3	0.847	mc_{FFMC}	Measured	SFC + LF
12	-3.9781*	1.4918***	-0.59139***	-0.071333***	4.4694**		45	57	48.4	0.855	mc_{SA}	Measured	SFC + LF·M
13	-4.2653**	1.4355***	-0.48859***	-0.073616**	4.3019***		45	57	49.4	0.851	mc_{FFMC}	Measured	SFC + LF·M
					SFC.C2	SFC.C3							
	β₀	*β₁*	*β₂*	*β₃*	*β₄*	*β₅*			AIC		mc	FSG	SFC
9	-4.8217**	1.561***	-0.50588***	-0.083235**	1.9676·	5.3355**	43	55	56.8	0.826	mc_{FFMC}	Adjusted	SF only

Asterisks represent significance levels as follows: < 0.001 (***); <0.01 (**); <0.05 (*); <0.1 (·).

In the test dataset, the models from this study predicted surface or crown fire correctly 11 - 13 times out of 16 (69 - 81 %), while the Logit 1 and Logit 2 models previously described by Cruz et al. (2003) predicted fire type correctly 10 and 12 times out of 16 (63 - 75 %; Table 4). The main source of incorrect predictions was the Archer Lake fires, where crown fires occurred at lower-than-expected FFMC-wind speed combinations (Table XX#To do). The best performing model in the test dataset, Model 12, correctly predicted 87% of all fires and crowning events correctly, including 81% of test fires (13/16) and 93% of upper crown transitions in the spruce-pine crown plots at Kenshoe Lake and ICFME.

Table 4. Test data results including independent experiments and upper (jack pine) crown fire initiation modelling using various fitted models. Models m7 through m13 refer to the model forms from Tables 2 and 3, while Logit1 and Logit2 are tests of Cruz et al.'s (2003) LOGIT 1 and LOGIT 2 models. SFC_g and SFC_{scale} refer to surface fuel consumption at the ground (true SFC) and scaled upwards (reduced); CFC is estimated crown fuel consumption. SFC_{final} is the total SFC evaluated in the model; this is the same as SFC_g for simple canopy stands, but for upper canopy crowning is CFC * 2.59 + SFC_{scale}, as described in text.

Project	SF / CF	SFC_g	SFC_{scale}	CFC	SFC_{final}	m7	m8	m9	m11	m12	m13	Logit1	Logit2
1. Ft Providence FT	2 / 2	3 (2.7-3.4)	--	--	3 (2.7-3.4)	1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.75
2. Archer Lk	4 / 6	1.9 (1.8-2.5)	--	--	1.9 (1.8-2.5)	0.70	0.50	0.50	0.50	0.70	0.50	0.70	0.50
3. Pelican Mt	0 / 2	1.6 (1.5-1.7)	--	--	1.6 (1.5-1.7)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4. Upper Kenshoe Lk	3 / 3	1.1 (0.8-1.5)	0.5 (0.4-0.8)	1 (0.5-1.7)	2.4 (1.5-3.8)	--	--	--	0.83	1.00	1.00	--	--
5. Upper ICFME	0 / 9	2.5 (1.5-3.4)	1 (0.6-1.3)	0.2 (0.1-0.3)	1.7 (1.2-2.1)	--	--	--	0.89	0.89	0.89	--	--

Overall test fires	6 / 10	--	--	--	--	0.81	0.69	0.69	0.69	0.81	0.69	0.75	0.63
Overall upper crown	3 / 12	--	--	--	--	--	--	--	0.87	0.93	0.93	--	--
Overall test + upper	**9 / 22**	--	--	--	--	--	--	--	**0.77**	**0.87**	**0.81**	--	--

Based on these results, Model 12 was selected for displaying further data figures. The probability distribution of crown fire at different ws and FSG values is shown in Figure 5. Fires are shown as surface, passive crown and active crown fire observations.
The distribution of observations is further shown in Figure 6, with all fire environment variables displayed. Iso-lines representing 50% probability are shown for mc values of 6-15%, as indicated; these were calculated at SFC of 1.5 kg m^{-2} using Model 12.

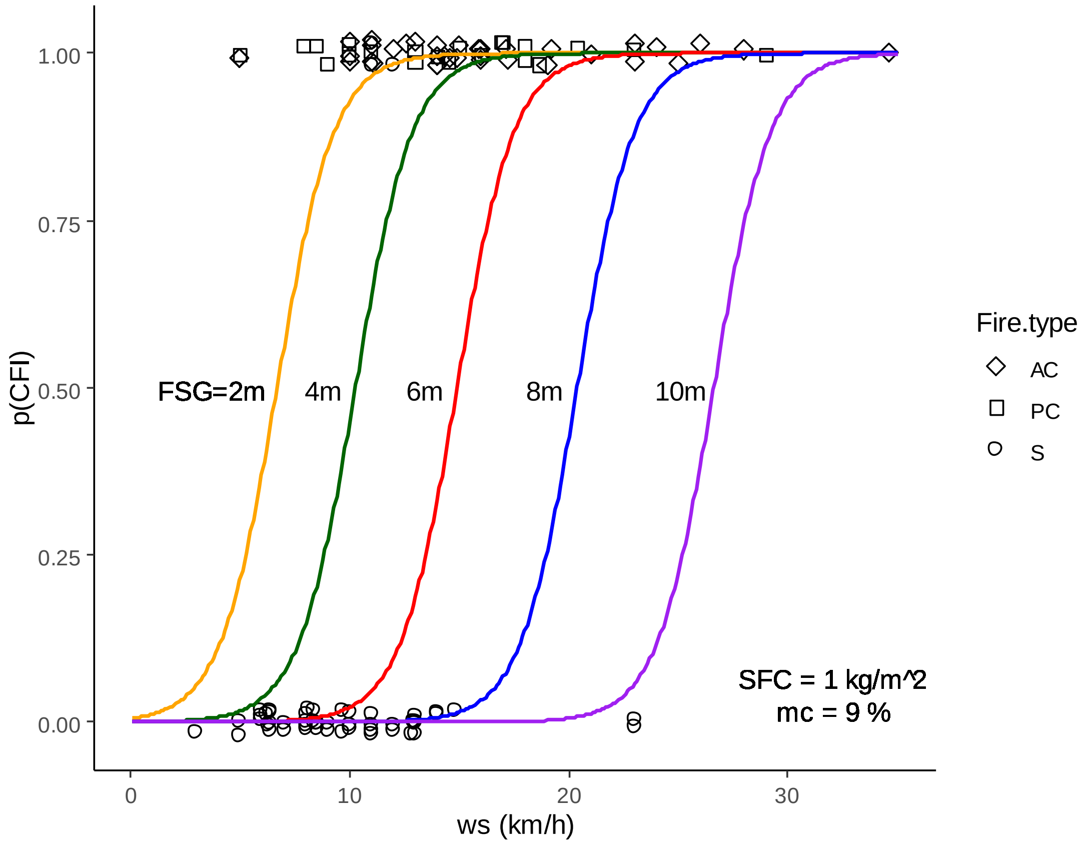

Figure 5. Probability of crown fire initiation (Model 12) under varying combinations of wind speed (ws) and Fuel Strata Gap (FSG), calculated at surface fuel consumption of 1 kg/m^2 and mc of 9%; fire observations (vertically jittered for clarity) are shown as surface (S), passive crown (PC) or active crown (AC).

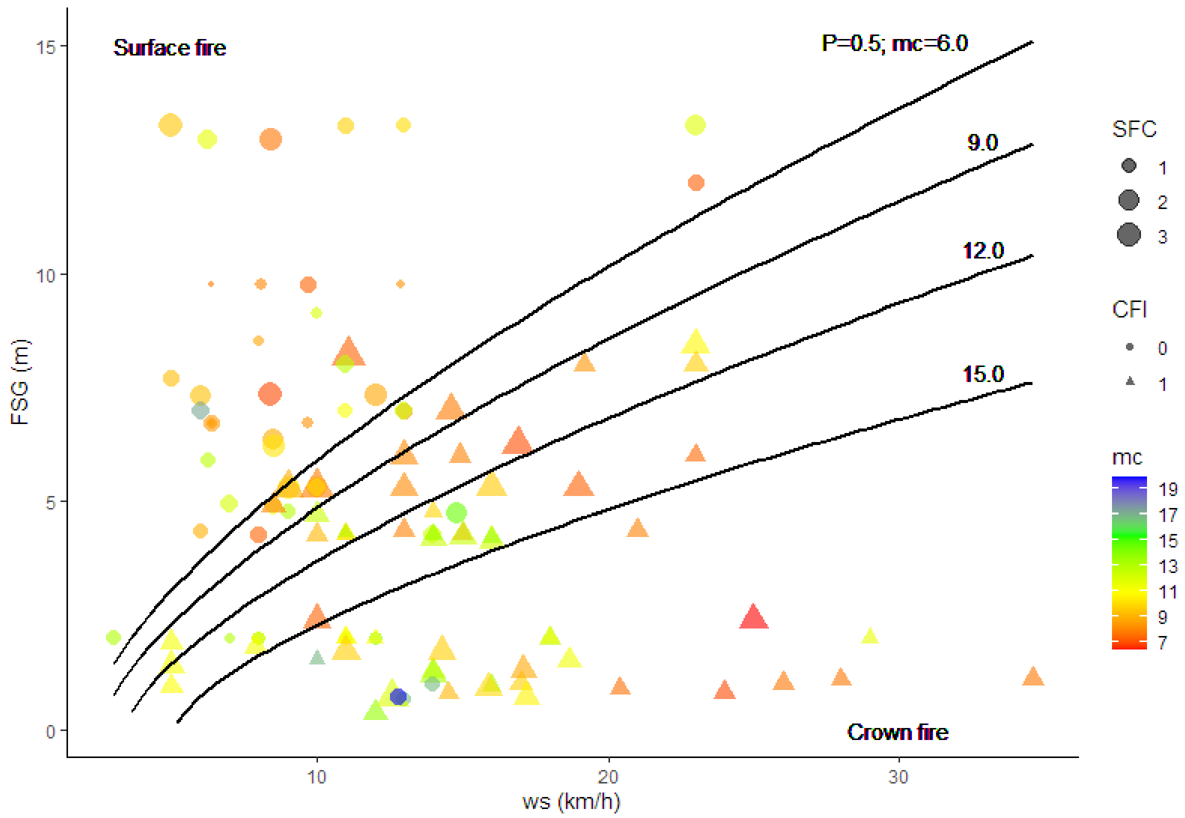

Figure 6. Scatter plot of fire observations, showing the distribution of primary fire environment variables for all surface and crown fires. Triangles represent active or passive crown fires (CFI=1) while circles represent surface fires (CFI=0). Iso-lines represent *P* = 0.5 for crown fire initiation based on Model 12, calculated at SFC=1.5 kg m^{-2}, at various indicated mc_{SA} values (6-15 %). Observation space below and right of the isolines predicts crown fire behaviour, while observation space above and left of the lines predicts surface fire.

Discussion

Based on the models presented in this study, crown fire initiation in boreal and sub-boreal conifer forests can be accurately predicted approximately 9 times out of 10 based on ambient wind speed, estimated litter moisture content, fuel strata gap, and estimated surface fuel consumption. Our overall findings were largely consistent despite the variability in source data, with a range of plot sizes, tree species, measurement protocols and study leaders conducting individual experiments over several decades. Empirical fire behaviour models have always been constrained by small sample sizes. In keeping with the successful approach used in the original FBP System, we have relied on a few physical principles to guide the modelling logic but aimed to produce practical and operationally-usable models for decision support. Thus, we favor retaining the 1.5 (or 3/2) power function associated with FSG as originally conceived by Van Wagner (1977) based on heat flux theories conceived by Lee and Emmons (1961) and Thomas (1963); empirical forms with this exponent performed better than those with a linear FSG term. We respected statistical significance and the accuracy rankings with respect to model forms, namely, retaining predictors only when supported by evidence, and favoring models with higher accuracy scores from the cross-validation. Our full-featured Model 12 showed the best performance, with non-linear terms for FSG and SFC based on physical principles and the ladder fuel influence on crowning incorporated by scaling fuel consumption down to the height of surface fuels. The wind speed × moisture content interaction term helps reduce crown fire probability under conflicting influences of high wind and high litter moisture content, further discussed below.

Wind speed and canopy influence

Wind speed remains the most significant variable in determining crown fire initiation. This unsurprising finding must be combined with the inherent bias towards dry conditions in experimental burn studies, since several studies noted cases where ignition was unsuccessful due to excessive moisture (e.g. Quintilio et al. 1977, Stocks 1987, Stocks 1989). The role of wind in fire behaviour is complex, with several known and observed physical mechanisms involved in how wind affects flames and combustion, including feedbacks between wind and other fire environment elements such as fuel moisture and firebrands (Finney et al. 2021). Numerous previous studies have demonstrated the role of ambient wind speed in fire spread, whether represented at a nearby station or at the flame front in surface (Rothermel 1972, Nelson and Adkins 1988) and crown fire behaviour (Rothermel 1991, Cruz and Alexander 2019) models. As with many empirical studies, the present analysis used measured wind speed a short distance (~0.5 - 2 km) from individual experimental plots at a height of 10 m, as per common fire weather station standards (Lawson and Armitage 2008). Canopy conditions are known to affect in-stand climate, including wind speed (Moon et al. 2016, Russell et al. 2018), and the question of in-stand wind and ignition are separate problems (Beverly and Wotton 2007).

