Simple models for conifer surface fires

D. D. B. Perrakis S. W. Taylor

## Abstract

Surface fire behaviour is the most frequent type of wildfire activity encountered during the fire season in conifer forests. Surface fire spread models can provide guidance under conditions less conducive to crown fire: 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 (FBP) System 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):

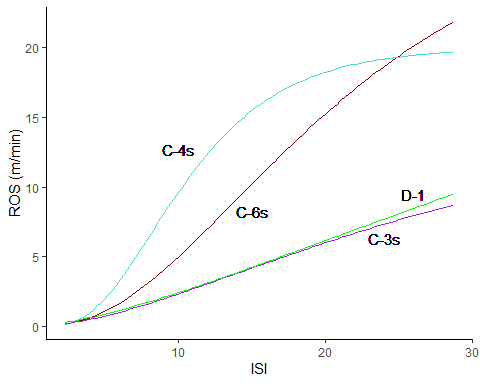
[1],

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 surface fire 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]



*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 empirically-based models for estimating the ROS of surface fires burning beneath the canopy of conifer stands. 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 developing generalized surface fire models. The present database contains over 120 conifer observations of experimental fire behaviour in stands of ~0.1-4.0 ha (median size: 0.4 ha). The present analysis was restricted to fires described as surface fires in primary literature, though some nuances related to torching and passive crowning are discussed below.

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 and Sando 1989), featuring fires from the US lake states, as well as Quintilio et al. (1991), and Van Wagner (Van Wagner 1973), describing fires in Alberta and Ontario, respectively. 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 fuel types.

### Modelling and spread indices

Consistent with longstanding theoretical understanding of fire processes (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 dead 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 (Van Wagner 1987). Other variables we examined for significance included moisture indices from the FWI System (the Fine Fuel Moisture Code, FFMC, and Duff Moisture Code, DMC), fuel type, and surface fuel consumption. For modelling, we tested linear regression forms with linear and quadratic predictors, as well as sigmoidal and exponential non-linear forms.

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 (WS10) is commonly measured at fire weather stations across Canada and internationally (Lawson and Armitage 2008) and provided by forecasters for operational purposes; using WS10 allowed us to sidestep the considerable challenge of in-stand wind speed modelling and kept us at the scale most applicable to the FWI System.

In addition to the base ISI, we also explored a modification using a more recent and flexible fuel moisture estimate. We tested 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 directly predicting the moisture content of dead litter; the *mcsa* is analogous to the ‘Accessory Fuel Moisture System’ noted by Stocks (1989) but never fully described. In order to leverage the additional flexibility of the *mcsa*, we calculated an alternative spread index, 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 *WS10* and *mcsa* as described here.

To test for novel influences, we tested all combinations of predictors: *WS10*, *FFMC*, *mcsa*, *DMC*, *ISI*, *ISIsa*, *SFC*, fuel type, and stand density class (‘light’, ‘moderate’, and ‘dense’ classes, as defined by (Wotton and Beverly 2007)). We first calculated transformed terms for several of these: *WS10*2, *ISI2*, *ISIsa2*, *SFC2*, and *sqrt(SFC)*, and tested all linear and quadratic variable combinations (1-4 predictors) using the ‘leaps’ package in R (Lumley and Miller 2024). 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, we sought to incorporate the effects of understory grass and herbaceous curing effects on fire behaviour (Agee and Lolley 2006, Youngblood et al. 2008). This involved normalizing all observations, following Cheney and Gould (1995), to a nearly fully cured grass condition (95 % C) in order to estimate near-peak fire behaviour. Although the grass biomass in these stands only represented a small fraction (~3 %) of the total available surface fuel, grass curing is often suspected of being highly influential on ROS in these stands (Beck 2003). We assumed that understory herbaceous curing would be 50 % as influential compared to a true grassland, given its fine texture and well-aerated structure. 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 (Wotton et al. 2009) 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 PPDF fires were then used in fitting the ‘aggregate’ model analyses, but excluded from the boreal conifer models.

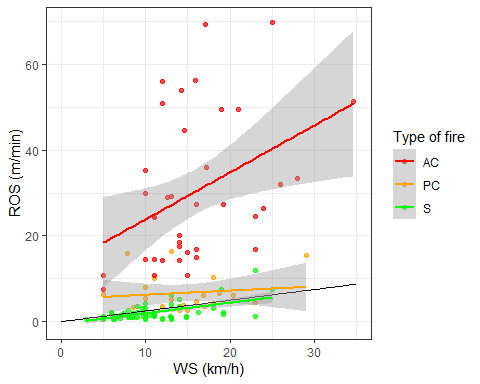
## 4. Results

#### 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 (surface and crown), 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 (ROS in m/min; WS in km/h).*

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 suggests that a very simple arithmetic model, similar to Model 1, would result from the 0.25 *WS10* function (Figure 2, black line). 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.

