Simple spread models for conifer surface fires

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## Abstract

Surface fire behaviour is the most frequent type of wildfire activity that occurs in conifer forests. Surface rate of spread (ROS) 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 ROS under light-to-dense canopy stands that can be readily integrated within operational decision support systems. Final models are based on the Canadian Initial Spread Index (ISI) or stand-adjusted ISI (ISIsa), with options for other predictors such as estimated surface fuel consumption (SFC) or fuel type. The simplest model finds surface ROS equal to 1.5 % of open 10 m wind speed. While imprecise, these models are usually accurate enough (within +/- 2–4 m min-1) for many forecasting and fire management purposes.

## 1. Introduction

The rate of spread (ROS), or rate of forward advance, of a wildfire is probably its most important descriptive characteristic for fire managers [1,2]. Fire behaviour in the conifer forests of Canada is often a story about crown fire, featuring high spread rate and intensity, a rain of lofted embers and few suppression options [3]. And yet in the chronology of fire events, most days between ignition and extinction feature only ground or surface fire behaviour [4]. Surface fires can often be safely and routinely actioned by suppression crews and equipment [5], 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 distinct conifer fuel complexes [6,7]. 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 CE Van Wagner during the system’s development [8]. However, more flexible conifer modelling schemes are emerging that specify 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 [9–11]. These systems 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 types lacking a flammable overstory: leafless deciduous forests (D-1), open vegetation (i.e. grassland; O-1), and scattered logging slash (S-1 through S-3) [6]. As with the conifer fuel types, surface ROS (sROS) equations are based on the sigmoidal Chapman-Richards function [8]:

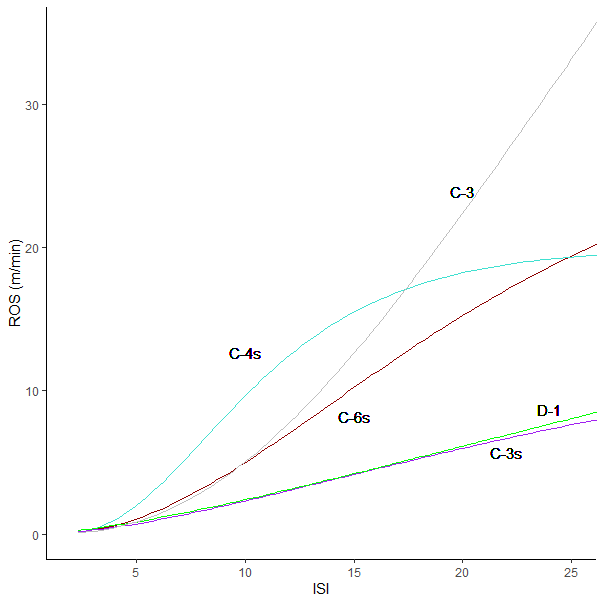
[1],

with the a, b, and c parameters assigned or fitted from data, and *ISI* representing the Initial Spread Index from the Fire Weather System [12]. Newer surface fire models have also been developed for grass [13,**Kidnie.Wotton2015?**] and Atlantic shrublands [14]. A few older sROS models were previously published based on individual field experiments [e.g., 15], 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, CE Van Wagner proposed a more flexible theoretical dual equilibrium conifer crown fire model concept. This involved two notional functions describing the expected ROS of crown fires, RSC, and “all possible surface fires”, RSS [8], with a crown fire initiation model representing the transition point between the two [16]. 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 (FCFDG 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 [17]. The immature stand was the source of many observations from the C-4 fuel type [18], with the following parameters (“C-4s”): *a*=20, *b*=0.20, *c*=5. Surface fire observations from mature pine stands [C-3; [19]] were used to form another RSS model (“C-3s”): *a*=15, *b*=0.05, *c*=2 [17]. No statistics or other source were provided for the origin of these models (C-3s, C-4s, C-6s). Figure 1 compares these notional conifer surface fire ROS models along with the D-1 and C-3 models for comparison (c.f. [6]). These existing surface ROS models will be used as benchmarks to compare with new formulations.

