Simple models for conifer surface fires

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## Abstract

Fire behaviour in conifer forests is often equated with predicting crown fire activity, though surface fire spread is more frequently encountered. Surface fire models can help predict fire behaviour under low to moderate fire danger conditions or in forest stands with a high crown base. We used a database of conifer-dominated experimental surface fires to fit simple empirical models of rate of spread (ROS) under light-to-dense canopy stands that can be readily integrated within operational decision support systems. Final models include the Canadian Initial Spread Index (ISI) along with a stand-adjusted version (ISISA) as predictors, along with estimated surface fuel consumption (SFC). While imprecise, these models are usually accurate enough (within +/- 2–4 m min-1) for many forecasting and fire management purposes.

### [Process - get SF data]

### [Proc. SF models and PPDF]

### [Complex modelling attempts]

### [graphs and functions]

## 1. Introduction

The rate of spread, or rate of forward advance, of a wildfire is probably its most important descriptive characteristic for fire managers (Van Wagner 1965b, Sullivan and Gould 2020). Fire behaviour in the conifer forests of Canada is often a story about crown fire – high intensity, rapidly spreading fires with flames overtopping the trees and ember spotting ahead of the front (Alexander and Cruz 2016). And yet in the chronology of fire events, most days between ignition and extinction feature only ground or surface fire behaviour (Wang et al. 2014). Surface fires can often be safely and routinely actioned by suppression crews and equipment (Wheatley et al. 2022), and managers need to be able to estimate the speed and intensity of fires even when crown fire activity is unlikely.

### Surface fire spread in the Canadian Fire Behavior Prediction System

Surface fire spread models have not been the primary focus of past Canadian fire behaviour modelling efforts, though they have made appearances. The present Fire Behavior Prediction System (FBPS) features fuel-type specific models encompassing the full range of surface through crown fire behaviour for a small number of conifer fuel complexes (Forestry Canada Fire Danger Group 1992, Tymstra et al. 2010). Thus, the majority of conifer ROS models do not discriminate between surface and crown fire behaviour but rather assume a gradual transition between fire types; a deliberate decision discussed by Van Wagner during the system’s development (Van Wagner 1989). However, more recent and flexible conifer modelling schemes exist that are specific in terms of the type of fire predicted under given weather and moisture inputs; these include CFIS (Crown Fire Initiation and Spread), Conifer Pyrometrics, and the forthcoming ‘next generation’ Fire Behavior Prediction System (Alexander et al. 2006, Perrakis et al. 2020b, CFS Fire Danger Group 2021). These models beg the question of what fire behaviour to expect (ROS, fire intensity, etc.) when crown fire behaviour is not predicted to occur. Pure surface fire models do exist in the FBPS for fuel complexes that do not exhibit crown fire behaviour: deciduous forests, open (treeless; i.e. grassland) communities, and scattered logging slash, in the form of the D-1, O-1 and slash (S-1 through S-3) fuel types, respectively (Forestry Canada Fire Danger Group 1992). As with the conifer fuel types, surface fire spread rate equations for these fuel types are based on the Chapman-Richards function (Van Wagner 1989):

[1],

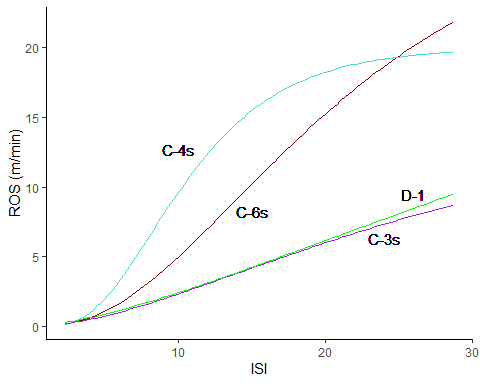
with the a, b, and c parameters assigned or fitted for each fuel type, and *ISI* representing the Initial Spread Index from the Fire Weather System (Van Wagner 1987). Newer models have also been developed for grass (Wotton 2009, Kidnie and Wotton 2015) and atlantic shrublands (Pepin and Wotton 2020). A few models were previously published for predicting surface fire spread in conifer stands based on sparse observations at individual research sites (e.g., Lawson 1972), but these data were eventually incorporated into the broader-scope FBP fuel type functions.

### CE Van Wagner’s surface fire models

As the FBP System was being developed, a more flexible theoretical dual equilibrium conifer crown fire model concept was proposed by CE Van Wagner. This involved a notional function describing the expected rate of spread of crown fires, RSC, as well as a separate function, RSS, representing “all possible surface fires”(Van Wagner 1989), with a crown fire initiation model representing the transition point between the two functions (Van Wagner 1977a). Suggested parameters for the RSS function appeared in the FBPS report in the form of the C-6s model, for the surface fire portion of the ‘Conifer Plantation’ fuel type: *a*=30, *b*=0.080, *c*=3; no explanation was provided as to the origin of these values (Forestry Canada Fire Danger Group 1992). Two additional sets of RSS parameters were published shortly thereafter, associated with surface fire spread in immature and mature jack pine stands in Ontario (Van Wagner 1993). The immature stand was the source of many observations from the C-4 fuel type (Stocks 1987), with the following parameters (“C-4s”): *a*=20, *b*=0.20, *c*=5. Surface fire observations from mature pine stands associated with the C-3 fuel type (Stocks 1989) were used to form another RSS model (“C-3S”): *a*=15, *b*=0.05, *c*=2. Again, no source was given for the origin of these parameters (Van Wagner 1993), and we presently assume they were derived by visual inspection from the limited underlying data. Figure 1 compares these notional conifer surface fire ROS models along with the D-1 model for comparison (*a*=30, *b*=0.0232, *c*=1.6). As the figure shows, as fire danger levels increase (i.e., higher ISI), predicted surface ROS predictions diverge widely between these models, with C3S and D1 curves predicting the lowest and the C4S predicting the highest values, respectively.