Since the present analysis relied primarily on small-block experimental burns ignited at the windward edge, the findings from the latter burning experiments at Sharpsand Creek are worth considering here. In that study, point ignitions inside dense conifer stands demonstrated only creeping and smouldering behaviour (ROS < 1 m min^{-1}) even under high fire danger conditions, while nearly simultaneous ignitions along stand edges exhibited much more active behaviour, including active crown fire spread (McRae et al. 2017). These examples highlight the importance of canopy effects on wind speed at the flame surface as well as the relatively poor predictability of point fires in closed conifer stands. As noted in the FBP System document (FCFDG 1992), very small ('point') fires under a canopy exist in an unstable state; the right combination of fine-scale fuel conditions and microclimate are required for fires to grow and accelerate in order to attain equilibrium spread rate and intensity for ambient fire environment conditions. The influence of flame front width on surface fires has been a subject of several studies. Wotton et al.'s (1999) field experiments of low-moderate intensity (FWI 2-17) fires in red pine plantations suggested that flame front width appeared to have little influence on ROS above ~ 2 m. In contrast, evidence from grassfire experiments suggests frontal widths are influential up to ~ 50 m or so (Cheney and Gould 1995); Finney et al. (2021) suggested that the influence of flame width on fire spread may depend on flame length, due to the increasing role of convective forces in higher intensity flame zones.

The present models (similar to the FBP System ROS models, or CFIS models) are therefore most appropriate for predicting the probability of crown fire initiation in conifer stands when a surface fire enters a conifer stand from an untreed opening, such as a roadside, harvest block, or large canopy gap that allows open winds to influence the flame front. These models are likely to overpredict the probability of crown fire initiation if applied to point ignitions or creeping surface fires in wind-sheltered locations, such as underneath a continuous canopy. Additionally, in the wake of a spreading crown fire, the immediate loss of canopy fuel allows for much higher leeside winds (Taylor et al. 2004). Therefore, the present models should be informative for predicting the probability that a spreading crown fire will change fire type when stand conditions change (different age-class or species composition). In our dataset, transition from surface to crown fire due to fuel type change was observed in the Gwatkin Lake (Van Wagner 1965), while crown-surface transitions were observed in the Fort Providence fuel treatment experiments (Schroeder 2010). In the Pelican Mountain experiment (Thompson et al. 2020), a fuel type change (control to thinned stands of black spruce) failed to produce a change in fire type, despite a reduction in fire intensity, with both stand types supporting crown fire behaviour under relatively homogeneous weather conditions.

Foliar Moisture Content
Foliar moisture content, from experimental sampling or estimation using the FBP System equation, was not a significant predictor of crown fire behaviour in our final models, matching previous findings (Cruz et al. 2004). While there appears to be little doubt that FMC is influential on the ignition of conifer foliage in a physical sense (Xanthopoulos and Wakimoto 1993, Alexander and Cruz 2013, Pimont et al. 2019, Fazeli et al. 2022), and FMC appeared related to crown fire initiation in a simple bivariate comparison (Figure 4), it was significantly correlated to other variables in our dataset (wind speed, FSG), and as such had minimal explanatory power. More robust tools for assessing or modelling foliar phenology are likely needed. Despite the convenient mnemonic of a pan-specific 'spring dip' in foliar moisture causing an uptick in crown fire hazard (Van Wagner 1974a), increased foliar flammability of conifer foliage during certain times of year are likely related to several physiological changes, including moisture, density, and chemical proportioning associated with bud burst and the growing season (Jolly et al. 2014). Species differences are clearly significant, as acknowledged by Van Wagner (1993), who suggested lower FMC for the mid-canopy black spruce (82%) compared with the jack pine overstory (104.5 %) in his analysis of the Kenshoe Lake fires. FMC differences between species or between other stand characteristics are not represented by any of the modelling approaches related to the FBP or CFIS Systems, including the present one, although several studies have identified regional species trends in FMC (Van Wagner 1967, Chrosziewiecz 1986, Agee et al. 2002). Under wildfire conditions, Van Wagner's (1977) model suggests that realistic FMC differences, such as between species (~ 70-130 %) could affect critical FSG by 2 m or more, depending on surface fire intensity (Keyes 2006). Other recent studies have also significant differences in live conifer shoot and foliage flammability compared with FBP System predictions (Melnik et al. 2022), and echoed the need for better methods for estimating FMC to improve crown fire predictions in conifer forests. In the absence of a consistent and reliable way to assign FMC post-hoc to various fire observations, our attempts at combining the FBP equation with various in-situ measurements and estimates did not identify FMC as a significant factor in crown fire initiation. Additional studies on the influence of stand factors and phenology on conifer foliar flammability are warranted.

Fine Dead Moisture content, Stand-Adjusted - mc_{SA}
Moisture content (mc) of fine forest floor litter has long been known to be a key variable of influence on fire behaviour (Van Wagner 1968, Viney 1991, Dimitrakopoulos and Papaioannou 2001). Our results showed that the FFMC, an index based on weather conditions alone, remains a significant predictor of crown fire initiation in a variety of conifer forests. Fuel moisture studies have generally supported the validity of the FFMC, but also identified over- under-prediction instances suggesting that additional variables (possibly stand characteristics) should be incorporated for better results (e.g. Beck and Armitage 2004, Wotton 2009, Gibos 2010). Theoretical and empirical studies from various forest types have also shown how overstory characteristics can significantly affect mc and overall fire danger

(Rothermel et al. 1986, Tanskanen et al. 2005, Whitehead et al. 2008, Matthews 2014, van der Kamp et al. 2017, Kreye et al. 2018). For this study, we sought to incorporate stand-level information on mc estimates in experimental stands, such that broad differences in stand structure, such as canopy closure, for instance, could potentially be estimated by operational users.

Model 12, using the mc_{SA} to estimate of litter moisture, performed well, with the lowest AIC and one of the highest accuracy scores; overall it did not unequivocally outperform the FFMC, either alone or as an interaction term. By examining the list of correct and incorrect predictions, it is clear that the FFMC-based models work well under average boreal conifer stand conditions, analogous to the mc_{SA} for moderate density pine stands in summer conditions with a moderate DMC (Wotton and Beverly 2007). However, under different conditions, such as when evaluating the influence of changing stand structure (e.g., from 'moderate' to 'light' density class; see below) or longer-term weather conditions (e.g., comparing different seasons, or between greatly differing DMC values), the mc_{SA} model forms provide additional value. The predictors of the mc_{SA} also lend it a certain similarity with the FBP System BUI effect on ROS (FCFDG 1992). While the BUI effect (increasing or decreasing predicted ROS based on the underlying duff moisture) was not justified from experimental data, the DMC influence on the mc_{SA} model in Model 12 provides some empirically-based influence of duff moisture on crown fire initiation, and therefore ROS and overall fire behaviour.

For interpreting density classes in mc_{SA} model, as a starting point, we assumed that density class was roughly similar to common canopy closure classes representing low to high density conifer stands: 'light' (26-45 %), 'moderate' (46-65 %) and 'dense' (>65 %), based on point-based measures, such as hemispherical photography.[2] In a physical sense, crown closure is closely tied to in-stand solar radiation, which directly affects litter moisture and ignition processes (Vezina and Pech 1964, Tanskanen et al. 2005, van der Kamp et al. 2017). Season was a significant predictor of mc in the full WB07 dataset as well as for the pine stands analyzed alone, for reasons that were not fully explored, but may be related to vegetation phenology, including evapotranspiration of leafed-out understory species.

There is likely room for additional improvement in the stand-adjusted mc model, either the originally described WB07 version or the adjusted interpretation in the present study. For instance, the present density categories may be usable for simple ocular use by operational users but a more flexible representative continuous function likely exists between stand density and mc, such a power relationship based on canopy closure (e.g., Vezina and Pech 1964). The present WB07 model also contains some illogical behaviour at high FFMC levels. Stands classified as 'dense' begin to show a reverse density influence on mc above approximately FFMC 92.93, such that 'dense' stands are predicted to have slightly lower mc_{SA} than 'moderate' stands, a result likely resulting from small sample sizes in this class of observations and the inclusion of several density interaction terms in the WB07 model. Similarly illogical differences between 'light' and 'moderate' categories exist above approximately FFMC 96.15, where 'light' density stands are predicted to be moister than 'moderate' density stands; below these thresholds, the density classes behave as expected. This was not an issue with the present study, since all burns with FFMC > 92.9 (10

[2] See, for example, the density classes in the BC Vegetation Resource Inventory data dictionary (p. 16): https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/standards/vegcomp_poly_rank1_data_dictionaryv5_2019.pdf [accessed Aug. 2020]

observations) were classed as 'light' or 'moderate' density, and no observations had FFMC > 96 (see Table 1) but represents a point of uncertainty with the WB07 model as published under high or extreme danger conditions.

SFC

Surface fuel consumption must be estimated as an input to predict crown fire initiation with the present equations. This adds an additional element of uncertainty, as the relevant inputs to fuel consumption models will rarely be on hand in wildfire situations, for instance. A number of existing models presently exist for estimating SFC based on elements of the CFFDRS, the most familiar of which are probably the FBP System equations (FCFDG 1992) that require only the BUI and the FBP fuel type as inputs. The FBP equations could be the best option in cases of a good match with a standard fuel type but little other knowledge of surface fuels in a stand. Individual studies among the 'core' sources that comprise our main dataset reported several significant site-specific SFC models based on FWI indices and surface fuel loading; the references in Table 1 can be consulted for the main sources (Stocks 1989, Alexander et al. 1991, Stocks et al. 2004, etc.). For our modelling, when SFC values were missing, we used one of DeGroot et al.'s (2009) updated forest floor consumption model based on regressions fitted to portions of the FBP experimental data. For estimating the SFC for some unmeasured plots in the test dataset, the model using DMC and forest floor fuel loading was particularly suitable, and we suspect it would be a useful tool for future research or operational decision support purposes. Note that fine woody fuel loads must still be estimated or assumed to be negligible; for sites with high loads of fine woody debris, these equations may be inaccurate. For predicting crowning activity in future fires, we expect good results when surface fuel conditions resemble those of the input data: surface fuels characteristic of boreal and sub-boreal conifer forests, featuring moderately compact needle litter, compact duff layers, and relatively smaller contributions of woody fuels. Stands featuring much higher coarse woody debris loads (e.g. Agee and Huff 1987, Perrakis and Agee 2006) would likely require calibration or validation to improve results.

Canopy structure: LCBH and FSG

The separation distance between surface and canopy fuels has long been known to be a critical forest structure measure influencing crown fire initiation in conifer stands (Van Wagner 1977, Cruz et al. 2006). By locating and analyzing original source data associated with several burning experiments, we estimated plot-based LCBH and FSG values for many more observations than have previously been presented. This may have contributed to more accurate characterization of the fire environment in our database of observations and, ultimately, more accurate models for predicting crown fires.

Issues with varying definitions of LCBH have frequently been explored (e.g. Reinhardt et al. 2006, Cruz and Alexander 2010, Keane 2015). While LCBH is conceptually convenient as a measure of separation between surface and crown fuels, it fails to adequately characterize the variable canopy fuel structure in more complex stands. Van Wagner's concept of the canopy fuel layer was 'a layer of uniform bulk density and height above ground' and noted in his experiments that critical surface intensity occurred when the surface fire produced a flame front 'whose tip is just reaching into the crown layer' (Van Wagner 1977). Additional studies have suggested that flame tips do not need to actually contact the crown base for crown fire initiation to occur, with time-temperature curves and net energy release being more representative of the canopy ignition process (Xanthopoulos and Wakimoto 1993, Cruz et al. 2006, Melnik et al. 2022). The image of a surface fire flame height reaching the vicinity of the lower live canopy remains useful for visualizing crown fire initiation (e.g. Alexander and

Cruz 2016), although it likely exaggerates the critical surface fire intensity needed for crown fire to occur. The biggest difference between the present analysis and previous CFIS models is the use of the 1.5 exponent for the FSG/LCBH term. Experiments and physical theory have identified non-linear functions describing heat flux above a flame. These include Thomas (1963), the basis for Van Wagner's work, as well as experiments by McCaffrey (1979), who found the relationship between temperature change and height above a pulsing flame varied from z^{-1} to $z^{-1.67}$ depending on the plume region in question.[3] This aligns well with the 1.5 power we kept for our final empirical models (12 and 13), which, for predictive purposes, must be applicable to a wide range of flame heights and *z* values. Variability in LCBH has also been identified in physical modelling studies as a potentially important factor (Parsons et al. 2011), although the varied nature of the LCBH data at our different sites precluded studying the effects of variability in our analyses, since several studies reported only mean LCBH values.

The question of how to interpret the relationship between measured FSG (or LCBH) and crown fire initiation thresholds remains. Since our analysis used mean estimated LCBH at the plot-level, and we left the original assignments of surface or crown fire unchanged from the source observations, it is left to the original observers to define crowning thresholds. While the FBP System defines a 'crown fraction burned' function (FCFDG 1992, Van Wagner 1993) which defines 'intermittent crown fires' as those with CFB > 10% and 'continuous crown fires' as those with CFB > 90%, CFB does not appear in the original experimental burn studies. Various anecdotes, photographs, and recollections from our authors suggest that a more likely crown fire threshold would be something closer to involvement of > ~25% of overstory tree canopies, although this may be a matter of debate.

The best example of the challenge of modelling crown fire initiation in our dataset is by comparing the ICFME and Kenshoe Lake experiments. Despite very similar relative proportions of overstory pine and spruce (both density and basal area; Alexander et al. 2004), these two stand types varied greatly in vertical dimensions: at ICFME, there was some overlap between the spruce and pine strata, with the authors calculating a separate crown bulk density for the midstory spruce, intercanopy space, and upper overstory pine cohorts. At Kenshoe Lake, in contrast, mean spruce heights were several metres below the pine LCBH (See Appendix A), requiring much greater ignition energy in order to ignite the upper canopy. Crown involvement in the pine layer at Kenshoe Lake, with pine LCBH > 10 m from the ground, only occurred in 3 of the 12 plots. For assessing the upper canopy ignition probability, we assumed full consumption of spruce needles and a portion of live fine roundwood, along with the scaled SFC; in this case SFC was reduced, since the heat flux from surface fuels is well below the crown centroids, and presumably lower in influence.