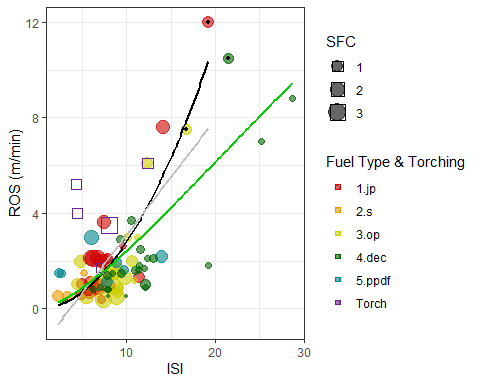
### Initial data exploration and model building

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 fitted to the boreal and sub-boreal conifer observations was another linear model, 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. Colours indicate fuel type and fire characteristics as follows: jp- jack pine; s- black spruce or pine-spruce mix; op- other pine; dec- deciduous; ppdf- ponderosa pine-Douglas-fir; Torch- torching or passive crown fire behaviour (removed from surface model analysis). Size indicates relative surface fuel consumption. The lines represent linear (Model 2: gray) and quadratic (Model 3: black) models fitted to conifer observations (jp, s, op), and the FBP D-1 model (green).*

The influence of conifer fuel type was first tested using the *ISI2* form of Model 3. Only one surface fire observation was in a black spruce (BS) stand while five were in mixed jack pine- black spruce stands (JP-BS), 19 in pure jack pine (JP), and 26 in stands dominated by other pine species (OP). OP observations included lodgepole (*P. contorta*), red (*P. resinosa*), and white pine (*P. strobus*)-red pine stands. Fuel type was a significant variable in this model; however, the only significant contrast (‘emmeans’ package) was between OP and JP stands (Tukey HSD: ), with OP fires exhibiting slightly slower ROS compared with JP fires (Fig. 3).

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

Seven\* experimental fires were conducted in Ponderosa pine-Douglas-fir forest stands in the Dewdrop Range near Kamloops, British Columbia, in 1978-79. These fires were documented in theses by Nyberg(1979) and Smaill (1980), while summary information and photos were incorporated into the FBP System C-7 fuel type (FCFDG 1992, De Groot 1993). 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) total SFC value of 5.3 kg m-2, including > 5 kg m-2 of woody fuel consumption.

Original copies of these documents were located and reanalyzed for the purposes of incorporating into the surface ROS modelling. Stand structure consisted of open forests of Ponderosa pine and Douglas-fir, with mostly herbaceous understory structure; mean canopy closure was 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). While methodologically consistent with other FBP experimental burns (e.g., Stocks 1987, 1989), this inclusion appears to skew the Dewdrop SFC values due to the high contribution from CWD. For instance, the mean CWD proportion of SFC at the Ontario Kenshoe Lake and Sharpsand Creek sites was 9.2 % (cf. Stocks 1987, 1989). In contrast, at Dewdrop, the proportion was significantly higher, 50.2 % (Mann-Whitney U-test: p < 0.001). The difference is explained by both higher seasonal drought conditions during the Dewdrop burns (mean Drought Code (DC): 394 at Dewdrop vs 111 at Kenshoe Lake and 161 at Sharpsand; see Van Wagner 1987 for DC description), 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)).

Including contributions from large diameter logs in surface fires is also at odds with current understanding of flame front dynamics. Consumption studies suggest that most CWD consumption in PPDF stands occurs during post-frontal smoldering rather than during flaming combustion (Brown et al. 2003, Monsanto and Agee 2008, Ottmar 2014). The high SFC at Dewdrop from CWD therefore could overpredict fire intensity and crown fire tendency (Van Wagner 1977; Perrakis et al. 2023). To compensate, new SFC values at Dewdrop were calculated excluding the CWD contribution. Including only consumption from finer fuels (grass and herbs, litter, duff, and woody debris < 7.6 cm) resulted in a recalculated (notably lower: 2.01 kg m-2) value for Plot 9.\*\* SFC values calculated using the same methods for Plots 1-6 were 0.47 – 1.39 kg m-2.