### [Fig1]

fig1 <- ggplot(data=s.fires, aes(x=ISI, y=ROS)) +  
 stat\_function(fun=c6s, colour='darkred') +  
 stat\_function(fun=c4s, colour='turquoise') +  
 stat\_function(fun=c3s, colour='purple') +  
 stat\_function(fun=d1, colour='green') +  
 geom\_text(x=10, y=c4s(10)+3, label='C-4s') +  
 geom\_text(x=15, y=c6s(15)-2, label='C-6s') +  
 geom\_text(x=26, y=d1(26)+1, label='D-1') +  
 geom\_text(x=24, y=c3s(24)-1, label='C-3s') +  
 theme\_classic() +  
 labs(y='ROS (m/min)')  
   
  
fig1



*Caption: Figure 1. Comparison of FBP System and associated fuel type surface fire rate of spread (ROS) models. D-1 and C-6S are described by Forestry Canada Fire Danger Group (1992). C-4S and C-3S refer to the surface fire models proposed by Van Wagner (1993) for immature and mature jack pine fires, respectively. ISI refers to the Initial Spread Index (Van Wagner 1987).*

### Objectives

The objective of this study was to use the Canadian database of experimental fires to produce simple and rapid models for estimating the ROS of surface fires burning beneath the canopy of conifer stands. Since fires in conifer stands spreading under higher danger conditions tend to be crown fires (Van Wagner 1977a, Beverly et al. 2020, Cruz et al. 2022), the majority of surface fires involve occurred during moderate-level fire danger indices and wind speeds, or under higher danger conditions in stands with high crown base height (CBH; > 6 m) in a few cases. Such models can be used to inform dynamic fire behaviour predictions sytems, where surface fire, crown fire initiation, and crown fire spread are modelled as separate but related processes (Scott and Reinhardt 2001, Perrakis et al. 2020a, CFS Fire Danger Group 2021).

Previous studies have suggested that wind speed at the ground or flame height level is the most relevant and important predictor of ROS (e.g., Van Wagner 1968, Catchpole et al. 1998). However, this involves detailed studies of wind interactions with fuel structure, including edge effects (Schlegel et al. 2015, Moon et al. 2019), which is seldom available in operational situations. The present models therefore rely only on the standard 10 m open wind speed, as was measured in field experiments and is typically used for wildfire weather forecasts (Lawson and Armitage 2008). This provides a suite of tools that is readily adapted to operational use, but is less accurate due to the significant influence of forest structure, including the effects of edges and openings on ground-level winds (Chen et al. 1999, Ma et al. 2010).

## 2. Methods

### Fire database

The source data for much of the FBPS, including the observations described above, is a slowly growing database of field-scale experimental burns conducted at various sites across Canada since the 1960s. These data have been previously described and analyzed (e.g. Alexander and Quintilio 1990, Cruz 1999, Perrakis et al. 2023), but never before for the purpose of examining generalized surface fire models. The present database contains over 120 conifer observations of experimental fire behaviour in stands of various sizes, but primarily 0.1-1.0 ha (median size: 0.4 ha). All fires used in the present analysis were classed as surface fires in primary literature, though some nuances related to torching and canopy fuel consumption were explored in individual records.

In addition to the boreal conifer data, 32 experimental fire observations were available in deciduous stands. These were originally described by Alexander and Sando (**Alexander.Sando1989?**), featuring fires from the US lake states, Quintilio et al. (1991), and Van Wagner (**vanwagner1973b?**). A small number of experimental fires in Ponderosa pine- Douglas-fir (PPDF) stands in British Columbia were also included; these stands were structurally distinct from the boreal conifer sites and analyzed somewhat differently (see Box 1). Some models were fitted exclusively to the boreal conifer data, while the deciduous and PPDF data were included in other models in order to explore more generic tools for surface fire prediction across a range of forest types.

### Modelling and spread indices

Consistent with longstanding theoretical understanding (Curry and Fons 1940, Van Wagner 1968, Campbell-Lochrie et al. 2021) and the majority of existing empirical models (Fernandes et al. 2009, Sullivan 2009), we focused on wind speed and fuel moisture content as primary variables of interest. Our starting point for operational models was the aforementioned unitless *ISI* that combines empirical functions representing wind speed and fuel moisture influences in a power function (Van Wagner 1987), as used by all fuel types in the Canadian FBP System (Forestry Canada Fire Danger Group 1992). Other variables of potential interest including fuel type and surface fuel consumption were also examined for significance. For modelling, we tested linear regression forms with linear and quadratic predictors, as well as sigmoidal and power-law non-linear forms.

In addition to the base ISI, we also explored a modification using a more recent and flexible fuel moisture estimate. We utilized the stand-adjusted moisture content (*mcsa*) model of Wotton and Beverly (**Wotton.Beverly2007?**, see also Perrakis et al. 2023) that combines the effects of the FFMC and DMC indices along with stand type, density, and season for predicting the moisture content of dead litter. In order to leverage the additional flexibility of the *mcsa*, we calculated an alternative spread index based on the ISI equation, the stand-adjusted ISI (*ISIsa*). The ISIsa involves the same ISI formulation as originally described but with the mcsa value in place of the mcFFMC [estimated fine fuel moisture content based on the FFMC; Van Wagner (1987)]. The full *ISIsa* equation is provided for completeness:

[5], with *ws* representing the 10 metre open wind speed and *mc* representing mcSA in this case.

To test for novel influences, we tested *ws*, *FFMC*, *mcsa*, *DMC*, *ISI*, *ISIsa*, *SFC*, fuel type, and stand density class predictor variables . We first calculated transformed terms for several of these: *ws2*, *ISI2*, *ISIsa2*, *SFC2*, and *sqrt(SFC)*, and tested all variable combinations (1-4 predictors) using the ‘leaps’ package in R (ref#). We also tested for a non-linear response using the sigmoidal Chapman-Richards form previously described, as well as the nonlinear form. All analyses were performed in RStudio 2024.04 (Posit Software, Boston, MA, USA) with R version 4.2.1.

### Grass curing in PPDF fires

For the PPDF fires, with a mixed litter and open grass understory, we sought to incorporate grass curing effects into the analysis to account for the unique role of the herbaceous understory in these stands (Agee and Lolley 2006, Youngblood et al. 2008). This involved normalize all observations, following Cheney and Gould (1995), to a nearly fully cured understory grass condition (95 % C). Although the grass biomass in these stands only represented a small fraction (~3 %) of the total available surface fuel, we made the assumption that grass curing would influence ROS half as much (50 %) as it would was compared with a true grassland, due to its fine texture and well-aerated nature. The new adjusted ‘fully cured’ ROS (*ROS’*) was computed using the following equation:

[6], where *ROS0* represents the observed rate of spread with measured curing *C*, *cf(95)* represents the calculated curing factor at 95% C (**wotton2009?**) and *cf(C)* represents the curing factor of measured % C values (see Box 1). Moisture content of the remaining surface fuel complex of forest litter and woody debris were assumed to be unaffected by seasonal curing. *ROS’* values for these seven fires were then used in fitting the ‘aggregate’ model analyses, while PPDF fires were excluded from the boreal conifer models.

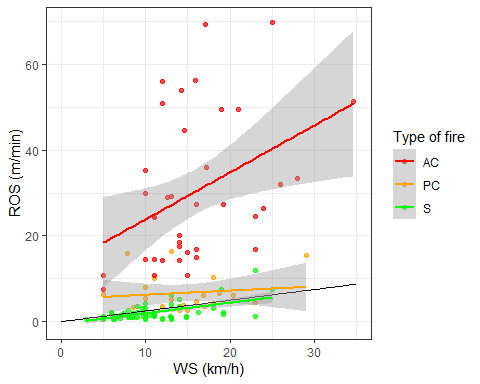
## 4. Results

#### Dataset description and types of fires

Our database of 153 observations resulted in 61 crown fires and 92 surface fires. Among fires in conifer fuel types, a clear relationship is evident between fire type and rate of spread predicted by wind speed (Fig. 2).