Overall, our analyses showed FSG once again as a highly significant factor in crown fire initiation, regardless of its form in the equation. The FSG concept recognizes that understory conifers frequently act as ladder fuels and are elements long observed to be important in crown fire initiation (Alexander and Cruz 2012) #Jakala 1995?. It is intuitively logical that consumption of ladder fuels would be much more likely to contribute to crown ignition than the equivalent biomass consumption within the surface fuelbed; this was described in detail, for instance, in white pine experiments with an understory of balsam fir, where torching firs caused crown scorch to overstory pines (Methven 1973). Using the semi-physical

[3] The actual exponent used by McCaffrey (1979) for the 'intermittent flame zone' was $z^{-5/3}$. We use the approximate decimal notation here for ease of comparison.

formulation of Van Wagner's crown initiation model to account for ladder fuel consumption, including both the high density of small-diameter snags at the Sharpsand Creek experiments, as well as for estimating the probability of upper canopy involvement given the ignition of a mid-story conifer layer, is a novel approach of the present study that will require additional investigation. However, our results suggest that incorporating ladder fuel influence in the manner of our final models (12 and 13) improves prediction results significantly. Several of the original reports noted the presence of lichen hanging from lower branches as a possible factor facilitating crowning (e.g., Quintilio et al. 1977, Schroeder 2010); this was also noted by author MEA as a possible factor explaining the largest outlier in the dataset (BigFish Lake Plot 9). However, understory structure was not available for many sites, and the fine scale patterns of the smallest ladder fuels (seedlings and saplings of height < 1.4 m, shrubs, bark flakes, etc.) are unknown, resulting in some unavoidable noise and a lower limit to the resolution of measures such as LCBH and FSG. Live understory fuels can take many forms, including conifer, flammable shrub, or deciduous (low flammability) herbs and forbs; future research will have to identify how and when these act to reduce or increase surface fire intensity. For instance, green 'understory' vegetation reduced flame length but not ROS in a series of small laboratory fires in red pine needles (Stocks and Walker 1968). Other influences of understory vegetation structure and chemistry are complex and prone to oversimplification (Fernandes and Cruz 2012, Varner et al. 2015) and not readily extracted post-hoc in studies such as this one. Work in shrublands has shown variable results, but recent empirical analyses suggest influence from live foliar moisture content as a small but potentially significant predictor (Anderson et al. 2015), even more important when shrub FMC drops below ~ 90% (Pimont et al. 2019). Modelling experiments also suggest that the wind reduction from understory vegetation can be significant in reducing surface fire spread under a conifer canopy, ultimately contributing to reducing probability of crowning (Banerjee et al. 2020).

At some of our sites, original studies noted significant understory cohorts of conifer seedlings and small saplings with live crowns down to ground level, such as black spruce or other shade-tolerant conifers (Stocks 1989, Alexander et al. 2004, Lawson 1972); at other sites, the separation distance between strata appeared lower than the actual LCBH, due to elevated surface fuels, including flammable shrubs and standing dead trees, or more flammable crown fuels from hanging lichens, dead branches, or bark flakes reducing the effective crown height. Considering the unknown variability in most field situations, it is unlikely that real-world differences of LCBH or FSG are meaningful below about ~1 m. And while our data sources included primarily traditional (manual) measurements of LCBH used to create stand models, newer technologies are not yet a panacea for such measurements. A recent comparison of high-resolution scanning methods in interior Douglas-fir in British Columbia found frequent differences of several metres between manual and automated methods (using aerial scanning) used to measure or estimate LCBH or crown length (Arkin et al. 2021).

Validation dataset

The inclusion of a small validation dataset can help greatly to prevent overfitted or misleading results. In our analysis, the largest source of test data, the Archer Lake study, was slightly compromised due to some missed measurements (SFC) that required imputation to generate the inputs for testing. The Archer Lake observations were also the largest source of error, with 30-50% incorrectly classified using the fitted models. Notably, all erroneous observations were crown fires incorrectly predicted as surface fires. A closer examination of these records shows crown fire behaviour recorded at significantly lower fire danger levels than in similar fires in the training dataset.

An examination of relevant ISI values (reflecting both wind speed and estimated litter moisture; Van Wagner 1987) is illustrative. Within the training database, a query of all crown fires with FSG > 4 m and FSG < 6 m returned 20 fires from Darwin Lake and various plots at Sharpsand Creek (IM, TH, and SM). From these observations, the bottom 5 ISI values for these fires are ISI 6.8 - 8.3; conversely, multiple surface fires occurred at ISI values between 7 and 8. In addition, the crown fires with lowest ISI were all from sites with abundant standing dead ladder fuels (Sharpsand-IM and SM); for similar sites without the copious snags (ie, Sharpsand-TH and Darwin Lk), the lowest ISI associated with crown fire behaviour was 10.4. In contrast, at Archer Lake (FSG of 4.4 – 5.3 m), three crown fire records had ISI values of 4.6, 5.3 and 5.4 (misclassified by all models), and ISI 6.2 and 6.6 (missed by 5 out of 8 models; Table 4); surface fires at this site had ISI up to 4.8. What explains the difference between crowning thresholds at Archer Lake (ISI ~ 5) and other sites (ISI ~ 7-10) with similar FSG? SFC values for Archer Lake are unknown, as noted; higher SFC values could suggest a greater probability of crown fire using, for example, Model 12 in this study (e.g. doubling SFC from 2 to 4 ··m^{-2}, would increase p(CFI) for plot A9 from 15% to 83%). However, with relatively low forest floor and woody debris loading values of 2.4 and 0.75 kg m^{-2}, respectively (site averages; Schroeder and Mooney 2012), total SFC appears unlikely as an explanation. The lichen litter type at Archer Lake could potentially be the cause, as lichen litter is known to dry more rapidly than other litter types (Alexander et al. 1991, Ivanova et al. 2020) and ignite at lower fire danger conditions than other conifer litter types (Beverly and Wotton 2007). Drier or more porous forest floor characteristics at Archer Lake could account for a greater heat flux contribution, despite the modest fuel loading.

The Fort Providence experiments also required post-hoc estimation to generate inputs, in this case the FSG and other canopy fuel measures in the ‘control-side’ plots. The fuel treatment plots that were the main focus of the Fort Providence experiments were adequately described, showing an impressive effect in reducing active crown fire behaviour in the control plots down to moderate surface fire behaviour in thinned stands, readily actioned by fire crews. Overall, these experiments showed good, if not spectacular, validation results, with up to 81 % of fires correctly predicted as surface or crown behaviour.

Management considerations and Conclusion

Our results expanded empirical fire behaviour models of crown fire initiation and offer some evidence that fire behaviour models will continue to improve as experimental databases improve. Compared with previous studies using Canadian experimental burn data, this analysis used a larger observation dataset and made use of more continuous predictor variables; this provided higher degrees of freedom for modelling but demands more detailed inputs from users. The 20th Canadian experimental burning program resulted in over 100 observations of fire behaviour in boreal and sub-boreal pine and spruce forests, the majority carefully established and monitored. Results here appear promising, although many questions remain. With all the low-FSG experiments comprised of spruce-containing stands, the influence of species is unresolved. Some studies (Xanthopoulos and Wakimoto 1993, Fazeli et al. 2022) have shown that inter-specific differences in crown ignition thresholds can be significant. In the Canadian context, the data would suggest that additional tests in BC are strongly warranted, given the limited observations in that province: only 8 observations, all surface fires in lodgepole pine stands, with the majority of SFC measures near or below 0.5 kg m^{-2}.

Aside from its better performance indicators (MCC, AIC), the form of Model 12 possesses certain advantages compared to simpler model forms. The ws × mc_{SA} interaction term has the ability to address uncertainties relating to competing influences of fuel moisture and wind speed. For instance, simpler model forms are prone to overprediction of crown fire probability during moist, marginal conditions for ignition or sustainable spread. For instance, under high wind conditions (e.g., ws=40) and high fuel moisture (e.g., mc_{SA}=25, approximately equal to FFMC 78 conditions) [4], a main effects model, such as Model 3[check#], predicts very high probability of crowning (P = 0.993) with moderate values of other predictors (FSG=4, SFC=1). The same predictors using Model 12 suggest a very low chance of crowning (P < 0.001). The probability of ignition in such conditions is low (#Beverly and Wotton 2007), suggesting even a surface fire is highly unlikely spreading under such conditions is unlikely.

The purpose of these models remains largely operational, to create tools usable by managers for predicting how various elements of the fire environment influence crown fire occurrence by harnessing the best elements of the FWI System with more detailed fuel structure and consumption data. Wherever possible (e.g. prescribed fire situations, operational monitoring during the wildfire season), use of these models should be accompanied by additional measurements of the predictor variables. Since the mc_{SA} model in particular may be prone to error, field measurements of mc may improve model performance considerably rather than relying only on derived estimates based on weather and stand influences. We expect considerable interest in these models for planning and evaluating fuel treatments to reduce wildfire hazard (Hirsch et al. 2001, Agee and Skinner 2005, Keeley and Syphard 2019). Ignoring changes in fine fuel moisture dynamics caused by landscape fuel treatments is a common fire behaviour modelling error (Varner and Keyes 2009). Additional studies will be needed to continue refining the effects of stand density on fuel moisture and other fire environment factors, and how these might influence stand-level fire behaviour.

This analysis was also intended to form a key component of the Canadian Conifer Pyrometrics system (CCP; Perrakis et al. 2020), a linked system for predicting surface fire, crown fire initiation, and crown fire type based largely on experimental data and established physical principles; this will likely be packaged as an user option within the 'Next Generation-CFFDRS' along with a suite of additional changes and improvements to the overall system (CFS Fire Danger Group 2021). The next steps for this process include describing surface fire (see Appendix B, below) and integrating crown fire modelling options (Cruz et al. 2005) for these systems once the prediction of crown fire probability is documented.

The models presented here come well short of answering all questions related to fire behaviour in conifer forests. The use of data spanning several decades, with varying standards of documentation, quality of measurements, and spatial and temporal resolution, means we are limited in the phenomena that can be explored via empirical means. The influence of phenomena such as fuelbed characteristics (e.g. porosity, surface to volume ratio, influence of larger woody debris), contributions of ember lofting and spotting, influence of variations in upper air profiles or acceleration of point fires within a stand are not addressed. Nonetheless, we anticipate that operational users and practically-minded researchers will find the present approach and models useful. As previous studies have noted

[4] Approximately 25% moisture content would be predicted using the standard FFMC model at FFMC 78, or using the mc_{SA} under the following conditions, for example: FFMC 78, DMC 30, pine, moderate density, summer.

(Cruz and Alexander 2017), linked models of surface and crown fire, where thresholds representing sudden non-linear increases in ROS, for instance (i.e. due to crown fire transition) are superior to single functions representing all types of fire in these forests. However, also true is the observation that solely empirical methods are rarely as revealing as mechanistic investigations and understanding (Michaletz and Johnson 2008, Cruz and Gould 2009). Thus, more targeted experiments will be needed to help identify and quantify biophysical factors such as the variability in conifer FMC (Agee et al. 2002, L. Collins, Pacific Forestry Centre, Victoria, BC, In prep.), conifer species differences, or understory vegetation on crown fire dynamics.

Finally, during earlier presentations of this work, the question of climate change has come up: how well might we expect these experiments, some of them conducted over 50 years ago, to represent fire conditions under extreme conditions in the future? While recent seasons in Canada and elsewhere have indeed produced extreme and in some cases unprecedented conditions, there is no shortage of crown fires in our data set. Conditions that produce greater fire danger (e.g., lower fuel moisture) may well increase the probability of crown fire behaviour, and models described here are anticipated to remain useful for managers and researchers alike.

References

Affleck, D. L., C. R. Keyes, and J. M. Goodburn. 2012. Conifer crown fuel modeling: current limits and potential for improvement. Western Journal of Applied Forestry **27**:165-169.

Agee, J. K., B. Bahro, M. A. Finney, P. N. Omi, D. B. Sapsis, C. N. Skinner, J. W. van Wagtendonk, and C. P. Weatherspoon. 2000. The use of shaded fuelbreaks in landscape fire management. Forest ecology and management **127**:55-66.

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.

Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management **211**:83-96.

Agee, J. K., C. S. Wright, N. Williamson, and M. H. Huff. 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. Forest ecology and management **167**:57-66.

Alexander, M., and R. Lanoville. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada.[Poster with text.]. Edmonton, AB and Fort Smith, NT: Forestry Canada, Northern Forestry Centre and Government of Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre.

Alexander, M. E. 1988. Help with making crown fire hazard assessments. Pages 147-156 *in* Symposium and Workshop on Protecting People and Homes from Wildfire in the Interior West, Missoula, MT.

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.

Alexander, M. E., and M. G. Cruz. 2012. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. International Journal of Wildland Fire **21**:95-113.

Alexander, M. E., and M. G. Cruz. 2013. Assessing the effect of foliar moisture on the spread rate of crown fires. International Journal of Wildland Fire **22**:415-427.

Alexander, M. E., and M. G. Cruz. 2016. Crown fire dynamics in conifer forests. In 'Synthesis of knowledge of extreme fire behavior: Volume 2 for fire behavior specialists, researchers, and meteorologists'. Pages 163-258 in General Technical Report PNW-GTR-891, USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Alexander, M. E., M. G. Cruz, and A. M. G. Lopes. 2006. CFIS: A software tool for simulating crown fire initiation and spread. Pages 1-13 *in* D. X. Viegas, editor. Vth International Conference on Forest Fire Research, 27-30 November 2006. Elsevier B.V, Amsterdam, The Netherlands.

Alexander, M. E., and W. De Groot. 1988. Fire behavior in jack pine stands: as related to the Canadian Forest Fire Weather Index (FWI) System [poster with text]. Natural Resources Canada - Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.

Alexander, M. E., and D. Quintilio. 1990. Perspectives on experimental fires in Canadian forestry research. Mathematical and computer modelling **13**:17-26.