Another feature of interest was the summer weather pattern and understory condition during these fires. The 1978 season was described as unusually wet, with measurable rainfall received at the Dewdrop site nearly weekly from April-August (Nyberg 1979), an unusual occurrence in this very dry climate. Consequently, understory vegetation remained relatively green during that year’s experimental fires. 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, and *GBD* and *GBL* represent dead and live grass and forb biomass (kg 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 slightly lower overall grass moisture value (22.7 %) and late summer date, % C for that plot was estimated at 80%.

These analyses allowed us to incorporate the Dewdrop experimental fires in our surface fire models (aggregated fuels), even though they stood apart from the primarily boreal conifer and dediduous experiments.

\*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 description or details have been located.

\*\*SFC estimates represent the differences between pre-burn and post-burn fuel loading, including contributions from 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 1.50 2.49 4.13  
## 8 8 isim2.agg I(isi.m^2) - 1 91 0.44 1.76 3.97  
## 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 2.29 4.42  
## 12 12 axb.isi.agg a \* ISI^b 91 0.90 2.37 4.18  
## 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 0.660 0.258 381.4  
## 6 1.79 1.190 0.566 0.361 367.8  
## 7 1.58 1.110 0.734 0.516 321.2  
## 8 1.47 1.060 0.562 0.564 332.9  
## 9 1.32 0.957 0.602 0.662 291.0  
## 10 1.62 1.160 0.732 0.474 352.2  
## 11 1.43 1.050 0.659 0.590 329.3  
## 12 1.62 1.170 0.750 0.471 352.6  
## 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 of *ISI* or *ISIsa* (5, 10, 15). 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 (Box 1); 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 (see 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, 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.

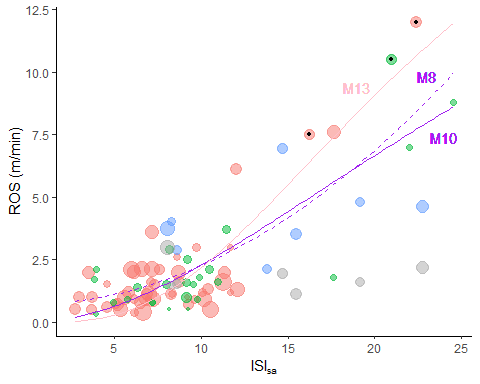
### [Table 2: Extended SFC predictions]

## num Model SFC ISI.5 ISI.10 ISI.15  
## 1 1 ISI2SFC.agg 0.7 1.13 2.12 3.76  
## 2 2 ISI2SFC.agg 1.5 1.50 2.49 4.13  
## 3 3 ISI2SFC.agg 3.0 1.99 2.98 4.62  
## 4 4 ISI2SFC.agg 5.0 2.47 3.46 5.10  
## 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 1.42 2.57 4.49  
## 8 8 isim2SFC.agg 5.0 1.72 2.87 4.79

*Caption: Table 2. Extended predictions for models 7 and 9, using varying values of predicted SFC from 0.7 kg m-2 to 5.0 kg m-2. and ISI or ISIsa values from 5 to 15, as in Table 1.*

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*: Efron’s R2=0.5159); *ISIsa*: adjusted R2=0.6623) than an untransformed *SFC* term (*ISI*: r``ef.sfc.mod10 %>% round(4) ; *ISIsa*: 0.6476 , 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]



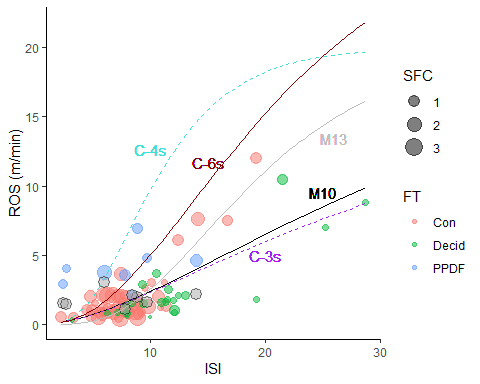
*Caption: Figure 4. Surface fire rate of spread (ROS) observations and selected fitted models, using the stand-adjusted initial spread index (ISIsa). Colours indicate fuel type (red: boreal conifer; blue: adjusted ponderosa pine-Douglas-fir (PPDF); green: deciduous; gray: original PPDF (not modelled)).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

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]



*Caption: Figure 5. Surface fire observations by ISI and ROS (m min-1), along with selected ‘aggregated data’ models (M10, M13) and FBP-era surface fire models (C-3s, C-4s, C-6s).*

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) performed worse (higher MAE, MAPE, lower Efron’s R-squared) than the boreal conifer-based models (e.g. M13) when using ISI-based predictors. Also evident from this figure are the overprediction tendencies of the C-6S and (especially) C-4S models, irrespective of fuel type (Table 1).