### [Fig 2 simple ROS graph by fire type and eval for m25 and FBP mods]

## `geom\_smooth()` using formula = 'y ~ x'



*Caption: Figure 2. Overview of experimental burn observations by wind speed (WS), rate of spread (ROS) and type of fire showing simple linear trends. S, PC, and AC refer to surface, passive crown, and active crown fire behaviour types, respectively (Van Wagner 1977). The black line represents the ‘25 % model’ for surface fire behaviour: ROS=0.25 \* WS.*

Surface fire ROS in conifer stands ranged from 0.4 – 12 m min-1, with most fires’ sROS values well below the maximum (95th percentile sROS of 5.92 m min-1.). The fitted linear trend shown in Fig 2 (green line) represents a very simple, albeit weak, baseline linear surface ROS model for conifer observations (Model 1, n= 65 ):

[1], with *P*<0.01 and adjusted *R2* = 0.319. As indicated by the negative y-intecept, this model is limited to conditions where *WS10* > 2.38 km h-1. Simple inspection suggested that a very simple arithmetic model, similar to Model 1, would result from the 0.25 *WS10* function (Figure 2, black line, forced through the origin). Therefore, a rough but easily calculated approximation of surface fire ROS in conifer stands, in m min-1, can be estimated by 1/4 of the 10 m open wind speed in km h-1.; this is termed the ‘25% model’ hereafter.

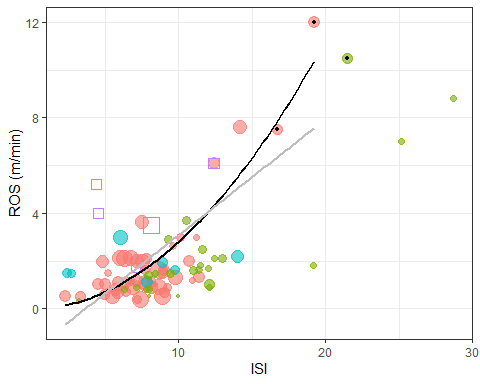
### Initial data exploration and model testing

Figure 3 shows the ROS of surface fires classified by fuel type and surface fuel consumption level, displayed by ISI value, along with the next set of fitted models. Despite identifying these fires as surface fires in primary sources, a few observations appeared anomalous; a closer examination identified several fires with significant estimated levels of canopy fuel consumption (CFC). Fires with estimated CFC > 0.2 kg m-2 (mean CFC: 0.35 kg m-2; highlighted in Figure 3) were then removed from the surface model-fitting, as these fires were considered transitional to passive crown fire and not representative of typical surface fire spread. Other questionable inclusions included non-boreal forest types, including PPDF fires noted previously as well as the few included wildfire observations.

The simplest ISI-based model was a simple linear fit for the boreal and sub-boreal conifer observations, with deciduous and PPDF fires excluded (Model 2: n=56):

[7]. This model had an adjusted *R2* of 0.459. As with Model 1, this model predicts illogical results (ROS < 0) at low ISI values, with ROS=0 predicted when *ISI*=3.64. Figure 3 also shows a model forced through the origin and with an *ISI2* term, a much better fit (Model 3). Deciduous and PPDF fires are shown in the figure but were not included in dataset for fitting these models.

### [Fig3]



*Caption: Figure 3. Fire observations showing rate of spread (ROS) by ISI (unitless). Colours indicate fuel type (red: boreal conifer; blue: Ponderosa pine-Douglas-fir; green: deciduous; purple squares: torching or partial passive crown fires. Size indicates relative surface fuel consumption. The two lines represent linear (gray) and quadratic models representing the boreal conifer observations only.*

### [Box 1] Fires in Ponderosa Pine-Douglas-fir stands in BC

Experimental burns were conducted in Ponderosa pine-Douglas-fir forest stands in the Dewdrop Range near Kamloops, British Columbia, in 1978 and 1979. These seven\* experiments were documented in a Master’s (Nyberg 1979) and undergraduate thesis (Smaill 1980). Summary fire weather and behaviour information were also incorporated into the FBP System C-7 fuel type (FCFDG 1992). Other than these documents and two plot photos (De Groot 1993), the data and findings were otherwise unpublished. Nevertheless, the experiments they describe remain valuable and seldom replicated. Surface fuel consumption (SFC) was reported for only one of the burn experiments (Plot 9, burned on 17 September 1978), with a very high (possibly suspect) estimate of > 5 kg m-2 of woody fuel consumption and total SFC of 5.3 kg m-2, the highest of any experimental fire to our knowledge in Canada.

During the course of the present project, original copies of these documents were located and the surface fuel consumption and grass curing values were reanalyzed. Stand structure consisted of open forests of Ponderosa pine and Douglas-fir, with mostly herbaceous understory and mean canopy closure of 27.2 % (Nyberg 1979). Litter and duff cover were described as patchy to nonexistent.

The original SFC estimate for Plot 9 included consumption of all downed woody fuels, including from large diameter coarse woody debris (CWD; > 7.6 cm). Although this is methodologically consistent with other FBP experimental burns (e.g., Stocks 1987, 1989), it appears to skew results due to the high contribution from CWD at Dewdrop. For instance, the contribution to SFC of CWD at Kenshoe Lake and Sharpsand Creek ranged from 0 to 22 % (mean: 9.2 %; cf. Stocks 1987, 1989). In contrast, at Dewdrop, the proportion ranged from 11 to 77 % (mean: 50.2 %), a highly significant difference (Mann-Whitney U-test: p < 0.001). The cause of the difference can be explained by both higher seasonal drought conditions during the Dewdrop burns (mean Drought Code: 394 at Dewdrop vs 111 at Kenshoe Lake and 161 at Sharpsand; see Van Wagner 1987 for Drought Code details), and probably the overall frequency of larger diameter trees at Dewdrop (> 17 % of trees in the ‘>25 cm’ DBH class; cf. Nyberg 1979); compared with other experimental burn sites (e.g., ~ 1 % of trees in the ‘> 23 cm’ DBH class at Kenshoe Lake (‘White River’); Walker and Stocks (1975)). This would result in higher pre-burn loading (both absolute and proportionally) from CWD at Dewdrop compared with the boreal sites.