### [Fig1]



*Caption: Figure 1. Comparison of FBP System and associated fuel type surface fire rate of spread (ROS) models. D-1, C-6s, and C-3 have previously been described. C-4s and C-3s refer to surface fire models proposed by Van Wagner for immature and mature jack pine fires, respectively. ISI refers to the Initial Spread Index. See text for references.*

### 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 [10,11,20].

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., 21,22,23]. However, this involves detailed studies of wind interactions with fuel structure, including edge effects [24,25], 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 [26]. This is appropriate for such tools as can be readily adapted to operational use, but means they are less accurate due to the significant influence of forest structure, including the effects of edges and openings on moisture and ground-level winds [27,28].

## 2. Methods

### Fire database

The source data for these analyses is a slowly growing database of field-scale experimental burns conducted at various sites across Canada since the 1960s. These data have previously been described and analyzed [e.g. 29,30,31], 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). In addition to the boreal conifer data, 32 experimental fire observations were available in deciduous stands. These were originally described by Alexander and Sando [32], featuring 6 fires in aspen stands from the US lake states; Quintilio et al. [33]: 14 aspen stands near Hondo, Alberta; and Van Wagner [34]: aspen (9), oak (2), and aspen-dominated mixedwood (1) at Petawawa, Ontario. Seven experimental fires in Ponderosa pine- Douglas-fir (PPDF) stands in British Columbia were also included, analyzed uniquely (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. This generated a full database of 153 observations: 61 crown fires and 92 surface fires, as described in primary sources. The present analysis was restricted to surface fires, though some nuances related to torching and crown fuel consumption are discussed below. Models were compared using common evaluation metrics for linear and non-linear models: root mean squared error, mean absolute error, mean absolute percentage error Ephron’s pseudo r-squared.

### Modelling and spread indices

Consistent with longstanding theoretical understanding of fire processes [21,35,36] and the majority of existing empirical models [37,38], we anticipated that wind speed and dead fuel moisture content would be primary variables of interest. In particular, the aforementioned unitless *ISI* that combines empirical functions representing wind speed and fuel moisture influences [12] was already the main independent variable used for predicting ROS in the FBP System [39]. Other variables we examined for significance included moisture indices from the FWI System (the Fine Fuel Moisture Code, FFMC, and Duff Moisture Code, DMC), and surface fuel consumption (SFC), which must be estimated or modelled separately for prediction purposes.

In addition to the basic ISI, we also explored a modification using a more flexible fuel moisture model, the stand-adjusted moisture content (*mcsa*) model of Wotton and Beverly [31,40]. The *mcsa* combines the effects of the FFMC and DMC indices along with categorical stand type, density, and season variables for directly predicting the moisture content of dead litter. The *mcsa* was combined with wind speed using the same formulation as originally described for the ISI, but with the mcsa in place of the simple FFMC-based estimate for dead fuel moisture [12]. The full *ISIsa* equation is provided for completeness:

[5].

For model feature selection, 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 [40]); this included transformed terms: *WS10*2, *ISI2*, *ISIsa2*, *SFC2*, and *sqrt(SFC)*. All variable combinations (1-4 predictors) were tested using the ‘leaps’ package in R [41]. We also tested 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

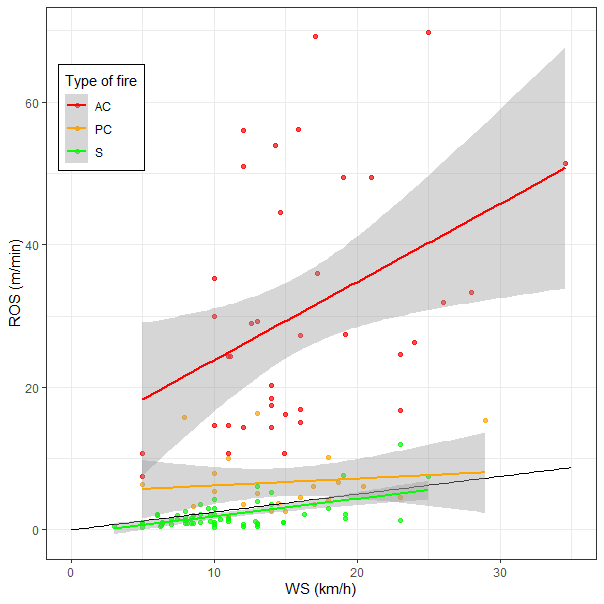
For the PPDF fires, we sought to incorporate the effects of understory grass and herbaceous curing effects on fire behaviour [42,43]. This involved normalizing all observations, following Cheney and Gould [44], to a nearly fully cured grass condition (95 % C) in order to estimate near-peak seasonal spread rate. Although the grass biomass in these stands only represented a fraction (~3 %) of the total available surface fuel, grass curing is has been observed by operational practitioners to have a strong influence on ROS in these stands [45]. We assumed that understory herbaceous curing would be 50 % as influential compared to a true grassland, and calculated new 95% C estimated ROS (*ROS’*) values for these plots, as follows:

[6], where *ROS0* represents the observed rate of spread with measured curing *C* (see Box 1), and *cf(C)* and *cf(95)* represent the calculated curing factors at measured % C values and 95% C, respectively [46]. *ROS’* values for these seven PPDF fires were then used in fitting the ‘aggregate’ model analyses and fuel type-based models, but excluded from the boreal conifer models.

## 4. Results

### Initial data exploration and model building

Simple inspection our fire database revealed obvious patterns. Among fires in conifer fuel types (surface and crown), a clear, though noisy relationship is evident between fire type and rate of spread predicted by wind speed (Fig. 2).



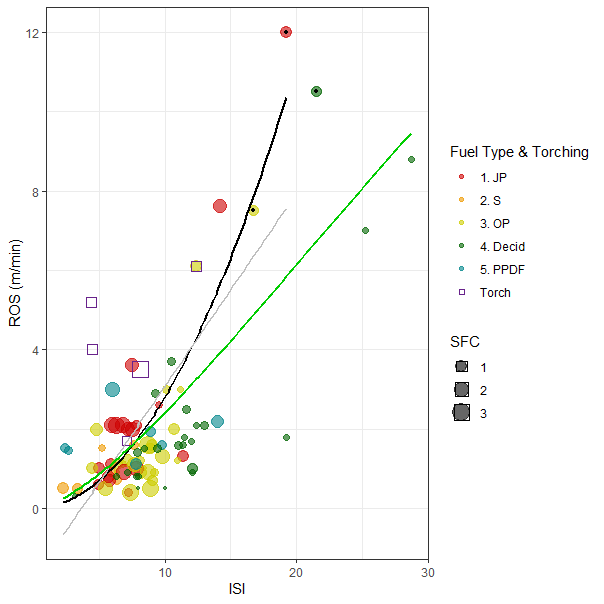
*Caption: Figure 2. Overview of experimental burn observations by wind speed (WS), rate of spread (ROS) and type of fire showing simple linear trends. S, PC, and AC refer to surface, passive crown, and active crown fire behaviour types, respectively. The black line represents the ‘25 % model’ for surface 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.). Surface and passive crown fire observations overlap above ROS of approximately 4 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 ; adjusted *R2* = 0.319), with a slope of 0.2459. We noted that this is quite close to a slope of 0.25, a model conducive to mental arithmetic and rapid emergency use, particularly if forced through the intercept.

The extensive search revealed ISI and ISIsa to be strong predictors of ROS, as expected. The best 1-4 variable sROS predictor combinations all contained one of these variables as linear or squared terms or in non-linear form*.* 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). In particular, *ISIsa2* was the best single predictor and part of all 2-4 variable combinations using the aggregate dataset. For the conifer-only data, ISI was slightly superior, with *ISI2* being the best single variable and present in half (6/12) of all best fit models.

We evaluated the most promising model forms based on search results in terms of variable significance and other diagnostics (Supplemental Table S1). Figure 3 shows the ROS of surface fires classified by fuel type (FT) and surface fuel consumption level, displayed by ISI value, along with a few simple fitted models and the D-1 FBP model. While all fires were initially classed as surface fires, several observations appeared anomalous, particularly those with significant levels of canopy fuel consumption (CFC), suggesting canopy fuel involvement. Fires with estimated CFC > 0.2 kg m-2 (mean CFC: 0.35 kg m-2; Fig. 3) were then removed from the dataset as these were considered transitional to crown fire. Figure 3 also shows a linear sROS model based on ISI (Model 2: ER2=0.469), as well as the better-fitting model forced through the origin using *ISI2* (Model 3: ER2=0.613).