Alexander, M. E., C. N. Stefner, J. A. Mason, B. J. Stocks, G. R. Hartley, M. E. Maffey, B. M. Wotton, S. W. Taylor, N. Lavoie, and G. N. Dalrymple. 2004. Characterizing the jack pine-black spruce fuel complex of the International Crown Fire Modelling Experiment (ICFME). Information Report NOR-X-393, Natural Resources Canada - Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Alexander, M. E., B. J. Stocks, and B. D. Lawson. 1991. Fire behaviour in black spruce-lichen woodland: the Porter Lake project. NOR-X-310, Forestry Canada Northwest Region, Edmonton, Alberta.

Anderson, W. R., M. G. Cruz, P. M. Fernandes, L. McCaw, J. A. Vega, R. A. Bradstock, L. Fogarty, J. Gould, G. McCarthy, and J. B. Marsden-Smedley. 2015. A generic, empirical-based model for predicting rate of fire spread in shrublands. International Journal of Wildland Fire **24**:443-460.

Arkin, J., N. C. Coops, L. D. Daniels, and A. Plowright. 2021. Estimation of Vertical Fuel Layers in Tree Crowns Using High Density LiDAR Data. Remote Sensing **13**:4598.

Babrauskas, V. 2006. Effective heat of combustion for flaming combustion of conifers. Canadian Journal of Forest Research **36**:659-663.

Banerjee, T., W. Heilman, S. Goodrick, J. K. Hiers, and R. Linn. 2020. Effects of canopy midstory management and fuel moisture on wildfire behavior. Scientific reports **10**:1-14.

Beck, J., and O. Armitage. 2004. Diurnal fine fuel moisture characteristics at a northern latitude. Pages 211-221 *in* 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal and Montane Ecosystems," Tallahassee, FL.

Beverly, J. L., S. E. Leverkus, H. Cameron, and D. Schroeder. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire **3**:35.

Beverly, J. L., and B. M. Wotton. 2007. Modelling the probability of sustained flaming: predictive value of fire weather index components compared with observations of site weather and fuel moisture conditions. International Journal of Wildland Fire **16**:161-173.

Byram, G. M. 1959. Combustion of forest fuels. Pages 61-89 *in* K. P. Davis, editor. Forest fire: control and use. McGraw-Hill, New York.

CFS Fire Danger Group. 2021. Overview of the next generation of the Canadian Forest Fire Danger Rating System. Information Report GLC-X-26, Natural Resources Canada-Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, Canada.

Cheney, N., and J. Gould. 1995. Fire growth in grassland fuels. International Journal of Wildland Fire **5**:237-247.

Chicco, D., and G. Jurman. 2020. The advantages of the Matthews correlation coefficient (MCC) over F1 score and accuracy in binary classification evaluation. BMC genomics **21**:6.

Chrosziewiecz, Z. 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. Canadian Journal of Forest Research **16**:157-162.

Coogan, S., L. D. Daniels, D. Boychuk, P. J. Burton, M. Flannigan, S. Gauthier, V. Kafka, J. Park, and B. M. Wotton. 2020. Fifty years of wildland fire science in Canada. Canadian Journal of Forest Research. In Press.

Cruz, M. G. 1999. Modeling the initiation and spread of crown fires. University of Montana.

Cruz, M. G., and M. E. Alexander. 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. International Journal of Wildland Fire **19**:377-398.

Cruz, M. G., and M. E. Alexander. 2017. Modelling the rate of fire spread and uncertainty associated with the onset and propagation of crown fires in conifer forest stands. International journal of wildland fire **26**:413-426.

Cruz, M. G., and M. E. Alexander. 2019. The 10% wind speed rule of thumb for estimating a wildfire's forward rate of spread in forests and shrublands. Annals of Forest Science **76**:44.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2003a. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. International Journal of Wildland Fire **12**:39-50.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2003b. Assessing the probability of crown fire initiation based on fire danger indices. Forestry Chronicle **79**:976-983.

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.

Cruz, M. G., B. W. Butler, M. E. Alexander, J. M. Forthofer, and R. H. Wakimoto. 2006. Predicting the ignition of crown fuels above a spreading surface fire. Part I: model idealization. International Journal of Wildland Fire **15**:47-60.

Cruz, M. G., and J. Gould. 2009. Field-based fire behaviour research: past and future roles. Pages 247-253 *in* Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation '13-17 July.

De Groot, W., J. Pritchard, and T. Lynham. 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Canadian Journal of Forest Research **39**:367-382.

Dimitrakopoulos, A., and K. K. Papaioannou. 2001. Flammability assessment of Mediterranean forest fuels. Fire Technology **37**:143-152.

Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Centre for Land and Biological Resources Research; Hull, Quebec: State of the Environment Directorate.

Fazeli, H., W. M. Jolly, and D. L. Blunck. 2022. Stages and time-scales of ignition and burning of live fuels for different convective heat fluxes. Fuel **324**:124490.

Fernandes, P. M., and M. G. Cruz. 2012. Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions. New Phytologist **194**:606-609.

Finney, M. A., S. S. McAllister, J. M. Forthofer, and T. P. Grumstrup. 2021. Wildland Fire Behaviour: Dynamics, Principles and Processes. CSIRO PUBLISHING.

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

Gibos, K. E. 2010. Effect of slope and aspect on litter layer moisture content of lodgepole pine stands in the eastern slopes of the Rocky Mountains of Alberta (Thesis). University of Toronto, Toronto, Ontario, Canada.

Hirsch, K., V. Kafka, C. Tymstra, R. McAlpine, B. Hawkes, H. Stegehuis, S. Quintilio, S. Gauthier, and K. Peck. 2001. Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. The Forestry Chronicle **77**:357-363.

Hirsch, K., D. Martell, and P. Corey. 2000. Probability of containment by medium initial attack crews in the boreal spruce fuel type.[Poster with text].

Hirsch, K. G., and I. Pengelly. 1999. Fuel reduction in lodgepole pine stands in Banff National Park. Pages 251-256 *in* Proceedings of the Joint Fire Science Conference and Workshop.

Holdaway, M. R. 1986. Modeling tree crown ratio. The Forestry Chronicle **62**:451-455.

Hummel, S. 1979. Ecological Effects of Seven Fires in a Jack Pine (Pinus Banskiana) stand. University of Toronto.

Ivanova, G. A., E. A. Kukavskaya, V. A. Ivanov, S. G. Conard, and D. J. McRae. 2020. Fuel characteristics, loads and consumption in Scots pine forests of central Siberia. Journal of Forestry Research **31**:2507-2524.

Jolly, W. M., J. Hintz, R. C. Kropp, and E. T. Conrad. 2014. Physiological drivers of the live foliar moisture content 'spring dip'in Pinus resinosa and Pinus banksiana and their relationship to foliar flammability. Advances in forest fire research:401-408.

Keane, R. E. 2015. Wildland fuel fundamentals and applications. Springer.

Keeley, J. E., and A. D. Syphard. 2019. Twenty-first century California, USA, wildfires: fuel-dominated vs. wind-dominated fires. Fire Ecology **15**:24.

Keyes, C. R. 2006. Role of foliar moisture content in the silvicultural management of forest fuels. Western Journal of Applied Forestry **21**:228-231.

Kiil, A. 1975. Fire spread in a black spruce stand. Bi mon Res Can For Serv **31**:2-3.

Kreye, J. K., J. K. Hiers, J. M. Varner, B. Hornsby, S. Drukker, and J. J. O'brien. 2018. Effects of solar heating on the moisture dynamics of forest floor litter in humid environments: composition, structure, and position matter. Canadian Journal of Forest Research **48**:1331-1342.

Lawson, B. D. 1972. Fire spread in lodgepole pine stands. Internal Report BC-36, Pacific Forest Research Centre, Victoria, British Columbia, Canada.

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

Lee, S.-L., and H. Emmons. 1961. A study of natural convection above a line fire. Journal of Fluid Mechanics **11**:353-368.

Ma, S., A. Concilio, B. Oakley, M. North, and J. Chen. 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. Forest Ecology and Management **259**:904-915.

Matthews, S. 2014. Dead fuel moisture research: 1991–2012. International Journal of Wildland Fire **23**:78-92.

McCaffrey, B. J. 1979. Purely Buoyant Diffusion Flames: Some Experimental Results. NBSIR 79-1910, Center for Fire Research, National Bureau of Standards, Washington, D.C., USA.

McRae, D., B. J. Stocks, G. R. Hartley, J. A. Mason, T. J. Lynham, T. W. Blake, and C. C. Hanes. 2017. Influence of ignition type on fire behavior in semi-mature jack pine. Information Report GLC-X-19, Natural Resources Canada - Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, Canada.

Melnik, O. M., S. A. Paskaluk, M. Y. Ackerman, K. O. Melnik, D. K. Thompson, S. S. McAllister, and M. D. Flannigan. 2022. New In-Flame Flammability Testing Method Applied to Monitor Seasonal Changes in Live Fuel. Fire **5**:1.

Methven, I. R. 1973. Fire, succession and community structure in a red and white pine stand.

Michaletz, S., and E. Johnson. 2008. A biophysical process model of tree mortality in surface fires. Canadian Journal of Forest Research **38**:2013-2029.

Moon, K., T. Duff, and K. Tolhurst. 2016. Sub-canopy forest winds: understanding wind profiles for fire behaviour simulation. Fire Safety Journal.

Mount, J., and N. Zumel. 2018. The vtreat R package: a statistically sound data processor for predictive modeling. Journal of Open Source Software **3**:584.

Nelson, R. M. J., and C. W. Adkins. 1988. A dimensionless correlation for the spread of wind-driven fires. Canadian Journal of Forest Research **18**:391-397.

Newstead, R., and M. Alexander. 1983. Short-term fire retardant effectiveness in a lowland black spruce fuel complex. Forestry Report 28 (September), p. 3-4, Environ. Can. Can. For. Serv., Northern Forestry Centre, Edmonton, AB.

Parsons, R. A., W. E. Mell, and P. McCauley. 2011. Linking 3D spatial models of fuels and fire: effects of spatial heterogeneity on fire behavior. Ecological Modelling **222**:679-691.

Paul, P. 1969. Field Practices in forest fire danger rating. Canadian Forest Service, forest Fire research Institute. Report FF-X-20.(Ottawa, ON).

Pelletier, G., J. St-Onge, P. Bordeleau, P. De Rainville, F. Bart, E. Aubin, J.-F. Roy, and G. Therriault. 2009. Classification of Forest Stands as Fuels According to the Canadian Forest Fire Behavior Prediction (FBP) System: third ten-year Quebec forest survey program. Société de protection des forêts contre le feu and Ministère des Ressources naturelles et de la Faune, Direction de l'environnement et de la protection des forêts, Quebec, Quebec, Canada.

Perrakis, D. D. B., and J. K. Agee. 2006. Seasonal fire effects on mixed-conifer forest structure and ponderosa pine resin properties. Canadian Journal of Forest Research **36**:238-254.

Perrakis, D. D. B., M. G. Cruz, M. E. Alexander, S. W. Taylor, and J. L. Beverly. 2020. Linking Dynamic Empirical Fire Spread Models: Introducing Canadian Conifer Pyrometrics. Proceedings from the 6th Fuels and Fire Behaviour Conference, 29 April-03 May 2019, Marseille, France. International Association of Wildland Fire.

Perrakis, D. D. B., G. Eade, and D. Hicks. 2018. British Columbia Wildfire Fuel Typing and Fuel Type Layer Description. Information Report BC-X-444, Natural Resources Canada, Pacific Forestry Centre, Victoria, British Columbia, Canada.

Pimont, F., J. Ruffault, N. Martin-StPaul, and J.-L. Dupuy. 2019. Why is the effect of live fuel moisture content on fire rate of spread underestimated in field experiments in shrublands? International Journal of Wildland Fire **28**:127-137.

Quintilio, D., G. R. Fahnestock, and D. E. Dube. 1977. Fire behavior in upland jack pine: the Darwin Lake Project. Information Report NOR-X-174, Fisheries & Environment Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB.

Reinhardt, E., J. Scott, K. Gray, and R. Keane. 2006. Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Canadian Journal of Forest Research **36**:2803-2814.

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

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

Rothermel, R. C., R. A. Wilson, G. A. Morris, and S. S. Sackett. 1986. Modeling moisture content of fine dead wildland fuels: input to the BEHAVE fire prediction system.

Russell, E. S., H. Liu, H. Thistle, B. Strom, M. Greer, and B. Lamb. 2018. Effects of thinning a forest stand on sub-canopy turbulence. Agricultural and Forest Meteorology **248**:295-305.

Schroeder, D. 2010. Fire behaviour in thinned jack pine: two case studies of FireSmart treatments in Canada's Northwest Territories. 12(7), FPInovations Advantage.

Schroeder, D., and C. Mooney. 2012. Fire behaviour in simulated pine beetle-killed stands. FP Innovations Advantage report, March 2012, Hinton, AB.

Schwilk, D. W. 2015. Dimensions of plant flammability. New Phytologist **206**:486-488.

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

Sharma, M., and J. Parton. 2007. Height–diameter equations for boreal tree species in Ontario using a mixed-effects modeling approach. Forest Ecology and Management **249**:187-198.

Stockdale, C., Q. Barber, A. Saxena, and M.-A. Parisien. 2019. Examining management scenarios to mitigate wildfire hazard to caribou conservation projects using burn probability modeling. Journal of Environmental Management **233**:238-248.

Stocks, B. 1987. Fire behavior in immature jack pine. Canadian Journal of Forest Research **17**:80-86.

Stocks, B. J. 1989. Fire behavior in mature jack pine. Canadian Journal of Forest Research **19**:783-790.

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. Blacke, 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.

Stocks, B. J., and G. R. Hartley. 1995. Fire behaviour in three jack pine fuel complexes.

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

Stocks, B. J., and J. Walker. 1973. Climatic conditions before and during four significant forest fire situations in Ontario. Information Report O-X-187, Department of the Environment, Canadian Forestry Service, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, Canada.

Stocks, B. J., and J. D. Walker. 1968. The effect of green vegetation on surface fire spread in the laboratory. Information Report PS-X-5, Petawawa Forest Experiment Station, Chalk River, Ontario, Canada.