## 5. Discussion

### Operational surface ROS models

This analysis presents a summary of several decades of experimental burning in conifer stands, focusing on fires identified as surface fires by original observers. 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. 2022a), the majority of surface fires occurred during moderate-level fire danger indices and wind speeds. Crown fire occurrence in conifer forests also depends on other factors such as canopy base height and surface fuel consumption (Cruz et al. 2004, Perrakis et al. 2023), factors which help explain the existence of a few surface fires (in tall jack pine or ponderosa pine stands) in our database under high danger conditions. 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).

There is therefore a paucity of surface fire observations under very dry and windy conditions (e.g, ISI > 15). As wildfire hazard reduction treatments become more popular, where stands with high CBH and low surface fuel loading are engineered to resist crown fire (Hirsch and Pengelly 1999, e.g., Agee and Skinner 2005), there is a need to estimate sROS under higher danger conditions.

##Indeed, some of the observations classed as surface fires clearly had some canopy fuel involvement, based on photographic evidence (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, for other observations, notably the two wildfires, we had no information on canopy fuel involvement. The uncertainty associated with these data adds to the lack of clarity around ROS under high danger (i.e., high ISI or ISIsa) conditions. ##move

##While physical fire spread models attempt to represent heat transfer and combustion processes, empirical and semi-empirical models are much easier and quicker to learn and use, and therefore preferable for operational fire predictions. ##delete?

The categorical fuel types of present Canadian FBP System rely 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 (Perrakis et al. 2018, Baron et al. 2024). Using continuous fuel attributes (rather than fuel types) is effective when stand attributes are measured or estimated, and provides users with greater control over model inputs. 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)). The present surface fire models involve mainly weather and moisture-related inputs, though fuel type and SFC were significant in some models. The primary value of such surface ROS models may be to inform modelling systems such as Conifer Pyrometrics (Perrakis et al. 2020a), where tools such as calculators and graphical dashboards allow users to test various fuel structure and weather scenarios. Since there was little difference in ROS between conifer fuel types, such models are inherently flexible and adaptable to a variety of stands and fire scenarios, though the expected accuracy may be lower than more refined models tailored to a specific fuel complex.

##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.

Our analysis suggested that little discernable difference between specific conifer fuel types exists at this scale. The influence of factors such as understory vegetation and phenology, 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). While the analysis suggested that the fastest spread was observed in jack pine stands compared to other pine species or mixed spruce-pine stands, there is little confidence in this finding, and the subtle differences would be better explored in theoretical or empirical laboratory experiments (Rossa and Fernandes 2018, e.g., Campbell-Lochrie et al. 2021). It seemed appropriate to aggregate boreal and sub-boreal pine and spruce fuel types 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). Deciduous observations were included for simple comparison purposes; however, no new data was provided beyond the range of the original D-1 spread model, which matches the noisy dataset adequately.

### Using final surface rate of spread models

Four models presented stand out as superior than the others (Table 1): Models 13 and 14 [crisi.con, crisim.con#], nonlinear curves fitted to boreal and sub-boreal conifer stands with the highest ER2 and lowest MAE values; Model 9 [isim2SFC.agg#], the best ‘aggregated data’ model and one of the lowest MAPE values; and perhaps the ‘25 % model’, the simplest model for rapid or emergency use. Model 13 uses the familiar ISI measure, based on open wind speed and the FFMC, while Models 9 and 14 take advantage of the additional flexibility of the Wotton and Beverly (2007) stand-adjusted litter moisture model and the *ISIsa* index introduced here. Although stand density class variables were not significant predictors of ROS on their own, 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 effect of such differences is small to moderate, however, and more extreme changes (e.g. deforestation or severe density reductions) are unlikely to be well represented. For instance, in a pine stand under FFMC 92, DMC 100, WS10=15 km h-1 conditions in summer, decreasing density from ‘high’ (H) to ‘moderate’ (M) or ‘low’ (L) conditions would result in an increase from 3.5 m min to 3.7 m min to 4.6 m min, respectively, using Model 9 and a constant estimated SFC of 1.5 kg m-2. Varying SFC between 0.6 and 3.5 kg m-2 would further stretch the prediction range, from 3.2 to 5.0 m min, holding weather indices constant. For models that include the SFC factor, the SFC influence is greatest at low ISI or ISIsa levels, and virtually disappears by ISI 15 or higher (Table 2).