### [Fig3]



*Caption: Figure 3. Fire observations showing rate of spread (ROS) by ISI. Most symbols represent experimental fires except those with a black centre are wildfires. Colours indicate fuel type and fire characteristics as follows: JP: jack pine; S: black spruce or pine-spruce mix; OP: other pine; Decid: deciduous; PPDF: ponderosa pine-Douglas-fir; Torch: torching or passive crown fire behaviour (removed from surface model analysis). Symbols with a black centre indicate wildfires. Size indicates relative surface fuel consumption (SFC, kg m-2). The lines represent linear (Model 2: gray) and squared (Model 3: black) ISI models fitted to conifer observations (JP, S, OP), along with the FBP D-1 model (green).*

The influence of conifer fuel type (FT) was only significant when combined with *ISI2* or *ISIsa2* in the boreal conifer-only fires. The lone surface fire observation in black spruce was grouped with five observations in mixed jack pine- black spruce in order to separate spruce-containing observations (S) from the pine-type fires. There were 19 fires in jack pine (JP), and 26 in stands dominated by other pine species (OP); see [31] for details. Although FT was significant, the only significant contrast (‘multcomp’ R package: Tukey HSD: ) was between OP and JP, with OP fires exhibiting slightly slower ROS compared with JP fires (Fig. 3).

Most model forms using more than one or two predictors were non-significant () owing to the modest sample size and high variability. Stand density class was not significant in any models.

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

Seven\* experimental fires were conducted in open 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[**Nyberg1979?**] and Smaill [47], while summary information and photos were incorporated into the FBP System C-7 fuel type [39,48]. In the FBP System database, surface fuel consumption (SFC) was reported for only one observation (Plot 9), with a very high total SFC value of 5.3 kg m-2, including > 5 kg m-2 of woody fuel consumption.

Original copies of these documents were reanalyzed in order to better describe these fires and improve the modelling database. Stand structure at Dewdrop consisted of a low density overstory and mostly herbaceous understory; mean canopy closure was 27.2 %. Litter and duff cover were described as patchy to nonexistent [**Nyberg1979?**].

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 [18,19], the Plot 9 CWD consumption represents the great majority of the total SFC and represents an outlier compared to other experiments. For instance, the mean CWD proportion of SFC at the Ontario Kenshoe Lake and Sharpsand Creek sites was 9.2 % [c.f. 18,19], compared with 50.2 % at Dewdrop (Mann-Whitney U-test: p < 0.001). The difference is accounted 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 [12] for DC description), and probably the overall frequency of larger diameter trees at Dewdrop (> 17 % of trees in the ‘>25 cm’ DBH class; cf. [**Nyberg1979?**]); compared with other sites (e.g., ~ 1 % of trees in the ‘> 23 cm’ DBH class at Kenshoe Lake (‘White River’); [49]).

Including contributions from CWD 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 [50–52]. The high SFC at Dewdrop from CWD therefore could overpredict fire intensity and crown fire tendency [31,53]. 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 [**Nyberg1979?**], an unusual occurrence in this summer-dry climate. Consequently, understory vegetation remained relatively green during the 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 [46,54]:

[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, reported values are unfortunately less explicit between live and dead biomass [47] and eq. B1 could not be used. Based on the slightly lower overall grass moisture value (22.7 %) and late season 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 deciduous experiments.

\*Plot numbers 1–6, burned in 1978, are described by [**Nyberg1979?**]. Plot 9, burned in 1979, is described by [47]. 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. [55], 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]