Tanskanen, H., A. Venäläinen, P. Puttonen, and A. Granström. 2005. Impact of stand structure on surface fire ignition potential in Picea abies and Pinus sylvestris forests in southern Finland. Canadian Journal of Forest Research **35**:410-420.

Taylor, S. W., and M. E. Alexander. 2006. Science, technology, and human factors in fire danger rating: the Canadian experience. International Journal of Wildland Fire **15**:121-135.

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**:1571-1576.

Thomas, P. 1963. The size of flames from natural fires. Pages 844-859 *in* Symposium (International) on Combustion. Elsevier.

Thompson, D. K., D. Schroeder, S. L. Wilkinson, Q. Barber, G. Baxter, H. Cameron, R. Hsieh, G. Marshall, B. Moore, and R. Refai. 2020. Recent crown thinning in a boreal black spruce forest does not reduce spread rate nor total fuel consumption: Results from an experimental crown fire in Alberta, Canada. Fire **3**:28.

Tymstra, C., B. J. Stocks, X. Cai, and M. D. Flannigan. 2020. Wildfire management in Canada: Review, challenges and opportunities. Progress in Disaster Science **5**:100045.

van der Kamp, D., R. Moore, and I. McKendry. 2017. A model for simulating the moisture content of standardized fuel sticks of various sizes. Agricultural and Forest Meteorology **236**:123-134.

Van Wagner, C. 1965. Story of an intense crown fire at Petawawa. Pulp Paper Magazine Canada **66**:WR 358.

Van Wagner, C. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires.

Van Wagner, C. 1972. Duff consumption by fire in eastern pine stands. Canadian Journal of Forest Research **2**:34-39.

Van Wagner, C. 1974a. A spread index for crown fires in spring. Canadian Forestry Service, Petawawa Forest Experiment Station. Information Report PS-X-55.(Chalk River, ON).

Van Wagner, C. E. 1963. Prescribed burning experiments: red and white pine. Department of Forestry Publication No. 1020, Department of Forestry, Forest Research Branch, Ottawa, Ontario, Canada.

Van Wagner, C. E. 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence.
Van Wagner, C. E. 1974b. Structure of the Canadian forest fire weather index. Publication No. 1333, Environment Canada, Forestry Service, Ottawa, Ontario, Canada.
Van Wagner, C. E. 1977. Conditions for the start and spread of crown fires. Canadian Journal of Forest Research **7**:23-34.
Van Wagner, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35, Canadian Forest Service, Petawawa National Forestry Institute, Chalk River, Ontario, Canada.
Van Wagner, C. E. 1990. Six decades of forest fire science in Canada. The Forestry Chronicle **66**:133-137.
Van Wagner, C. E. 1993. Prediction of Crown Fire Behavior in two Stands of Jack Pine. Canadian Journal of Forest Research **23**:442-449.
Varner, J. M., J. M. Kane, J. K. Kreye, and E. Engber. 2015. The flammability of forest and woodland litter: a synthesis. Current Forestry Reports **1**:91-99.
Varner, J. M., and C. R. Keyes. 2009. Fuels treatments and fire models: errors and corrections. Fire Management Today.
Vezina, P., and G. Pech. 1964. Solar radiation beneath conifer canopies in relation to crown closure. Forest science **10**:443-451.
Viney, N. R. 1991. A review of fine fuel moisture modelling. International Journal of Wildland Fire **1**:215-234.
Walker, J. D., and B. J. Stocks. 1975. The fuel complex of mature and immature jack pine stands in Ontario. Report O-X-229, Canadian Forestry Service, Department of the Environment, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, Canada.
Weber, M., C. V. Wagner, and M. Hummel. 1987. Selected parameters of fire behavior and Pinus banksiana Lamb. regeneration in eastern Ontario. The Forestry Chronicle **63**:340-346.
Whitehead, R. J., G. Russo, B. Hawkes, S. Taylor, B. Brown, O. Armitage, H. Barclay, and R. Benton. 2008. Effect of commercial thinning on within-stand microclimate and fine fuel moisture conditions in a mature lodgepole pine stand in southeastern British Columbia. Canadian Wood Fibre Centre Information Report FI-X-004, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.
Wotton, B., R. McAlpine, and M. Hobbs. 1999. The effect of fire front width on surface fire behaviour. International Journal of Wildland Fire **9**:247-253.
Wotton, B. M. 2009. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. Environmental and Ecological Statistics **16**:107-131.
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, Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault-Ste.-Marie, Ontario, Canada.
Wotton, B. M., and J. L. Beverly. 2007. Stand-specific litter moisture content calibrations for the Canadian Fine Fuel Moisture Code. International Journal of Wildland Fire **16**:463-472.
Xanthopoulos, G., and R. H. Wakimoto. 1993. A time to ignition–temperature–moisture relationship for branches of three western conifers. Canadian Journal of Forest Research **23**:253-258.
Zhang, P. 1993. Model selection via multifold cross validation. The annals of statistics:299-313.

Appendix A
20th Century Canadian Fire Behaviour Experiments and Experimental Sites, and Modelled Fuel Strata Gap estimates

Sharpsand Creek, Ontario:
Experiments were initiated in the early 1970's at this site north of Thessalon, Ontario and revisited over a 30-year period. This resulted in 27 separate and independent experimental fire observations, more than one quarter of our dataset. The stand consisted of densely stocked jack pine natural regenerated on gravelly soil (Walker and Stocks 1975) following the spring 1948 Mississagi fire (Stocks and Walker 1973). The dense stands in the earliest burns featured over 9000 live stems/ha and over 10,000 dead stems/ha as the stand underwent rapid stem-exclusion. Results from the earlier fires (1975-1981) were published in Stocks (1987) and included in the empirical derivation of the C-4 fuel type model (FCFDG 1992); these were also analyzed separately by Van Wagner (1993); see Figure 1b and 1c. Results from the later fires (1988-1991) were not included in the FBP System analyses and were fully documented only recently (McRae et al. 2017). The stand characteristics associated with the later burns highlighted significant structural and successional changes underway as stands evolved: the dense immature forest was rapidly self-thinning, from 9,276 live stems/ha and BA of 18.6 m^2 at the time of the original experiments (measured in 1973) to less than half the live density (4,375 stems/ha) and 53% more BA in 1984 (McRae et al. 2017). During the course of the earlier burn experiments, it was discovered that a portion of the plots had been hand-thinned in 1960 (Stocks 1987; B. J. Stocks, personal communication Jan. 2020), substantially affecting the stand structure. While these thinned stands were the same age and site characteristics as the denser C-4 stands, the burns in the thinned plots had been considered more representative of mature pine stands and previously included in the FBP System C-3 fuel type dataset (B. Stocks, personal communication 2020).

Between all years and stands, the Sharpsand plots exhibited a wide range of fuel structure characteristics influencing fire behaviour. With fire weather conditions varying greatly between burns, the associated fire behaviour characteristics and types of fire also ranged across several orders of magnitude in intensity – from slow surface fires near the ignition threshold to intense active crown fires spreading near 50 m min^{-1}. Burns were conducted in 1974-1976, 1981, 1988, 1990-1991; thus, at post-fire ages 26-43. Ignition dates ranged from 25 May to 15 July, coded as SP (2 fires), SST (6 fires) and SU (19 fires) for mc_{SA} calculations. The Sharpsand burns were grouped into 3 categories on the basis of pre-burn structure: the 13 observations in the original densely stocked immature stands, burned from 1975-1981 and described by Stocks (1987) (Sharp-IM); the 6 thinned stands, burned from 1974-1981 (Sharp-TH); and the 8 later semi-mature burns, from 1988-1991 and described by McRae et al. (2017) (Sharp-SM). A summary of fire weather and behaviour characteristics on one of the Sharp-SM burns was previously published in a wall poster (Stocks and Hartley 1995), identified as 'Experimental fire #3/91'; this is the same fire as No. 21 from McRae et al. (2017). For 'fire type' in the Sharp-SM burns, rather than using previously published descriptors, McRae et al. (2017) classified fire behaviour as 'Surface', 'Crown', 'Some Torching', or 'Torching'. Based on descriptions in the text and discussion with the report's co-authors, we considered the latter 2 classes to be consistent with passive crown fire (Van Wagner 1977) and coded them appropriately in our database. For purposes of the mc_{SA} density classes, the heavily overstocked Sharp-IM stands were classed as 'dense', while Sharp-TH and Sharp-SM stands were classed as 'moderate' on the basis of photographs and calculated stand structure. For the Sharp-SM burns, depth of burn (DoB) and total fuel consumption were published, but for crown fires, this value included contributions from crown fuel consumption. We used the DoB and TFC from the experimental burns and related point ignition experiments, the latter being independent data from the same site, to estimate SFC as a function of DoB. This gave the relationship shown in Figure A1, which was used to estimate SFC from DoB on crown fires.

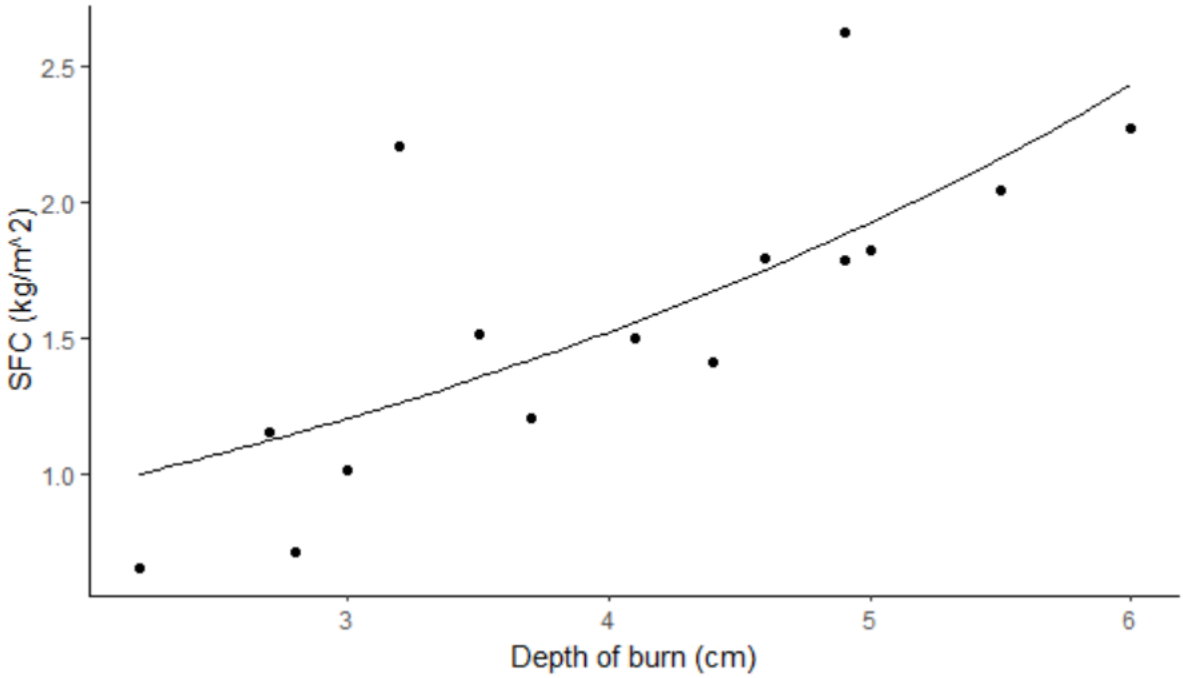

Figure A1. Depth of burn – surface fuel consumption (SFC) relationship for the semi-mature stands at Sharpsand Creek, Ontario. The curve represents the fitted line $SFC = 0.59505 \cdot (e^{DoB})^{0.23445}$, with units as indicated.

Previously unpublished field notes for the Sharpsand site (Sharp-IM and Sharp-TH) were located at the Great Lakes Forestry Centre (Sault Ste. Marie, Ontario, Canada) and analyzed to describe the forest structure at the Sharpsand site. These included detailed structure data from several trees measured for biomass and structure at the site in 1973-74 as well as forest cruise data (stand density by diameter class) from most experimental plots. We used these data to develop simple regression models of DBH-height for live and dead trees and then estimate LCBH values from average DBH values at the plot level. The biomass trees at Sharpsand Creek consisted of measurements of 33 live and 9 dead trees across a range of sizes in order to produce models of height and LCBH based on DBH (Figure A2, below). In the live tree sample, crown ratio (CR) was marginally significantly related to DBH (Pearson's correlation: p=0.075). We assumed this was a real effect and modelled CR as a linear function of DBH; this gave a CR range of 0.39-0.48 for trees from 2-12 cm DBH.

After some consideration of curve-fitting or other published tree models, we used a published mixed-effects modelling approach combining published empirical species curves with local site calibration. Sharma and Parton's (2007) models based on Ontario permanent sample plot data uses the sigmoidal Chapman-Richards curve between DBH and tree height along with parameters for basal area and tree density to account for stand structure and competition effects. The random effect in the model is a parameter representing site quality characteristics and can be fitted using as few as one single tree measured in the site of interest. For our present purposes, we used the live biomass tree data to estimate cohort height using the following relationship (Sharma and Parton 2007):

$$h = 1.3 + (\theta + u) \cdot SHT^{\delta} \cdot (1 - e^{-\beta \cdot \left(\frac{TPH}{BA}\right)^{\varphi} \cdot DBH})^{\gamma} \qquad [A1]$$

SHT, *TPH*, *BA*, and *DBH* represent stand height (from dominant and co-dominant trees), density (trees per ha), basal area, and diameter at breast height, respectively, and the 1.3 constant represents 1.3 m height (h) at 0 DBH; θ, β, γ, and φ are published species-dependent model parameters. The 'u' term is the site-dependent random variable. Stand height in this context represents the average of all dominant and sub-dominant trees in a given stand. Using published values from Walker and Stocks (1975) and Stocks (1989) along with the biomass tree dimensions, the ‘u’ value was significant (0.14, P =0.0004) in an overall height-DBH model for the site (Figure A2). This value was then used to estimate heights for all cohorts in the experimental plots (Sharp-IM). Using the CR function described above produced the model for estimating LCBH. The standing dead trees, previously noted as an important component of the fuel complex, were modelled using a simple linear height-DBH model (Figure A2).