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 (Van Wagner 1965a, 1973, Hummel 1979) 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, there is no substitute for additional surface fire observations. Additional observations spreading under high indices, necessarily with high LCBH and-or low SFC to avoid crowning, would 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. Extrapolation beyond the range of data (i.e. beyond ISI 19.2 or ISIsa 24.5 for conifer data) is not recommended. Should extrapolation be necessary, we recommend use of one of the sigmoidal-curve models (13 or 14), as the quadratic term models (with *ISI2* or *ISIsa2*) can easily produce extreme results. For example, the conditions in the above example (previous paragraph) but with WS10=40 km h-1 would produce predicted ROS of 51.4 m min-1 using Model 3. Model 13, a sigmoidal model, predicts much lower ROS (19.4 m min-1) under such conditions. While the actual sROS of this hypothetical example is unknown, ROS > 50 m min-1 in a conifer forest is much more likely to be encountered in fully developed active crown fires [Figure 2; see also Stocks (1989); Cruz et al. (2005)] than in any surface fire.

Finally, the 25% model is presented in the same vein as the Cruz and Alexander ‘10% rule’ (Cruz and Alexander 2019) and ‘20% rule’ (Cruz et al. 2022b) models - as an approximate value suitable for mental arithmetic and field use. However, the unit difference (km h-1 vs m min-1) is very important for users to understand. An equal comparison with, for instance, the 10% rule (same units) would actually equate to 1.5 % of the WS10, once the unit conversion is accounted for. This also suggests a finding of interest: on average, conifer crown fires are 5.6 times faster than surface fires under similar wind speeds, since the more accurate approximation for crown fires was 8.4 % of the WS10 (Cruz and Alexander 2019).

## `summarise()` has grouped output by 'isi.m < 12'. You can override using the  
## `.groups` argument.

## # A tibble: 4 × 4  
## # Groups: isi.m < 12 [2]  
## `isi.m < 12` `ROS < pred9` mape qape  
## <lgl> <lgl> <dbl> <dbl>  
## 1 FALSE FALSE 0.374 0.491  
## 2 FALSE TRUE 0.669 1.50   
## 3 TRUE FALSE 0.339 0.593  
## 4 TRUE TRUE 0.798 1.69

## `summarise()` has grouped output by 'isi.m < 12'. You can override using the  
## `.groups` argument.

## # A tibble: 4 × 4  
## # Groups: isi.m < 12 [2]  
## `isi.m < 12` `ROS < pred9` mae qae  
## <lgl> <lgl> <dbl> <dbl>  
## 1 FALSE FALSE 3.02 3.45  
## 2 FALSE TRUE 1.74 3.48  
## 3 TRUE FALSE 0.825 1.67  
## 4 TRUE TRUE 0.601 1.20

### Expected accuracy

The MAE and MAPE values (Table 1) can be used to calculate the mean and expected (e.g. 90th percentile) error associated with each model. 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.

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 some of the FBP-era models performed poorly. Negative values of Efron’s R-squared suggest that the C-4s and C-6s models perform worse than a null model using only the mean of all observations. Users of these models should expect significant overprediction using these models under most conditions.

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. Finally, it is evident from the database presented here that there is a need for more experimental burns, particularly in conditions where ISI > 12 or so. Given the current availability and familiarity with various fire behaviour models, it should not be an impossible task to plan for and execute moderate-speed and intensity experimental fires safely and fruitfully.

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## 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 0.000818 12.3 4.85e-21  
## 8 6. ISI2.agg I(ISI^2) 0.0164 0.00119 13.8 5.61e-24  
## 9 7. ISI2SFC.agg I(ISI^2) 0.0132 0.00127 10.4 1.29e-16  
## 10 . sqrt(SFC) 0.958 0.208 4.61 1.44e- 5  
## 11 8. isim2.agg I(isi.m^2) 0.0176 0.000982 18.0 1.68e-31  
## 12 9. isim2SFC.agg I(isi.m^2) 0.0153 0.00111 13.8 4.50e-23  
## 13 . sqrt(SFC) 0.596 0.183 3.25 1.65e- 3  
## 14 10. crisi.agg b 0.0421 0.00800 5.26 9.80e- 7  
## 15 . c 1.99 0.317 6.28 1.19e- 8  
## 16 11. crisim.agg b 0.0467 0.00707 6.60 2.88e- 9  
## 17 . c 2.20 0.308 7.14 2.46e-10  
## 18 12. axb.isi.agg a 0.0957 0.0348 2.75 7.22e- 3  
## 19 . b 1.39 0.132 10.6 2.19e-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