Table 1: Table 1

|  |  |  | Predicted ROS (m/min) | | | Evaluation metrics | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Num | Formula | N | ISI=5 | ISI=10 | ISI=15 | RMSE | MAE | MAPE | ER2 | AIC |
| 1 | b0 +ws | 65 | -0.3 | 2.9 | 4.8 | 1.60 | 1.130 | 0.788 | 0.330 | 251.7 |
| 2 | b0 +ISI | 56 | 0.7 | 3.1 | 5.5 | 1.53 | 1.140 | 0.851 | 0.469 | 212.3 |
| 3 | ISI2 | 56 | 0.7 | 2.8 | 6.3 | 1.30 | 0.940 | 0.668 | 0.613 | 192.7 |
| 4 | ISIsa2 | 56 | 0.6 | 2.3 | 5.3 | 1.39 | 0.984 | 0.639 | 0.560 | 199.8 |
| 5 | WS2 | 91 | 0.0 | 2.0 | 4.9 | 1.92 | 1.250 | 0.660 | 0.258 | 381.4 |
| 6 | ISI2 | 91 | 0.4 | 1.6 | 3.7 | 1.79 | 1.190 | 0.566 | 0.361 | 367.8 |
| 7 | ISI2 + sqrt(SFC) | 84 | 1.5 | 2.5 | 4.1 | 1.58 | 1.110 | 0.734 | 0.516 | 321.2 |
| 8 | ISIsa2 | 91 | 0.4 | 1.8 | 4.0 | 1.47 | 1.060 | 0.562 | 0.564 | 332.9 |
| 9 | ISIsa2 + sqrt(SFC) | 84 | 1.1 | 2.3 | 4.2 | 1.32 | 0.957 | 0.602 | 0.662 | 291.0 |
| 10 | 25 \* (1 - exp(-b \* ISI))^c | 91 | 0.8 | 2.4 | 4.4 | 1.62 | 1.170 | 0.735 | 0.474 | 352.2 |
| 11 | 25 \* (1 - exp(-b \* ISIsa))^c | 91 | 0.7 | 2.3 | 4.4 | 1.43 | 1.040 | 0.655 | 0.593 | 328.7 |
| 12 | a \* ISI^b | 91 | 0.9 | 2.4 | 4.2 | 1.62 | 1.170 | 0.750 | 0.471 | 352.6 |
| 13 | 25 \* (1 - exp(-b \* ISI))^c | 51 | 0.3 | 2.5 | 6.8 | 0.98 | 0.779 | 0.599 | 0.781 | 148.7 |
| 14 | 25 \* (1 - exp(-b \* ISIsa))^c | 51 | 0.3 | 2.2 | 5.5 | 1.08 | 0.852 | 0.646 | 0.733 | 158.8 |
| 15 | ISI \* FT | 91 | 0.2 | 3.0 | 5.8 | 1.36 | 1.020 | 0.779 | 0.629 | 328.3 |
| 16 | C-3s | NA | 0.7 | 2.3 | 4.2 | NA | 0.880 | 0.590 | 0.570 | NA |
| 17 | C-4s | NA | 2.0 | 9.7 | 15.5 | NA | 4.530 | 3.820 | -5.360 | NA |
| 18 | C-6s | NA | 1.1 | 5.0 | 10.2 | NA | 1.720 | 1.530 | -0.050 | NA |
| 19 | D-1 | NA | 0.9 | 2.4 | 4.2 | NA | 0.900 | 0.640 | 0.570 | NA |
| 20 | 25 % WS\_10 | NA | 0.1 | 3.5 | 5.5 | 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 (WS10), initial spread index (ISI), stand-adjusted ISI (ISIsa), surface fuel consumption (SFC, kg m-2), and fuel type (FT). ISI/ISIsa columns represent predicted ROS (m min-1) for given models at each predictor level. Constants used in prediction calculations include FFMC 91 (Models 1, 5, 19), SFC of 1.5 kg m-2 (Models 7 and 9), and fuel type ‘Conifer’ (Model 15). Evaluation metrics are unitless and 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 51 boreal 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, FT) were assigned 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 included fires in deciduous stands and PPDF fires (Box 1) as well as three wildfires. Boreal conifer models used only the aforementioned fires in spruce, pine-spruce, or boreal/sub-boreal pine [for site and experimental descriptions see 31]. Models 2–4 included all such fires, while models 5–15 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 analogous models fitted to the larger aggregated dataset (Models 5 – 12, 15). 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 [17], an intermediate value between the low (15: C-3s) and high (30: C-6s, D1) values used previously. 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 0.662, 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. When fitted to the deciduous data alone, the D-1 model had the following diagnostics: RMSE=0.568; MAE=1.297; MAPE=0.988; ER2=0.543.[[1]](#footnote-1) There were no advantages to the model (Model 12) over other model forms.