Estimated LCBH values in the Sharp-IM plots ranged from 4.13-4.44 m (mean: 4.28 m), representing measurements taken in 1974 (Walker and Stocks 1975). These values are in line with previously published estimates for this site of 4 m (Van Wagner 1993, Cruz 1999). One additional point of change was made to account for the varying burn years. As discussed by McRae et al. (2017), stands at Sharpsand Creek were changing rapidly as they underwent self-thinning, with measurable changes between the first measurements (1974) and subsequent measurements in 1984; a decade after the initial measurements, LCBH had increased by 1 m (from 4.3 m to 5.3 m; McRae et al. 2017). The latter measurements were considered by the authors to be more representative of the Sharp-SM experiments (1988-1991). However, due to a range of burn years (see Table 1), the Sharp-IM and Sharp-TH burns also included plots burned in 1981, closer to the date of the second measurement. To account for some of this change, we added 0.5 m to the estimated LCBH for the 1981 burns, these being temporally halfway between the two measurements dates. As discussed in the main text, due to the high density of standing ladder fuels, the FSG at this site was adjusted from the simple LCBH using various adjustments during the modelling process.

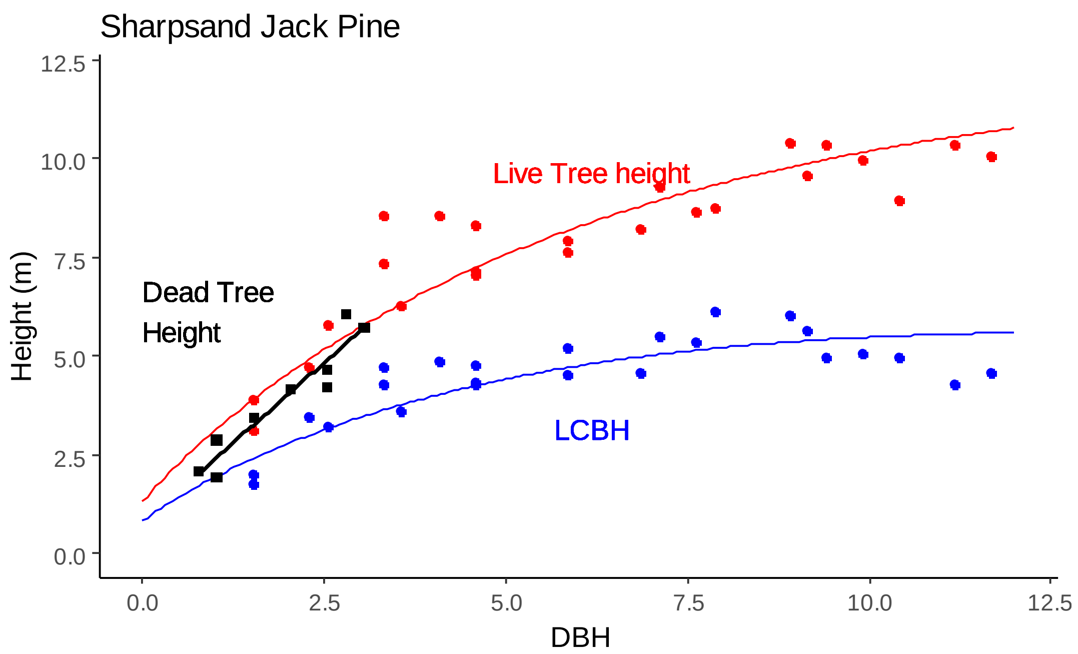

Figure A2. Biomass tree data and models from Sharpsand Creek: height-DBH data and model (red points and line), LCBH data and model (based on a low-slope increasing crown ratio model: blue points and line); and dead tree data and linear fit (black points and line). For estimating dead tree height, the linear model was used for DBH < 3 cm and the live tree height model was used for DBH ≥ 3 cm.

Kenshoe Lake, Ontario
The experiments at Kenshoe Lake, near White River, Ontario, represented the other significant Ontario burn project during the 1970's and 1980's (Stocks 1989) and provided a significant portion of the 'mature jack pine' (C-3 fuel type) dataset in the FBP System (FCFDG 1992). Stands at Kenshoe Lake were approximately 74-84 years old at the time of burning (1973-1983), and consisted of a mature overstory of jack pine, with dominant trees 15-20 m in height, over a well-developed understory of black spruce, described as 1-13 m in height (Stocks 1989; Figure 1f). For the stand-adjusted litter moisture model (mc_{SA}), the Kenshoe Lake burns included spring, transition, and summer season fires, between 17 May and 08 July. Kenshoe stands were classified as 'dense' for mc_{SA} purposes on the basis of high canopy fuel load and stand photographs showing evidence of dense, multi-storied stands with little light penetration to the forest floor.

As with the Sharpsand stands described above, original stand survey data from Kenshoe Lake were used to develop a model to estimate LCBH for the overstory jack pine based on local tree data, as well as a DBH-height model for the black spruce understory. In contrast with Sharpsand Creek, the crown ratio of the mature jack pines in the biomass sample was not variable across the range of DBH (Pearson's correlation: p=0.336; Figure A3). Therefore, LCBH was modelled assuming a constant crown ratio of 0.3405.

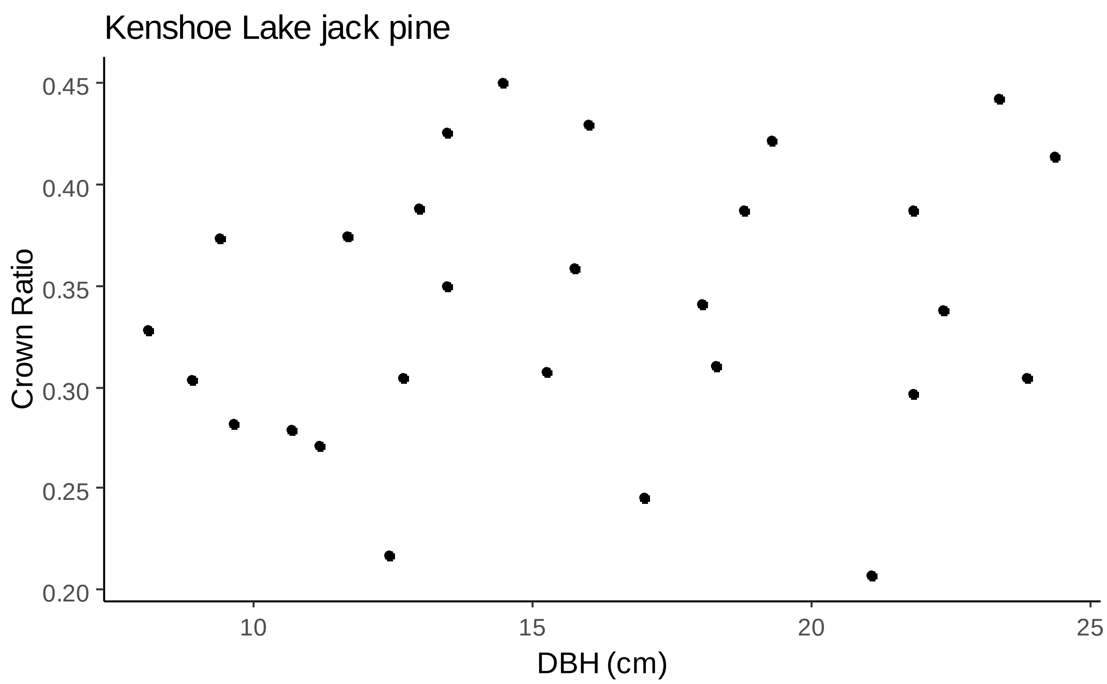

Figure A3. Crown ratio in the Kenshoe Lake overstory jack pines (mean: 0.341) did not vary significantly by DBH (α=0.1).

Similar to the Sharpsand, we parametrized the Sharma and Parton (2007) model to the biomass tree sample to account for local site quality. This was done separately for the overstory jack pine cohorts and understory black spruce, the latter assembled from both sapling and mid-story samples (Figure A4). The 'u' parameter was significant for spruce and marginally significant for pine (pine: 0.028, P=0.067; spruce: -0.489, P< 0.0001). As described above, approximate stand average values (height, density, basal area) were used with the site parameters to develop height-DBH functions, which were then used to estimate values for individual burn plots (Figures A4 and A5).

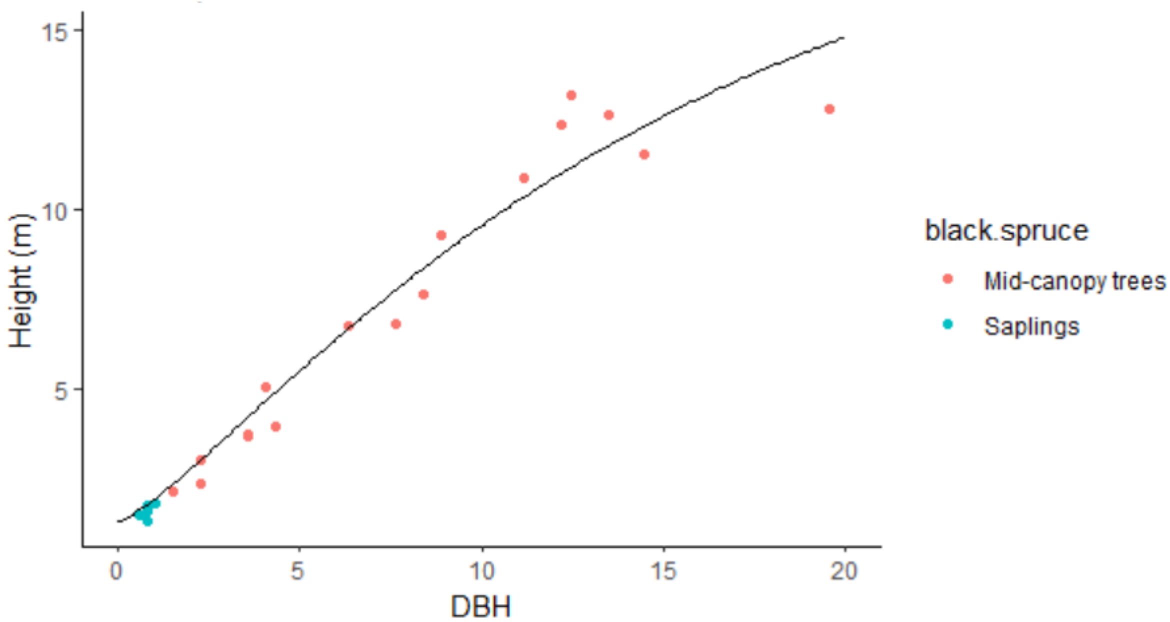

Figure A4: DBH-height relationship for black spruce at Kenshoe Lake, Ontario, based on biomass tree samples from saplings and mid-story trees and the Sharma and Parton (2007) mixed-effects height model.

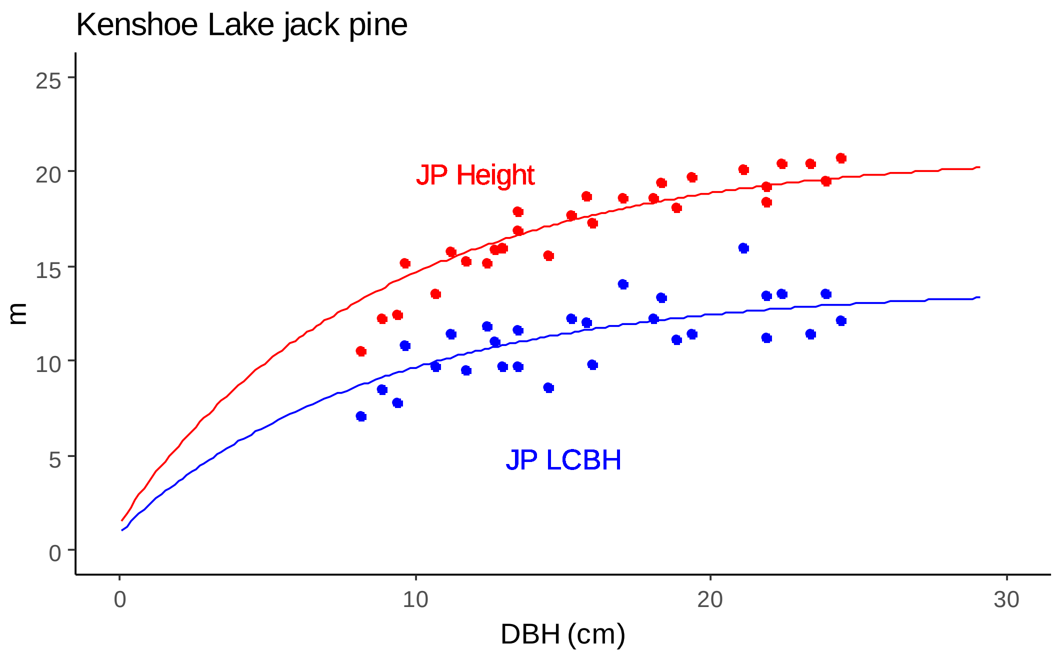

Figure A4. DBH-height and DBH-LCBH relationships for overstory jack pine, Kenshoe Lake.

Estimated pine LCBH values for the experimental plots based on the local stem-weighted model ranged from 10.2-11.0 m (mean: 10.4 m). As noted in the main study text, black spruce LCBH was not measured, but estimated to be 2 m for all plots as in previous studies. Also noted previously, crown fire 'events' in these stands (for the main model fitting) were considered separately for involvement of the mid-story spruce and overstory pine strata; FSG represented the mean distance between the spruce crown centroids and pine LCBH in each plot (see Figure 3). Thus, the key crown fuel structure measures include the spruce LCBH, spruce stratum heights and spruce-pine FSG. The variability in these measures is shown in Figure A6 for all 12 experimental plots. Spruce cohort heights (based on tree density-weighted mean) ranged from 5.4 to 7.8 m. Pine cohort heights (density-weighted) ranged from 15.3 to 16.7 m, although not included in the crown fire initiation model.