Including contributions from large diameter logs in surface fires is at odds with current understanding of flame front dynamics. Consumption studies suggest that most CWD consumption occurs during post-frontal smoldering rather than during flaming combustion (Brown et al. 2003, Monsanto and Agee 2008). The high SFC at Dewdrop from CWD therefore skews results considerably for the PPDF fires. To compensate, new SFC values at Dewdrop were calculated excluding the CWD contribution. Including only consumption from herbaceous matter, litter, duff, and woody debris up to 7.6 cm in diameter resulted in SFC values for Plots 1-6 (0.47 – 1.39 kg m-2), and a new (notably lower: 2.01 kg m-2) value for Plot 9.\*\*

Another feature of interest from the documentation was the summer weather pattern and understory condition during these fires. As Nyberg (1979) described, the 1978 season was unusually moist in the Kamloops area, including measurable rainfall received at the Dewdrop site nearly every week from April through end of August. Consequently, understory vegetation remained relatively green (uncured) for the six experimental burns. Relative proportions of live and dead grass and forb biomass were used to calculate percent curing values (% C) in the same manner as used in Australian and Canadian grass fire models (Cheney et al. 1998, Wotton et al. 2009):

[B1], where *C* is the percent curing (as per FCFDG 1992), and *GBD* and *GBL* represent dead and live grass and forb biomass (g m-2), respectively. Using mean values from experimental and control plot sampling on each given date (Nyberg 1979) gave *C* values of 56-66 % for Plots 1-6. For Plot 9, the reported values are unfortunately less explicit between live and dead biomass (Smaill 1980) and the above formula could not be used. Based on the date (17 September) and slightly lower overall grass moisture value [22.7 %; Smaill (1980)], % C for that plot was estimated at 85%.

\*Plot numbers 1–6, burned in 1978, are described by Nyberg (1979). Plot 9, burned in 1979, is described by Smaill (1980). Plot 8 from the same site was apparently burned in 1980, but no further notes or details have been located.

\*\*SFC estimates represent the sum of the differences between pre-burn and post-burn fuel loading, including woody fuels, grasses and forbs, and litter (the site featured negligible duff quantities). Estimating litter consumption values required an estimate of pre-burn litter depth, which was not reported but was instead taken from Ducherer et al. (2009), a series of experiments at the same site (mean litter depth from control sites across all years and canopy positions: 3.3 cm).

[end Box 1]

Further model testing included the terms and predictor combinations previously noted. Most model forms using more than one or two predictors were non-significant owing to the modest sample size and high variability. The best results were obtained using combinations with *ISI* or *ISIsa* as squared terms or in non-linear model forms; these were forced through the origin due to the known lack of fire spread potential during high moisture conditions (e.g. ISI < 2) and in order to produce models usable across the full range of possible wildfire conditions; i.e., ISI/ISIsa values of 0 – 20 or more.

### [Table 1: Model summary]

## Num Model Formula nobs ISI.5 ISI.10 ISI.15  
## 1 1 wslin.con ws 65 -0.34 2.86 4.82  
## 2 2 isilin.con ISI 56 0.66 3.09 5.51  
## 3 3 ISI2.con I(ISI^2) - 1 56 0.70 2.81 6.32  
## 4 4 isim2.con I(isi.m^2) - 1 56 0.58 2.34 5.26  
## 5 5 WS2.agg I(ws^2) - 1 91 0.01 1.98 4.88  
## 6 6 ISI2.agg I(ISI^2) - 1 91 0.41 1.64 3.70  
## 7 7 ISI2SFC.agg I(ISI^2) + sqrt(SFC) - 1 84 1.49 2.48 4.13  
## 8 8 isim2.agg I(isi.m^2) - 1 91 0.44 1.76 3.96  
## 9 9 isim2SFC.agg I(isi.m^2) + sqrt(SFC) - 1 84 1.11 2.26 4.18  
## 10 10 crisi.agg a.value \* (1 - exp(-b \* ISI))^c 91 0.73 2.38 4.41  
## 11 11 crisim.agg a.value \* (1 - exp(-b \* isi.m))^c 91 0.63 2.28 4.42  
## 12 12 axb.isi.agg a \* ISI^b 91 0.90 2.37 4.17  
## 13 13 crisi.con a.value \* (1 - exp(-b \* ISI))^c 51 0.24 2.53 6.79  
## 14 14 crisim.con a.value \* (1 - exp(-b \* isi.m))^c 51 0.29 2.19 5.50  
## 15 15 c3s 15 \* (1-exp(-0.05\*ISI))^2 NA 0.73 2.32 4.18  
## 16 16 c4s 20 \* (1-exp(-0.2\*ISI))^5 NA 2.02 9.67 15.49  
## 17 17 c6s 30 \* (1-exp(-0.08\*ISI))^3 NA 1.07 5.01 10.24  
## 18 18 d1 30 \* (1-exp(-0.0232\*ISI))^1.6 NA 0.87 2.41 4.23  
## 19 19 m25 0.25 \* ws NA 0.05 3.49 5.50  
## RMSE MAE MAPE ER2 AIC  
## 1 1.60 1.130 0.788 0.330 251.7  
## 2 1.53 1.140 0.851 0.469 212.3  
## 3 1.30 0.940 0.668 0.613 192.7  
## 4 1.39 0.984 0.639 0.560 199.8  
## 5 1.92 1.250 0.659 0.260 380.9  
## 6 1.78 1.190 0.566 0.364 367.2  
## 7 1.58 1.110 0.730 0.517 320.8  
## 8 1.47 1.050 0.562 0.567 332.2  
## 9 1.31 0.953 0.599 0.664 290.3  
## 10 1.62 1.160 0.730 0.476 351.5  
## 11 1.42 1.040 0.657 0.592 328.7  
## 12 1.62 1.170 0.749 0.474 352.0  
## 13 1.00 0.797 0.612 0.772 150.7  
## 14 1.10 0.875 0.660 0.723 160.7  
## 15 NA 0.880 0.590 0.570 NA  
## 16 NA 4.530 3.820 -5.360 NA  
## 17 NA 1.720 1.530 -0.050 NA  
## 18 NA 0.900 0.640 0.570 NA  
## 19 NA 1.300 1.230 0.310 NA

*Caption: Table 1. Model forms and evaluation metrics for the fitted sROS models. Formulae include variables representing 10-metre wind speed (WS), initial spread index (ISI), stand-adjusted ISI (ISIsa), and surface fuel consumption (SFC, kg m-2). ISI/ISIsa columns represent predicted ROS (m min-1) for given models at each predictor level. Constants used in calculations include FFMC 91 (Models 1, 5, 19), and SFC of 1.5 kg m-2 (Models 7 and 9). Evaluation metrics include root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), Efron’s R-squared (ER2), and Akaike’s Information Criterion (AIC). Predefined functions (not fitted) include C-3S, C-4S, C-6S, D-1, and M25, which were evaluated against the 65 conifer fire observations.*

### Final fitted models

Table 1 shows the predictors and evaluation metrics for the list of fitted models, as well as *ROS* predictions at three levels (5, 10, 15) of *ISI* or *ISIsa*. Other variables (FFMC, SFC) were assigned constant values where needed for calculation purposes, as noted. Also shown are evaluation results using the previously described Van Wagner and FBP surface fire models. As the table indicates, the datasets used varied from 51 to 91 observations. Models using the SFC predictor excluded observations without estimated SFC, resulting in slightly smaller datasets. ‘Aggregated data’ models included all surface fire observations except those with canopy fuel involvement, as noted previously. This includes fires in deciduous stands of aspen (29 observations), oak (2), or mixedwood (1) as well as seven PPDF fires; wildfires were also retained. Boreal conifer models used only fires in jack pine, black spruce, jack pine/black spruce, red pine, lodgepole pine, and red pine/white pine (Perrakis et al. 2023). Models 2–4 included all such fires, while models 5–14 excluded fires that exhibited more significant torching, as noted.