### [Table 2: Extended SFC predictions]

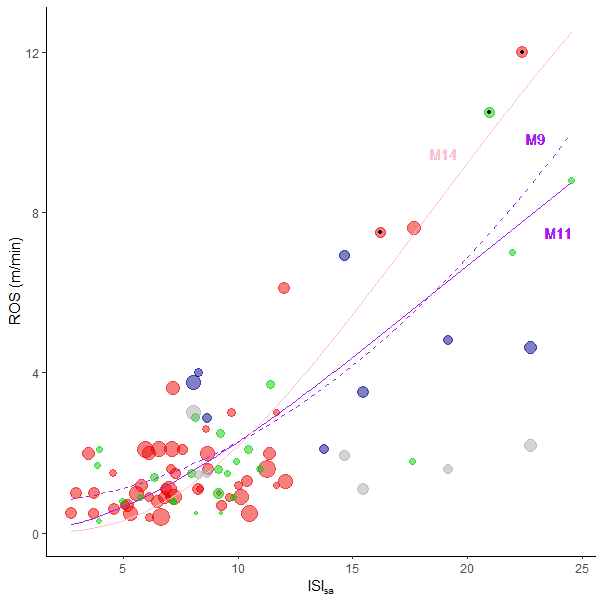
Table 1: Extended prediction table for multivariate models

|  |  |  | Predicted ROS (m/min) | | |
| --- | --- | --- | --- | --- | --- |
| Model (predictors) | SFC (kg/m2) | FT | ISI=5 | ISI=10 | ISI=15 |
| 7 (ISI, SFC) | 0.7 | Agg | 1.13 | 2.12 | 3.76 |
| 7 (ISI, SFC) | 1.5 | Agg | 1.50 | 2.49 | 4.13 |
| 7 (ISI, SFC) | 3.0 | Agg | 1.99 | 2.98 | 4.62 |
| 7 (ISI, SFC) | 5.0 | Agg | 2.47 | 3.46 | 5.10 |
| 9 (ISI\_sa, SFC) | 0.7 | Agg | 0.88 | 2.03 | 3.95 |
| 9 (ISI\_sa, SFC) | 1.5 | Agg | 1.11 | 2.26 | 4.18 |
| 9 (ISI\_sa, SFC) | 3.0 | Agg | 1.42 | 2.57 | 4.49 |
| 9 (ISI\_sa, SFC) | 5.0 | Agg | 1.72 | 2.87 | 4.79 |
| 15 (ISI, FT) | NA | Decid | 0.31 | 1.96 | 3.61 |
| 15 (ISI, FT) | NA | Con | 0.20 | 2.98 | 5.76 |
| 15 (ISI, FT) | NA | PPDF | 3.73 | 4.42 | 5.12 |

*Caption: Table 2. Extended predictions for models 7 and 9, using varying values of predicted Surface Fuel Consumption (SFC; Models 7 and 9) from 0.7 kg m-2 to 5.0 kg m-2, fuel types (FT; Model 15) Deciduous (Decid), Conifer (Con) or Ponderosa pine-Douglas-fir (PPDF, adjusted to 95% cured), and ISI or ISIsa values from 5 to 15. See Table 1 for model predictor forms.*

Table 2 shows extended ROS predictions for the three models with two predictors: *ISI* (or *ISIsa*) and *SFC,* and *ISI* and fuel type. SFC-based models used 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*: 0.489 ; *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]



*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 as follows: red: boreal conifer; blue: ponderosa pine-Douglas-fir (PPDF) adjusted to seasonally cured condition; 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: M9 (calculated at SFC=1.5 kg m-2), M11, and M14 (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. Fuel type (Con, PPDF, or Decid) was not significant in any form of model using ISIsa.