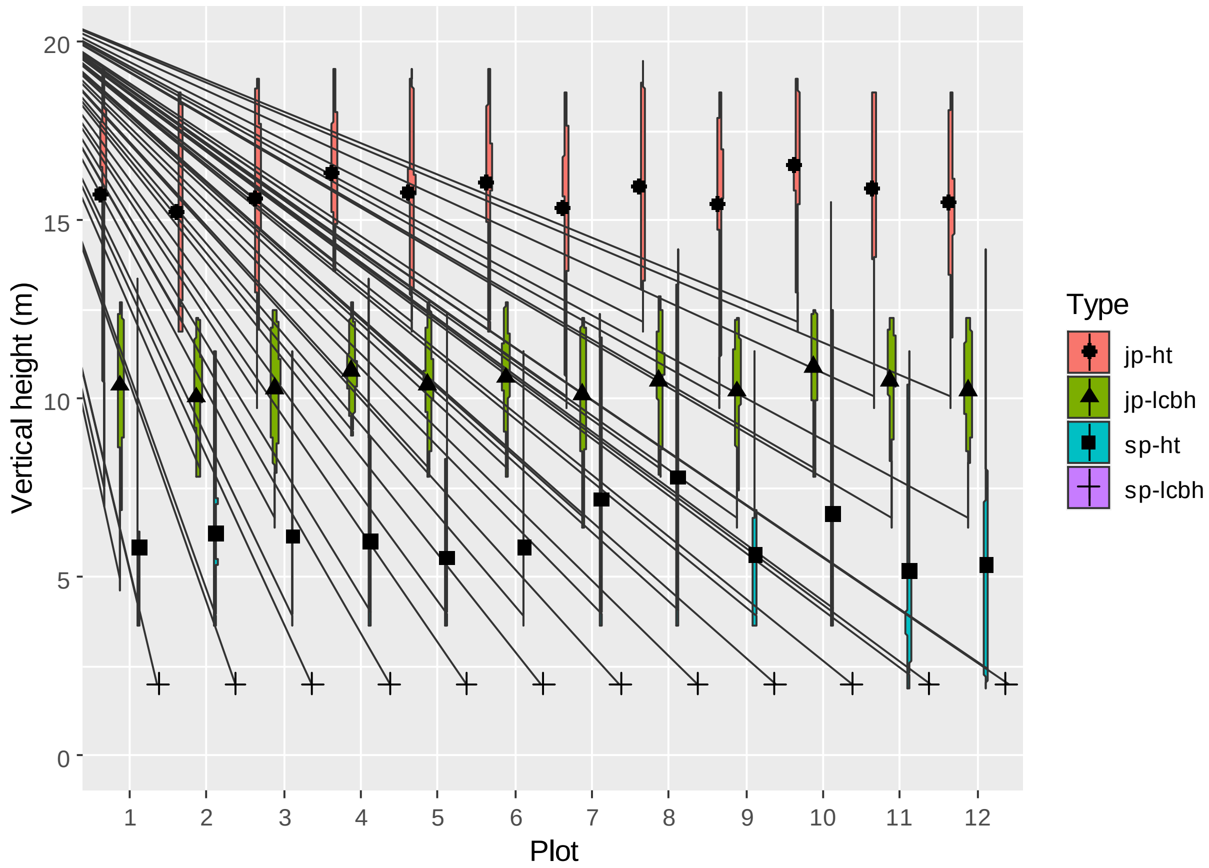

Figure A5. Overstory crown structure and variability of the 12 experimental plots at Kenshoe Lake. 'Type' symbols refer to jack pine (jp) or black spruce (sp), and stand height (ht) or live crown base height (lcbh); symbols show the stem density-weighted mean for each measure of crown fuel structure. Black spruce LCBH was not measured, so assumed to be 2 m for all plots, as discussed in text.

Darwin Lake, Alberta

Seven summer burns (23 July-06 August) were conducted in 1974 (Figure 1d) in jack pine-lichen stands in the western boreal shield landscape north of Fort Chipweyan, Alberta (Quintilio et al. 1977, Alexander and De Groot 1988). All completed burns were included in the present analysis: plots 1, 2, 3, 4a, 4b, 6, 7. These plots represented two stand types: an older structure described as 'old growth', with an overstory of open mature pine (mean density: 655 ha^{-1}), 13-14 m mean height (plots 1, 2, 6, and 7); and a younger and denser (mean density: 2189 ha^{-1}) pine structure, with ~10 m stand height (plots 3, 4a, 4b).[5] Despite the differences, basal area was similar between both stand types (14 - 19 m^2 ha^{-1}). We estimated the LCBH in these stands using the data from the destructive sampling conducted at the site, published in a separate document (Alexander et al. 1991, Table 4). Due to the small number of biomass trees measured (N=10) and the limited range of heights (7.9–12.4 m), we measured dominant tree heights off of 3 trees from a site photograph (the cover image from Alexander and DeGroot 1988). Although imprecise, this provided some important additional observations. The three additional estimates were as follows: (1) DBH: 28.4 cm,

[5] In Quintilio et al. (1977), the younger and older stands are described as 12 and 19 m tall, respectively. However, those heights represented only canopy dominant and sub-dominant trees; we estimated mean overstory heights in experimental plots to be significantly lower.

ht: 16.0 m; (2) DBH: 27.8 cm, ht: 16.0 m; (3) DBH: 33.9 cm, ht: 17.0 m. Relationships between height and DBH and between height and crown length were fitted, and ultimately a log(DBH) model was selected, with both a realistic curve shape and the best fit to the data (Figure A8#). This model was then used along with published mean DBH values from each burn plot (Quintilio et al. 1977) to estimate LCBH at the plot level. This resulted in the following final estimated stand height and FSG (same as LCBH for this site) ranges: 10.0-10.5 m (FSG: 4.7-4.8 m) and 12.8-14.2 m (FSG: 5.8-6.4 m) in the younger and older stand types, respectively.

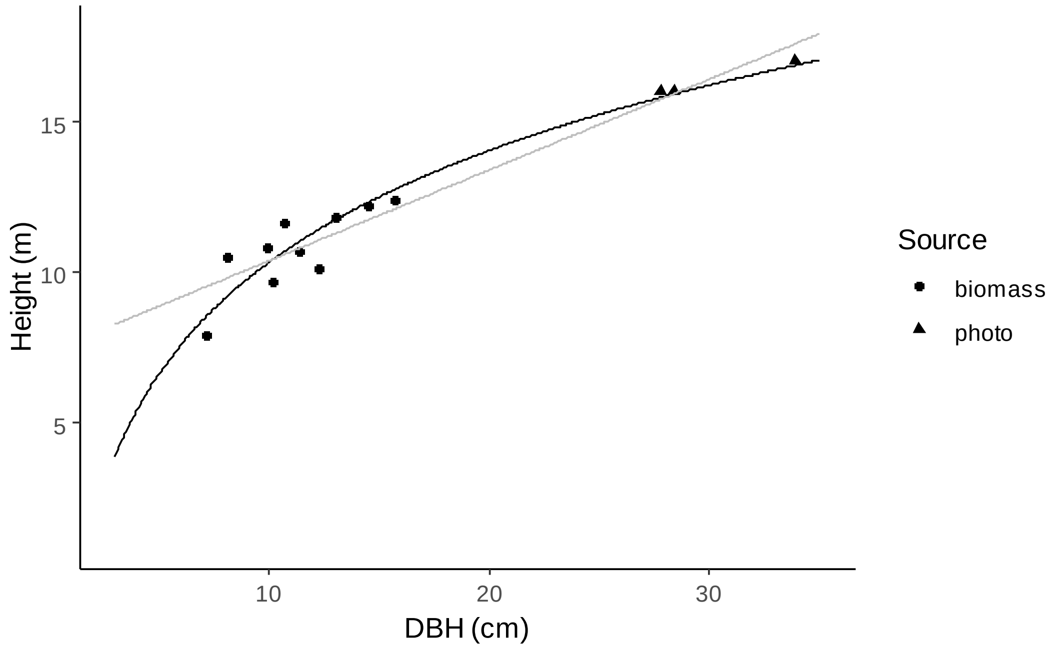

Figure A8#. Fitted DBH-height relationship for jack pines at Darwin Lake, Alberta. The log-model performed slightly better (black; R^2=0.931) and appeared more realistic for estimating burn plot heights than the linear model (gray; R^2=0.917).

Additional parameters for mc_{SA} calculations were as follows: season was 'summer' based on Julian date and stand density was 'low' for all burns, based on the stated 40-50% stand closure described by Quintilio (1977) for both stand types. As with the majority of observations, FWI components, fuel consumption and type of fire were unchanged from primary source documents.

Petawawa National Forestry Institute (PNFI), Ontario

The PNFI site in the Ottawa river valley provided the setting for the earliest experimental burns related to fire behaviour research in Canada. Pure jack pine (JP) (Hummel 1979, Weber et al. 1987), red pine (RP) (Van Wagner 1968), and white and red pine (WRP) (Van Wagner 1963, Van Wagner 1972) stands were burned starting in the early 1960s and used to develop Van Wagner's (1974a, 1977) theories and models on crown fire, in addition to several studies on fire effects. Although not an experimental burn, we add to this group the two distinct stand structures burned in the 1964 Gwatkin Lake wildfire, which was well-described by Van Wagner (1965, 1977) and occurred very close to the PNFI, in stands very familiar to that author.

Fuel characteristics and fire behaviour details were not documented in these early experiments as thoroughly as later projects and consequently few stand structure details are available at the plot level. The PNFI jack pine burns ('602' stands) were small (38 × 38 m, or 0.145 ha) plots within a 50-year-old stand on level sandy terrain noted for its 'great uniformity' in structure and substrates (Weber et al. 1985). LCBH for these plots were estimated using the forest structure measures from Hummel et al. (1979) and the McAlpine and Hobbs (1994) jack pine model, the latter which was derived from local PNFI stand data and therefore expected to be quite representative. Final values ranged from 8.2 to 8.5 m, very close to Cruz's (1999) estimated LCBH estimate of 8.5 m for all plots at this site. LCBH was 6 m for the shorter and more open 'SC Corner' burn (Van Wagner 1977). The red pine units (Figure 1a) were small square (23-30 m sided) plots described as 14-15 m in height, with LCBH of 7 m on most plots (Van Wagner 1977), with 8 m LCBH assigned to the latter two 1967 burns (Van Wagner 1968). The red pine plots were notable for their high crown fuel load (1.8 kg m^{-2}; FCFDG 1992, Cruz 1999) and sparsely vegetated, heavily-shaded understory; they were accordingly assigned to the 'dense' stand category for the purposes of mc_{SA} calculations.

The red and white pine experiments in the early 1960s required some assumptions and estimates for our purposes. The 1960 burns in this group were described by Van Wagner (1963), and include two main stand types among the experimental blocks: Block I, which had been partly harvested and was quite open (mean DBH 20.6 cm, basal area 8.0 m^2 ha^{-1}) and Block II, older and more fully stocked (mean DBH 34.8 cm, BA 23.0 m^2 ha^{-1}); some of these are also clearly part of the data used in Van Wagner (1972) studying post-fire effects, with little information pertaining to fuel structure at the time of ignition. We used Holdaway's (1986) crown ratio models, based on basal area and DBH, to estimate LCBH, and therefore FSG, for these stands using stand heights from Van Wagner (1963): this produced FSG estimates of 8.5 m and 12.0 m for Blocks I and II, respectively. The 1963-64 fires are contained in the FBP database (unpublished files held by Can. For. Serv.) and originate from the same stands described in the earlier paper. For these later burns, we used the average stand structure characteristics of Blocks II and III (mature, uncut stands): DBH 36.1 cm, BA 23.0 m^2 ha^{-1}, height 25.8 m; this yields an estimated LBCH and FSG of 12.5 m. These values are generally in line with the stand descriptions and reconstructions in Hummel (1979). However, these estimates rely on generalizations and assumptions and may be inaccurate.

Bigfish Lake and other AB black spruce experiments

The Bigfish Lake experiment (Figure 1e), along with 3 prior black spruce experimental fires from the 1970s (Kiil 1975, Newstead and Alexander 1983), were designed to study fire behaviour in boreal black spruce stands of northern Alberta. The Bigfish Lake study has never been formally published, but its observations were incorporated into the FBP System (FCFDG 1992) and several subsequent analyses (e.g. Cruz et al. 2004, Cruz et al. 2005). Lowland stands of the black spruce-Labrador tea (*Ledum groenlandicum*)-*Cladonia* vegetation type, common across the western boreal forest, are considered the most hazardous variant of the FBP System C-2 fuel type, and consequently one of the most volatile stand types in the country. Previously published photographs from Bigfish Lake show select examples of vegetation structure and fire behaviour (Hirsch et al. 2000) as well as plot layout and experimental design (Alexander and Quintilio 1990). Burn dates across all black spruce studies ranged from 11 July through 17 August, considered early summer through midsummer at that latitude. LCBH and FSG values for the early experiments were reported by authors at 1.4-1.9 m (Kiil 1975, Newstead and Alexander 1983). LCBH for all Bigfish Lake plots were calculated for this study at the plot level, based on unpublished data (from author MEA) collected from sampling a 2 m wide strip outside the perimeters of individual burn plots (N=987); this was done in order to avoid trampling the fuels prior to ignition.

These open stands are characterized by low LCBH values, with a range from 0.4 – 1.9 m (mean 1.1 m) among all boreal spruce plots. With low tree heights, open structure allowing direct sunlight to the forest floor, and low crown fuel loads (0.8 kg m^{-2}; FCFDG 1992), these stands were assigned the 'light' density class for mc_{SA} purposes.