Models forms 1–4 and 13–14, using the boreal conifer observations, had slightly better performance (higher Efron’s r-squared, lower MAE and MAPE) than models fitted to the larger aggregated dataset (Models 5 – 12). Non-linear model forms using the sigmoidal Chapman-Richards form had insufficient data to automatically fit the *a* parameter (‘nls’ function failed to converge); *a* was set to 20 following the value for Van Wagner’s C-4S model (Van Wagner 1993), an intermediate value between the low (15: C-3S) and high (30: C-6S, D1) choices. With the *a* parameter assigned, the remaining parameters were fitted to the data, producing relatively high-performing models, particularly those using the boreal conifer dataset with torching fires removed (Models 13, 14: Efron’s R-squared > 0.7, MAE < 0.7 m min-1). In contrast, when using the broader aggregated dataset, the best performance included ISIsa and SFC predictors (Model 9: Efron’s R-squared of 0.664), with MAE <1 m min-1.

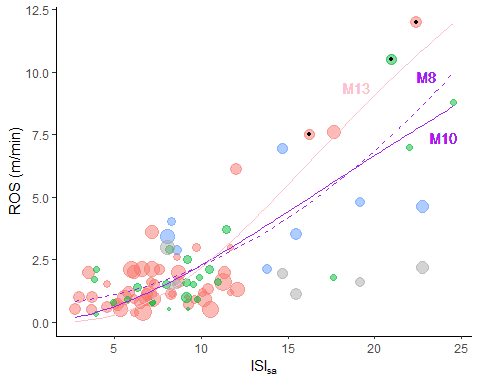
The evaluation measures in Table 1 show how the Van Wagner and FBP surface fire functions, as well as the ‘25%’ model, compare to the fitted models for precting ROS of the boreal conifer data. High MAE and MAPE values, and negative values for Efron’s R-squared, suggest very poor performance by the C-4S (especially) and C-6S models compared to the fire observations. The C-3S, D1, and 25% models, in contrast, are in the lower end of the range of model performance, but otherwise exhibit acceptable performance.

### [Table 2: Extended SFC predictions]

## num Model SFC ISI.5 ISI.10 ISI.15  
## 1 1 ISI2SFC.agg 0.7 1.12 2.11 3.76  
## 2 2 ISI2SFC.agg 1.5 1.49 2.48 4.13  
## 3 3 ISI2SFC.agg 3.0 1.98 2.96 4.61  
## 4 4 ISI2SFC.agg 5.0 2.46 3.44 5.09  
## 5 5 isim2SFC.agg 0.7 0.88 2.03 3.95  
## 6 6 isim2SFC.agg 1.5 1.11 2.26 4.18  
## 7 7 isim2SFC.agg 3.0 1.40 2.56 4.48  
## 8 8 isim2SFC.agg 5.0 1.70 2.85 4.77

Table 2 shows extended ROS predictions for the two models with *ISI* (or *ISIsa*) and *SFC* predictors. Both models were fitted with a *sqrt(SFC)* term, which performed slightly better (*ISI*: adjusted R2=0.7485); *ISIsa*: adjusted R2=0.825) than an untransformed *SFC* term (*ISI*: 0.7345 ; *ISIsa*: 0.8173 , respectively). As the table values indicate, the influence of SFC was highest at low *ISI* (or *ISIsa*) values, and diminished under higher ISI conditions.

### [Figure 4 and diagnostics]



*Caption: Figure 4. Surface fire rate of spread (ROS) observations and selected fitted models, using the stand-adjusted initial spread index (ISIsa). Colours indicate fuel type (red: boreal conifer; blue: adjusted ponderosa pine-Douglas-fir (PPDF); green: deciduous; gray: original PPDF (not modelled)). Size indicates surface fuel consumption. Observations with black centres are documented wildfires; the remainder are experimental fires.*

Figure 4 shows the surface ROS observations plotted by overall fuel type (boreal conifer, deciduous, or PPDF) and SFC against *ISIsa*, along with three of the fitted models: M8 (calculated at SFC=1.5 kg m-2), M10, and M13 (boreal conifer only). PPDF fires adjusted to 95% curing conditions were used in model fitting, while the original observations (not included in models) are shown in grey. Observations with a black centre are wildfires; the remainder represent experimental fires.

#### Influential observations

Individual observations were evaluated for undue influence in the best models using Cook’s Distance for linearized models (Models 5 and 7#) and jackknife resampling for non-linear models (‘nlstools’ R package, v2.1; Baty et al. (2015)). For non-linear models 11 and 12#, observations were flagged when the difference between model parameters calculated with and without individual estimates, , was , where *s* is the standard error of the parameter estimate and *n* is the sample size (Baty et al. 2015). For linearized models, observations with Cook’s D > 0.1 were flagged as most concerning. High influence observations are shown in Figures 4 and 5 (#to do), consisting generally of high *ISI*/*ISIsa* and high ROS observations, particularly wildfires. Due to the shortage of data at high fire danger conditions, there is no way of removing these observations without significantly diminishing the usable range of these models. However, primary source descriptions that exist for these fires (i.e., Van Wagner 1965a) suggest low confidence in these observations, unsurprisingly.

### [Fig 5]

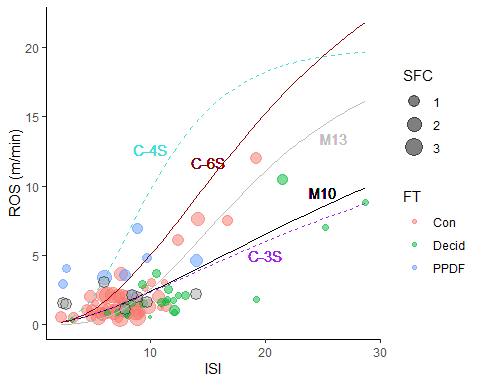


Figure 5 shows the observations and selected model predictions based on the ISI, along with certain FBP models. As indicated in Table 1, the ‘aggregated’ dataset models (e.g. M10) did not perform as well (higher MAE, MAPE, lower Efron’s R-squared) as the boreal conifer-based models (e.g. M13) when using the original ISI predictor. Also evident from this figure are the overprediction tendencies of the C-6S and (especially) C-4S models, irrespective of the fuel type being considered.