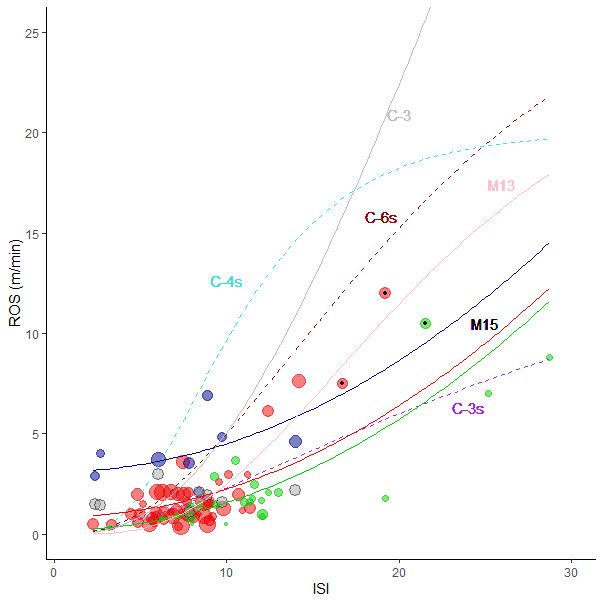
Figure 5 shows the observations and selected model predictions based on the ISI, along with certain benchmark models. Model 15 is shown separated by FT category, boreal conifer (Con), PPDF (95% cured), or deciduous (Decid) categories. For ROS prediction purposes, Decid < Con < PPDF (see Table 1 and Appendix 1); however, only the Con-PPDF and Decid-PPDF differences were significant (Tukey’s HSD; ). Also evident from Figure 5 are the noted overprediction tendencies of the C-6s and (especially) C-4s models.

As Table 1 indicates, ‘aggregated’ dataset models (e.g. M10, M15) performed generally worse (higher MAE, MAPE, lower Efron’s R-squared) than the boreal conifer-based models (e.g. M13) when using ISI-based predictors, although M15 performed relatively well overall, with MAE < 1 and ER2 of 0.585.

#### Influential observations #not sure if this is needed

Individual observations were evaluated for leverage in the best models using Cook’s Distance for linearized models (Models 7 and 9#) and jackknife resampling for non-linear models (‘nlstools’ R package, v2.1; [56]). For non-linear models 13 and 14#, 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 [56]. For linearized models, observations with Cook’s D > 0.1 were flagged as influential. 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 affecting the models and range of inference. Primary source descriptions that exist for these fires [e.g. 57] suggest low confidence in these observations, unsurprisingly.

### [Fig 5]



*Caption: Figure 5. Surface fire observations by ISI, ROS, and fuel type (FT): green (deciduous; Decid), blue (Ponderosa pine-Douglas-fir; PPDF), or red (boreal conifer; Con), along with sigmoidal model M13 (Con only), fuel type (FT) category model M15 (Con, Decid and PPDF), and FBP-era models (C-3s, C-4s, C-6s, C-3). PPDF fires are shown both with their original observed ROS (gray, not modelled), and normalized to 95% cured condition (blue, modelled). Model labels are colour-coded to line colour except for M15.*

## 5. Discussion

### Operational surface ROS models

This analysis summarizes the findings from Canadian fire behaviour experiments, 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 [16,58,59], 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 [31,60], 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 (i.e., dry and windy). 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). Overall, these fires represent a range of ROS values (0.3–12.0 m min-1) previously described as ‘slow’ to ‘fast’, but primarily in the ‘moderately slow’ (1–3 m min-1) to ‘moderately fast’ (3–10 m min-1) category [61].

There is therefore a paucity of surface fire observations under very dry and windy conditions (e.g, ISI > 15, ROS > 5 m min-1). As wildfire hazard reduction treatments become more popular, where stands with high CBH and low surface fuel loading are engineered to resist crown fire [e.g., 62,63], there is a need to estimate sROS under higher danger conditions. The lack of data creates uncertainty that cannot be solved by these models alone.

While the ISI is old and familiar, it was the strongest ROS predictor, performing better than other combinations of weather or moisture index variables. The ISI was recently found to be the variable most closely correlated to area burned during the record-breaking 2023 Canadian wildfire season [64]. Database values used in the analysis represent indices that best represent burning conditions according to primary sources; for forecasting purposes, we expect hourly ISI values to perform better than daily values [65]. The ISIsa adds some additional influences based the stand-adjusted moisture estimate models [40], including the ability to adjust for stand density and more persistent forest floor drought (as represented by the DMC).

The present surface fire models involve mainly weather and moisture-related inputs, with some influence from fuel type and SFC in some models. The primary value of such surface ROS models may be to inform varying fuel structure scenarios in modelling systems such as Conifer Pyrometrics [10,66], where tools such as calculators and graphical dashboards allow users to test various fuel structure and weather scenarios. There was little difference in ROS between most conifer fuel types (e.g., pine species, spruce); however, differences in experimental design (e.g. plot size, fuelbreak width, wind monitoring) preclude precise comparisons. Laboratory experiments have suggested that conifer litter characteristics, including species, affect flammability [36,67]; however, differences are not always exhibited in real world examples given the complexity of fuebeds and diversity in natural forest ecosystems. 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 deciduous fire experiment dataset adequately.