Prince George (Summit Lake), BC
Eight experimental headfires (Figure 1i) were conducted in June and July 1970 in sub-boreal lodgepole pine stands north of Prince George, BC (Lawson 1972). Among the various ignition types (point fires, backing fires, etc.), we only considered the 'strip headfires' in the present study (line ignition at windward edge), in keeping with the remainder of the dataset. Thus, four burn experiments were conducted in a dry pine site with a slight southerly aspect and mean stand height of 20.4 m, and four with a slight northerly aspect and 14.6 m stand height; LCBH for the two sites was reported as 9.8 m and 6.7 m, respectively. Despite a BUI range of 47-79 (mean: 69), this site featured the lowest of all surface fuel consumption values (mean SFC: 0.57 kg m^{-2}), a reflection of low forest floor fuel loading and sparse woody debris.

Fires in the taller, southerly stand were conducted from 17-20 June (classed as spring), while those in the shorter stand were conducted from 05-14 July, considered summer at this location. All burns were identified as surface fires; although some isolated torching was observed, it was limited to 1-5 trees per plot (Lawson 1972, Table 10). Due to the open, park-like stand structure and very low estimated crown fuel load (CFL: 0.59 $m^2 \cdot ha^{-1}$) of the shorter stand type, these burns were classed as 'light' density for purposes of the mc_{SA}. The taller stand type was slightly denser and had a higher estimated CFL (0.72 $m^2 \cdot ha^{-1}$), placing it structurally more similar to the majority of stands in our study; consequently, these plots were classed as 'moderate' density for mc_{SA} purposes. CFL estimates for these stands were based on the Cruz et al. (2003a) lodgepole pine model using height and basal area values from Lawson et al. (1972).

International Crown Fire Modeling Experiment (ICFME), NWT
The ICFME experimental fires (Figure 1g) were conducted between 1997 and 2000, a series of June-early July burns in dense jack pine-black spruce stands near Fort Providence, NWT. These experiments have been thoroughly documented in several technical publications (Alexander et al. 2004, Stocks et al. 2004, etc.). The eleven observations described by Stocks et al. (2004) are included in our database, including two data points from one burn (plot 8), which resulted from a significant change in wind magnitude mid-plot. The fuel structure has been described as well-stocked overstory (4110 ha^{-1}) of jack pine (70%) and black spruce (30%), 10-12 m overall mean stand height, with a dense mid-story and understory of black spruce. Detailed stand measurements and structure diagrams permit a more thorough description of the canopy fuel strata in individual experimental plots. As noted previously, in the main training database, FSG represented only the LCBH of the mid-story black spruce for most plots, termed overstory spruce in Alexander et al. (2004). As part of the test data, the FSG represented the distance between the spruce centroids and pine LCBH. The mid-story spruce stratum was absent for plots 3 and 4, so those observations were only used in the training data set (with pine LCBH as FSG). Relevant plot-level data were taken from Alexander et al. (2004), Table 12. Combined overstory LCBH values varied between 3.6 m and 8.2 m, while understory heights varied from 1.0–1.9 m; resultant FSG values ranged from 2.3–7.7 m. Vertical fuel profiles for each plot and aggregated are shown in Alexander et al. (2004: Figures 12, 13). Clearly, LCBH and FSG values calculated in this way are a

simplification of what are two separate canopy layers in most plots, a canopy dominant overstory of jack pine with a mid-story of black spruce that extends to the seedling layer.

Porter Lake, NWT
Six burns and one escaped wildfire, a total of seven observations, resulted from one productive week in 1982 in the black spruce-lichen woodlands of the southern NWT (Alexander et al. 1991). These burns were ignited from 30 June to 07 July 1982, considered spring at this latitude, temporally close to the time of estimated peak flammability. These stands are structurally unique compared to the other vegetation types in this study, being much more open, with very dense tree clumping interspersed with very exposed *Cladonia* sp. lichen-covered openings (Alexander and Lanoville 1989). Trees were short (mean height of spruce cohorts: 4.1-5.6 m; some jack pine cohorts as high as 7.6 m), but with moderate total stem density due to clumping (mean density: 1235 ha^{-1}). Due to the very open structure and low canopy fuel load (burn plot mean: 0.76 kg m^{-2}), these stands were classes as 'light' density for mc_{SA} purposes. Mean LCBH on each plot was measured prior to burning (range: 0.8 – 1.1 m) and these values were used unchanged for FSG. The mc_{SA} was used to estimate litter moisture in these stands as in the remainder of the study; however, due to the unique moisture absorption and adsorption properties of the lichen understory (ref#), the mc_{SA} (like the FFMC) was not expected to be particularly representative of moisture content of the dominant surface substrate (live lichen) in this fuel type.

Appendix B
Surface rate of spread model

Most of this study was not focussed on spread rate. However, as noted previously (Perrakis et al. 2020), a surface ROS model can readily be fitted to empirical observations as part of a dynamic conifer fire behaviour modelling system. We used the surface fires in our data to fit some simple ROS models for operational use, using wind speed and mc as predictors as well as ISI. Backwards stepwise regression was used for all model building.

Surface fire spread ranged from 0.4 up to 12.0 m min^{-1}, with most fires' ROS values well below the maximum value (95th percentile ROS of 4.7 m min^{-1}). Best-performing surface ROS models included squared terms for ws and mc as well as an interaction term (all terms significant at α = 0.05):

$ROS = 5.7422 + 0.02487 \cdot ws^2 + 0.06183 \cdot {mc_{SA}}^2 - 1.1592 \cdot mc_{SA} - 0.0001333 \cdot ws^2 \cdot mcSA^2$, adj. R^2 =0.521; [A2]
$ROS = 3.4205 + 0.03217 \cdot ws^2 + 0.05401 \cdot {mc_{FFMC}}^2 - 0.8636 \cdot mcFFMC - 0.000175 \cdot ws^2 \cdot {mc_{FFMC}}^2$, adj. R^2=0.554 [A3]
$ROS = 4.1985 - 0.8975 \cdot ISI + 0.06753 \cdot ISI^2$, adj. R^2 =0.663 [A4].

The drawback to the mc_{SA} and mc_{FFMC} models (Eq. A2 and A3) is some illogical behaviour at low wind speeds and high moisture contents, as shown in Figure A8#, below. Alternative tests with models that included other variables such as SFC, density (from mc_{SA}), FSG, or DMC were non-significant or had worse performance than the models shown above. Unfortunately, we could not perform a validation exercise using these ROS models on our test dataset, since it only included 3 surface fires with ROS data (all from Archer Lake).

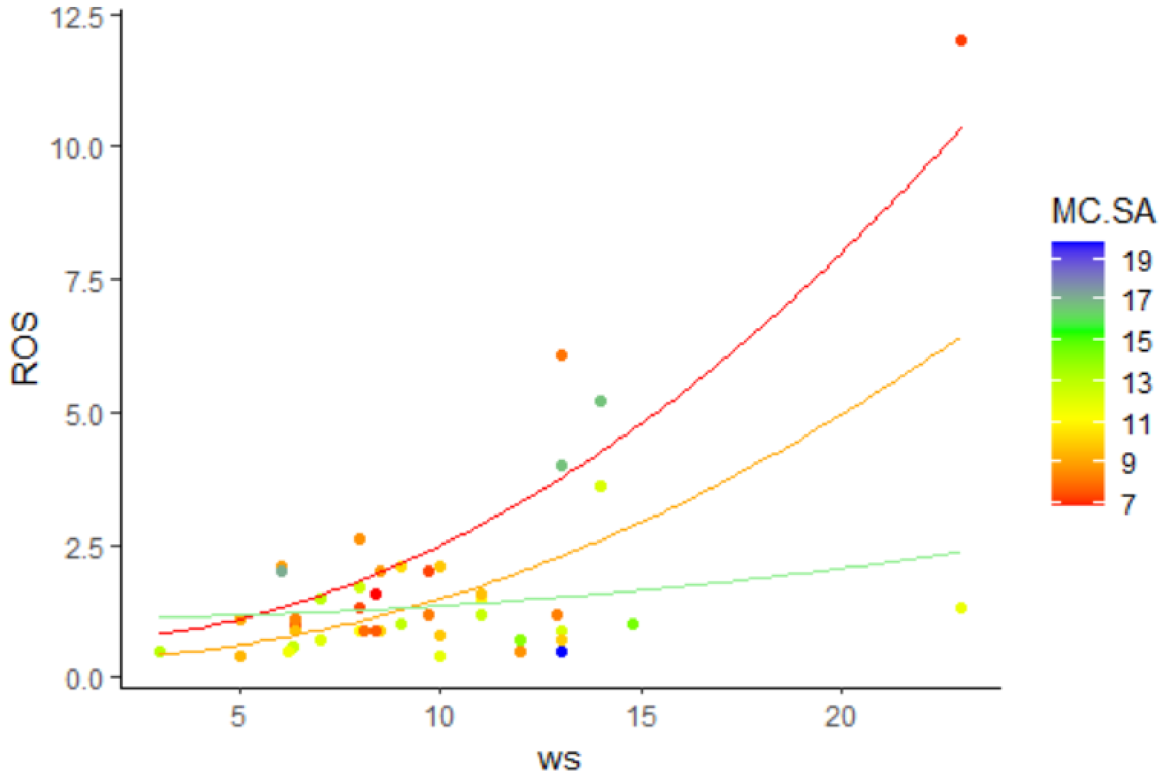

Figure A8. Surface ROS model based on wind speed (km/h) and mc_{SA} (Eq. A2). Fitted lines are calculated at mc_{SA} values of 7, 10, and 13 % (red, orange, green, respectively).

Note that equations A2 and A3 each had two fires with high Cook's distance values (> 1), indicating observations with disproportionate influence on the model. These observations were the jack pine portion of the Gwatkin Lake fire and one of the Red and White pine fires from Petawawa, the two surface fires with ws > 20 km/h (Figure A8#). Similar to the crown fire initiation models, the ROS models would benefit from validation from additional surface fires in conifer stands at higher wind speeds; in order to remain surface fires, these would require some combination of high FSG, high mc or low SFC.

In addition, fire weather-ROS relationships were also closely related to the type of fire. Among our experimental fire observations, ROS for passive crown fires ranged from 2.6 to 15.8 m min^{-1} while active crown fire ROS ranged from 7.5 to 69.8 m min^{-1} (Figure A9#). Figure A9# also shows the range of ROS by wind speed arranged by fire type, with linear trends for each (surface, passive crown, active crown; Van Wagner 1977), based on assigned fire types in the FBP System database (Cruz 1999).

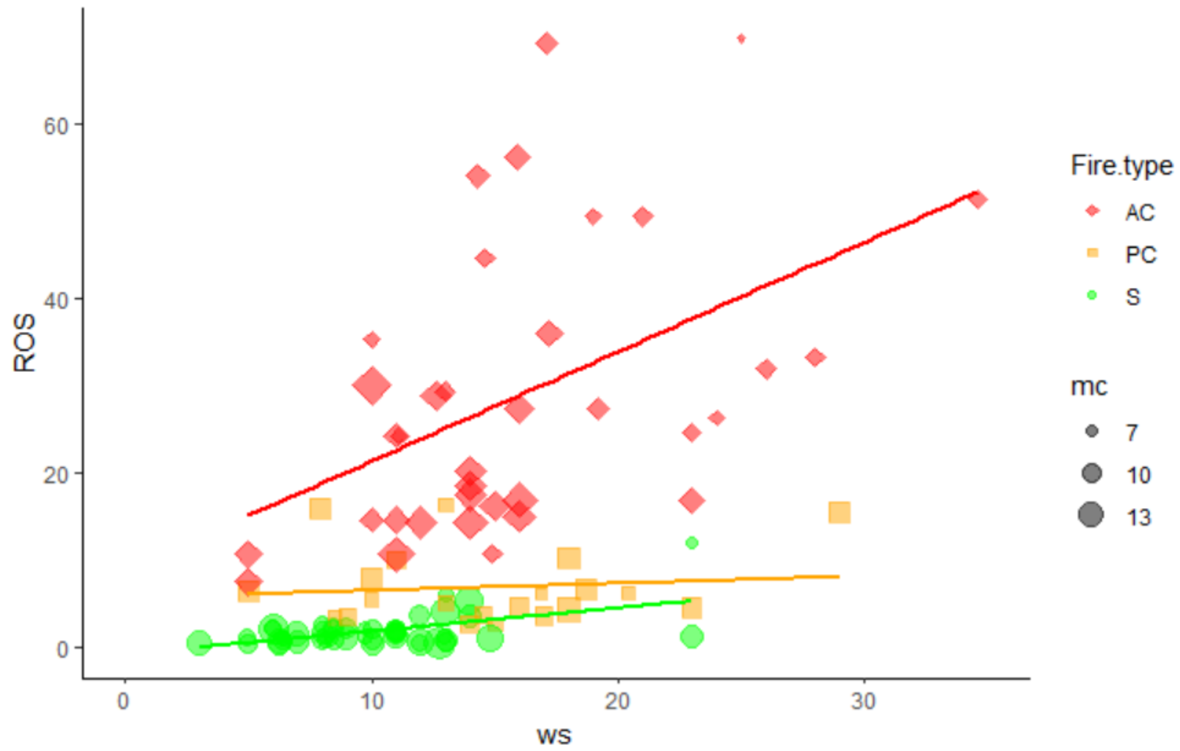

Figure A9. Wind speed-ROS graph, including linear trends by fire type, for the training database of 20th century Canadian experimental fires.

As Figure A9 demonstrates, discriminating between passive and active crown fires would clearly be a useful process in predicting ROS. These processes are out of scope for the present project, but we can refer to the CFIS studies and other papers on this topic for further guidance (Cruz et al. 2005, Cruz and Alexander 2019). However, we also noted some inconsistencies in how fire type was defined in the original observations; additional efforts to tidy up these records are warranted here prior to further analyses.