## 5. Discussion

This analysis presents a summary of several decades of experimental burning in conifer stands, focusing on fires identified as surface fires by original observers. A small number of wildfires (exhibiting surface fire behaviour) were also included due to their obvious importance in representing ‘high end’ burning conditions (i.e., high ISI or ISIsa). It is apparent that as surface fires spread under more extreme conditions (high wind, lower moisture conditions), ROS begins to overlap with the range of so-called passive crown fire behaviour [Figure 1; Van Wagner (1977b); Cruz et al. (2005)], although this will also depend on other factors such as canopy base height and surface fuel consumption (Cruz et al. 2004, Perrakis et al. 2023). Indeed, some of the observations classed as surface fires clearly had some canopy fuel involvement, based on photographs (see, e.g., Alexander and De Groot 1988, Hirsch et al. 2000) and estimated crown fuel consumption; these were removed from the dataset for most model fitting. However, a few other observations, notably the two wildfires, had no information on canopy fuel involvement and were left in as surface fires. The great uncertainty associated with these data adds to the lack of clarity around ROS under high danger (i.e., high ISI or ISIsa) conditions. In many conifer stands, these conditions represent crown fires, reducing the need for a surface ROS model. However, as we consider the value of hazard reduction treatments, for instance, where stands with high CBH and low surface fuel loading are engineered to resist crown fire (Hirsch and Pengelly 1999, Agee and Skinner 2005), there is a greater need to estimate sROS under higher danger conditions.

Although the most relevant value related to wind velocity might be the mid-flame wind speed (as per (Rothermel 1972)), the 10-m open wind speed is commonly measured at fire weather stations across Canada and internationally (Lawson and Armitage 2008), and avoids the major challenge of in-stand wind speed modelling. We tested other associated forest structure variables, including canopy closure class, FSG, and ignition line exposure, in order to account for wind reduction between 10-m open conditions and flame-level (~1 m) sub-canopy conditions.

While physical fire spread models attempt to represent heat transfer and combustion processes, empirical and semi-empirical models are much easier and quicker to use and learn, and therefore preferable for operational fire predictions. The FBP System initially relied on categorical fuel types. While existing fuel types remain useful constructs, selecting the best-fit fuel type can sometimes present a subjective and challenging dilemma, where structural attributes can present a conflicting picture and fail to represent observed fire behaviour (Perrakis et al. 2018, Baron et al. 2024). A switch to continuous fuel attributes (rather than fuel types) presents a greater range of options. For instance, black spruce stands with a higher crown base (Wilkinson et al. 2018, e.g., Thompson et al. 2020) may support surface fire at higher danger levels than suggested by the best FBP System categorical fuel type (i.e., C-2; Forestry Canada Fire Danger Group (1992)). However, differentiating surface fire behaviour between specific conifer fuel types is not possible at this time. The variability in factors such as understory vegetation, shrub cover, and tree density suggest that considerable variability is expected between individual sites, in addition to between overall fuel or vegetation types (overstory and understory). Our findings suggest that boreal and sub-boreal pine and spruce fuel types can be aggregated for this purpose, provided precise prediction accuracy is not required or expected. However, this error will be compounded when surface ROS or intensity is required to predict additional fire behaviour properties, such as crown fire initiation using Van Wagner’s model (Van Wagner 1977b, Scott and Reinhardt 2001).

#### Using final surface rate of spread models

Four models shown here stand out as superior: Models 11 and 12, for boreal/sub-boreal conifer stands, and Models 5 and 7, somewhat more fuel type independent. Models 5 and 11 use the traditional ISI measure, based on open wind speed and the FFMC, while Models 7 and 12 take advantage of the additional flexibility of the Wotton and Beverly (2007) stand-adjusted litter moisture model and the *ISIsa* index introduced here. Neither overstory genus (pine vs spruce) nor stand density class variables were significant predictors of ROS in any models on their own; however, the models using *ISIsa* incorporate effects of stand density and DMC indirectly via their influence on fuel moisture (the mcsa). This is in line with findings from physical modelling studies that suggest, for instance, that thinning treatments can increase surface ROS via higher effective in-stand wind speed in more open stands (e.g., Parsons et al. 2018, Marshall et al. 2020).

The major limitation of the sROS models and dataset are the paucity of observations at higher danger conditions (ws or ISI) and the importance of various low-confidence data points. The reconstructions of various wildfires (Hummel 1979, **vanwagner1965a?**, **vanwagner1973b?**) will necessarily result in less accurate ROS observations, including estimated predictors, than those from experimental fires. While we assumed that these observations were reconstructed as accurately as possible by experienced personnel, there is no substitute for additional surface fire observations. Those spreading under high indices, necessarily with high LCBH and-or low SFC to avoid crowning, will help greatly to improve the accuracy and utility of surface ROS models. Some of the variability in the data is undoubtedly due to the varying canopy influence (including edge effects) on in-stand wind speed and turbulence, as previously discussed. These factors, potentially exacerbated by varying plot sizes, are not accounted in our models. The present sROS models appear crude, but will likely provide a useful first approximation decision support tool for fire managers based on real-world fire data. Surface ROS errors of 1-2 m min-1 should be expected below ISI (or ISIsa) 10; and larger errors of perhaps 2-5 m min-1 (occasionally more) may be encountered in real world use between *ISI* / *ISIsa* 10 and 25. Use of these models above ISI 25 involves extrapolation and should be undertaken only with great caution.

For models that include the SFC factor, the SFC influence is greatest at low ISI or ISIsa levels, and appears minimal by ISI 15.

### Expected accuracy

Mean and 90th percentile overprediction vs. mean underprediction - best 4 models.

While it is perhaps unfair to compare the performance of fitted models to supposedly independently-derived models, it is apparent that the FBP-era models performed poorly. Negative values of Efron’s R-squared suggest that these models perform worse than a null model using only the mean of all observations.

Finally, the ‘25 percent model’ identifies that a rough but usable approximation of surface fire ROS in conifer stands is rapidly estimated, in m min-1, as one quarter of the 10-m open wind speed (in km h-1). The use of this model is not unlike the ‘10 % wind speed rule of thumb’ model for crown fire spread in conifer stands (Cruz and Alexander 2019), where a statistically better fit is forgone in favour of a close but much more easily calculated model for operational purposes. The important distinction is the difference in units, with wind speed and ROS kept in the units typically used by Canadian fire management crews. If we held the units for wind speed and ROS constant, e.g. km h-1, this model works out to a ‘1.5 % wind speed rule’, which is not as easily calculated in the field. As with all such tools, proper training is key to avoid confusion, lest personnel be misled into thinking a fire will spread much faster than this model suggests (if it were actually 25 % of the wind speed, in km h-1).

Under very low danger conditions (e.g., FFMC < 75 or ISI < 1), ignition in needle fuel substrates becomes highly unlikely (Beverly and Wotton 2007, Nadeem et al. 2020), so ROS is a minimal concern.

Other researchers have developed surface fire spread models usable in conifer forest litter, typically using empirical or semi-empirical approaches based on laboratory experiments(e.g., Rothermel 1972, Rossa and Fernandes 2018). Australian models?# Log-transformation common, but seemed unhelpful with present small and variable dataset.

It is expected that the quality and quantity of source data will improve over time, allowing for periodic reanalysis and improvement of these models.

## 6. References

Agee, J. K., and M. R. Lolley. 2006. Thinning and prescribed fire effects on fuels and potential fire behavior in an eastern Cascades forest, Washington, USA. Fire Ecology 2:142–158.

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

Alexander, M. E., and M. G. Cruz. 2016. Crown fire dynamics in conifer forests. Pages 163–258 *in* P. A. Werth, editor. Synthesis of Knowledge of Extreme Fire Behavior: Volume 2 for Fire Behavior Specialists, Researchers, and Meteorologists. USDA Forest Service Pacific Northwest Research Station, Portland, OR.

Alexander, M. E., M. G. Cruz, A. M. G. Lopes, and D. X. Viegas. 2006. CFIS: A software tool for simulating crown fire initiation and spread. 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.

Baron, J. N., P. F. Hessburg, M.-A. Parisien, G. A. Greene, Sarah. E. Gergel, and L. D. Daniels. 2024. [Fuel types misrepresent forest structure and composition in interior British Columbia: A way forward](https://doi.org/10.1186/s42408-024-00249-z). Fire Ecology 20:15.

Baty, F., C. Ritz, S. Charles, M. Brutsche, J.-P. Flandrois, and M.-L. Delignette-Muller. 2015. [A Toolbox for Nonlinear Regression in R: The Package nlstools](https://doi.org/10.18637/jss.v066.i05). Journal of Statistical Software 66:1–21.

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.

Brown, J. K., E. D. Reinhardt, and K. A. Kramer. 2003. [Coarse woody debris: Managing benefits and fire hazard in the recovering forest](https://doi.org/10.2737/RMRS-GTR-105). Gen. Tech. Rep. RMRS-GTR-105. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p. 105.

Campbell-Lochrie, Z., C. Walker-Ravena, M. Gallagher, N. Skowronski, E. V. Mueller, and R. M. Hadden. 2021. [Investigation of the role of bulk properties and in-bed structure in the flow regime of buoyancy-dominated flame spread in porous fuel beds](https://doi.org/10.1016/j.firesaf.2020.103035). Fire Safety Journal 120:103035.

Catchpole, W., E. Catchpole, B. Butler, R. Rothermel, G. Morris, and D. Latham. 1998. Rate of spread of free-burning fires in woody fuels in a wind tunnel. Combustion Science and Technology 131:1–37.

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

Chen, J., S. C. Saunders, T. R. Crow, R. J. Naiman, K. D. Brosofske, G. D. Mroz, B. L. Brookshire, and J. F. Franklin. 1999. Microclimate in forest ecosystem and landscape ecology: Variations in local climate can be used to monitor and compare the effects of different management regimes. BioScience 49:288–297.

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

Cheney, N., J. Gould, and W. R. Catchpole. 1998. Prediction of fire spread in grasslands. International Journal of Wildland Fire 8:1–13.

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

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 P. Fernandes. 2022. [Evidence for lack of a fuel effect on forest and shrubland fire rates of spread under elevated fire danger conditions: Implications for modelling and management](https://doi.org/10.1071/WF21171). International Journal of Wildland Fire.

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.

Curry, J. R., and W. L. Fons. 1940. Forest-fire behavior studies. Mechanical Engineering. 62: 219-225 62:219–225.

De Groot, W. J. 1993. Examples of fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System [poster with text]. Pages 5320–122. Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Canada.

Ducherer, K., Y. Bai, D. Thompson, and K. Broersma. 2009. [Dynamic Responses of a British Columbian Forest-Grassland Interface to Prescribed Burning](https://doi.org/10.3398/064.069.0118). Western North American Naturalist 69:75–87.

Fernandes, P. M., H. S. Botelho, F. C. Rego, and C. Loureiro. 2009. [Empirical modelling of surface fire behaviour in maritime pine stands](https://doi.org/10.1071/WF08023). International Journal of Wildland Fire 18:698.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, Ontario, Canada.

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

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].

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

Kidnie, S., and B. M. Wotton. 2015. Characterisation of the fuel and fire environment in southern Ontario’s tallgrass prairie. International Journal of Wildland Fire 24:1118–1128.

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.

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.

Marshall, G., D. K. Thompson, K. Anderson, B. Simpson, R. Linn, and D. Schroeder. 2020. The impact of fuel treatments on wildfire behavior in North American boreal fuels: A simulation study using FIRETEC. Fire 3:18.

Monsanto, P. G., and J. K. Agee. 2008. Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington. Forest Ecology and Management 255:3952–3961.

Moon, K., T. Duff, and K. Tolhurst. 2019. Sub-canopy forest winds: Understanding wind profiles for fire behaviour simulation. Fire Safety Journal 105:320–329.

Nadeem, K., S. Taylor, D. G. Woolford, and C. Dean. 2020. Mesoscale spatiotemporal predictive models of daily human-and lightning-caused wildland fire occurrence in British Columbia. International journal of wildland fire 29:11–27.

Nyberg, J. B. 1979. Seasonal effects of fire on Ponderosa pine / bunchgrass range: Year 1. PhD thesis, University of British Columbia, Department of Forestry.

Parsons, R. A., F. Pimont, L. Wells, G. Cohn, W. M. Jolly, F. de Coligny, E. Rigolot, J.-L. Dupuy, W. Mell, and R. R. Linn. 2018. Modeling thinning effects on fire behavior with STANDFIRE. Annals of forest science 75:1–10.

Pepin, A.-C., and M. Wotton. 2020. Fire behaviour observation in shrublands in Nova Scotia, Canada and assessment of aids to operational fire behaviour prediction. Fire 3:34.

Perrakis, D. D. B., M. G. Cruz, M. E. Alexander, C. C. Hanes, D. K. Thompson, S. W. Taylor, and B. J. Stocks. 2023. [Improved logistic models of crown fire probability in Canadian conifer forests](https://doi.org/10.1071/WF23074). International Journal of Wildland Fire 32:1455–1473.

Perrakis, D. D. B., M. G. Cruz, M. E. Alexander, S. W. Taylor, and J. L. Beverly. 2020a. 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. Natural Resources Canada, Pacific Forestry Centre, Victoria, British Columbia, Canada.

Perrakis, D. D. B., S. W. Taylor, R. Stohmann, and J. Ussery. 2020b. Analysis of wildfire risk elements for the Greater Victoria Water Supply Area, southern Vancouver Island (British Columbia, Canada). In prep.

Quintilio, D., M. E. Alexander, and R. L. Ponto. 1991. Spring fires in a semimature trembling aspen stand in central Alberta. Natural Resources Canada Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.

Rossa, C. G., and P. M. Fernandes. 2018. [An Empirical Model for the Effect of Wind on Fire Spread Rate](https://doi.org/10.3390/fire1020031). Fire 1:31.

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

Schlegel, F., J. Stiller, A. Bienert, H.-G. Maas, R. Queck, and C. Bernhofer. 2015. [Large-Eddy Simulation Study of the Effects on Flow of a Heterogeneous Forest at Sub-Tree Resolution](https://doi.org/10.1007/s10546-014-9962-y). Boundary-Layer Meteorology 154:27–56.

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

Smaill, G. 1980. Seasonal effects of fire on Ponderosa pine / bunchgrass and Douglas-fir / pinegrass ranges. PhD thesis, Washington State University.

Stocks, B. J. 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.

Sullivan, A. L. 2009. Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. International Journal of Wildland Fire 18:369–386.

Sullivan, A. L., and J. S. Gould. 2020. Wildland Fire Rate of Spread. Pages 1095–1098 Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer.

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., R. W. Bryce, B. M. Wotton, S. W. Taylor, and O. B. Armitage. 2010. Development and structure of Prometheus: The Canadian wildfire growth simulation model. Natural Resources Canada Canadian Forest Service, Edmonton, AB.

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

Van Wagner, C. E. 1965b. Describing forest fires - old ways and new.

Van Wagner, C. E. 1968. Fire behaviour mechanisms in a red pine plantation: Field and laboratory evidence. Departmental Pub. No. 1229. Ministry of Forestry and Rural Development, Forestry Branch, Ottawa, Ontario, Canada.

Van Wagner, C. E. 1977a. Effect of slope on fire spread rate. Environment Canada, Canadian Forestry Service Bi-Monthly Resource Notes 33:7–8.

Van Wagner, C. E. 1977b. 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. Canadian Forest Service, Petawawa National Forestry Institute, Chalk River, Ontario, Canada.

Van Wagner, C. E. 1989. Prediction of crown fire in conifer stands. Pages 207–212 *in* D. C. McIver, editor. 10th Conference on Fire and Forest Meteorology, April 17-21, 1989. Ottawa, ON.

Van Wagner, C. E. 1993. Prediction of Crown Fire Behavior in two Stands of Jack Pine. Canadian Journal of Forest Research 23:442–449.

Walker, J. D., and B. J. Stocks. 1975. The fuel complex of mature and immature jack pine stands in Ontario. Canadian Forestry Service, Department of the Environment, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, Canada.

Wang, X., M.-A. Parisien, M. D. Flannigan, S. A. Parks, K. R. Anderson, J. M. Little, and S. W. Taylor. 2014. The potential and realized spread of wildfires across Canada. Global Change Biology 20:2518–2530.

Wheatley, M., B. M. Wotton, D. G. Woolford, D. L. Martell, and J. M. Johnston. 2022. [Modelling initial attack success on forest fires suppressed by air attack in the province of Ontario, Canada](https://doi.org/10.1071/WF22006). International Journal of Wildland Fire 31:774–785.

Wilkinson, S., P. Moore, D. Thompson, B. M. Wotton, S. Hvenegaard, D. Schroeder, and J. M. Waddington. 2018. The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research 48:1433–1440.

Wotton, B. 2009. A grass moisture model for the Canadian Forest Fire danger Rating System. Pages 13–15 Eighth Symposium on Fire and Forest Meteorology.

Wotton, B. M., M. E. Alexander, and S. W. Taylor. 2009. Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System. 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.

Youngblood, A., C. S. Wright, R. D. Ottmar, and J. D. McIver. 2008. [Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, northeastern Oregon](https://doi.org/10.1016/j.foreco.2007.09.032). Forest Ecology and Management 255:3151–3169.

## 7. Appendix: Final model coefficients

## # A tibble: 23 × 6  
## Model Term Estimate std.error Stat p.value  
## <chr> <chr> <dbl> <dbl> <dbl> <dbl>  
## 1 1. wslin.con (Intercept) -0.584 0.510 -1.15 2.56e- 1  
## 2 . ws 0.246 0.0442 5.57 5.72e- 7  
## 3 2. isilin.con (Intercept) -1.77 0.590 -3.00 4.09e- 3  
## 4 . ISI 0.486 0.0703 6.91 5.76e- 9  
## 5 3. ISI2.con I(ISI^2) 0.0281 0.00188 14.9 5.65e-21  
## 6 4. isim2.con I(isi.m^2) 0.0234 0.00170 13.8 1.88e-19  
## 7 5. WS2.agg I(ws^2) 0.0101 0.000816 12.4 4.32e-21  
## 8 6. ISI2.agg I(ISI^2) 0.0164 0.00119 13.9 4.66e-24  
## 9 7. ISI2SFC.agg I(ISI^2) 0.0132 0.00126 10.4 1.07e-16  
## 10 . sqrt(SFC) 0.951 0.207 4.59 1.57e- 5  
## 11 8. isim2.agg I(isi.m^2) 0.0176 0.000978 18.0 1.32e-31  
## 12 9. isim2SFC.agg I(isi.m^2) 0.0154 0.00111 13.9 3.38e-23  
## 13 . sqrt(SFC) 0.589 0.182 3.23 1.79e- 3  
## 14 10. crisi.agg b 0.0422 0.00798 5.29 8.64e- 7  
## 15 . c 2.00 0.317 6.31 1.08e- 8  
## 16 11. crisim.agg b 0.0468 0.00705 6.64 2.45e- 9  
## 17 . c 2.21 0.308 7.16 2.23e-10  
## 18 12. axb.isi.agg a 0.0950 0.0345 2.76 7.10e- 3  
## 19 . b 1.40 0.132 10.6 1.79e-17  
## 20 13. crisi.con b 0.112 0.0123 9.12 3.96e-12  
## 21 . c 5.21 0.851 6.12 1.51e- 7  
## 22 14. crisim.con b 0.0866 0.0114 7.58 8.40e-10  
## 23 . c 4.05 0.700 5.79 4.90e- 7