### Using final surface rate of spread models

Four or five models presented stand out as superior than the others (Table 1): Models 13 and 14, sigmoidal 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; Model 15, which showed some flexibility to fuel type, particularly between PPDF and the other conifer and deciduous fires; and perhaps the ‘25 % model’, the simplest model for rapid or emergency use. Model 13 used the familiar ISI measure, based on open wind speed and the FFMC, while Models 9 and 14 took advantage of the additional flexibility of the stand-adjusted litter moisture model and the *ISIsa* index.

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., 68,69]. However, the effects of such differences are relatively small in the present models 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 to 3.7 to 4.6 m min-1, respectively, using Model 9 (assuming SFC of 1.5 kg m-2): a maximum density-dependent difference () of 1.1 m min-1. Varying SFC between 0.5 and 3.5 kg m-2 would further stretch to 1.8 m min-1, holding weather indices constant. This is a small difference for capturing the sometimes significant changes that can ensue from partial harvesting , for instance; tree density can potentially decrease by 70-80% or more as in certain hazard reduction treatments [70,71]. The present models are appropriate for moderately closed to closed conifer stands; a lower limit for crown closure would likely to be near 20 % (the level of opening of the more open PPDF and jack pine experiments). Below this limit, very open forest and parkland or savannah-type stand structure would have much greater wind penetration [24,72] and could potentially support significantly faster surface fire spread than appears in our data. 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 [34,57,73] 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, monitoring techniques were very simplistic compared to modern methods [e.g. 74,75]. In general, for improving empirical models, there is no substitute for additional high quality observations. Additional surface fire 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. At present, 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), to avoid the more extreme results potentially generated by quadratic term models (with *ISI2* or *ISIsa2*). For example, the conditions in the previous example (pine stand in summer, density discussion) but with WS10=40 km h-1 (producing ISI of 42.8) would produce predicted ROS of 51.4 m min-1 using Model 3. Model 13, a sigmoidal model, predicts much lower ROS (22.9 m min-1) under such conditions. While the actual sROS of this hypothetical example is unknown (and users might expect true ROS to be +/- 50 % of the predicted value), 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 [19]; [76]] than in any surface fire under a canopy.

Finally, the 25% model is presented in the same vein as the Cruz and Alexander ‘10% rule’ [77] and ‘20% rule’ [78] models - as an approximate value suitable for mental arithmetic and rapid field use. However, the unit difference (km h-1 vs m min-1) is critical for proper usage. An equal comparison with, for instance, the 10% rule (same units) equates to 1.5 % of the WS10. This also suggests a finding of interest: on average, experimental conifer crown fires are 5.6 times faster than experimental surface fires under similar wind speeds, since the more accurate approximation for crown fires was 8.4 % of the WS10 [77] (8.4/1.5=5.6).

[Table 3. ]

| ISI\_sa | Prediction | MAE | Q90AE | MAPE | Q90APE |
| --- | --- | --- | --- | --- | --- |
| High | over | 1.74 | 3.48 | 0.67 | 1.50 |
| High | under | 3.02 | 3.45 | 0.37 | 0.49 |
| Low | over | 0.60 | 1.20 | 0.80 | 1.69 |
| Low | under | 0.83 | 1.67 | 0.34 | 0.59 |
| Note: The threshold between 'High' and 'Low' ISI\_sa values is 12 | | | | | |

*Caption: Table 3. Expected model accuracy, Model 9.*

### Expected accuracy

The MAE and MAPE values (Table 1) can be used to calculate the mean and expected (e.g. 90th percentile or quantile) error associated with each model. Table 3 shows the mean and 90th quantile absolute error (MAE, Q90AE, respectively) and absolute percentage error (MAPE, Q90APE, respectively) using the example of Model 9, with . Since there appeared to be a difference between the over- and under-prediction error potential at lower versus higher fire danger levels (e.g., Fig. 4), these categories are shown separately. Thus, Surface ROS errors of 1-2 m min-1 (approximate rounding of mean and Q90 absolute error of 0.6 – 1.7; Table 3) should be expected below ISIsa 12; and larger errors of perhaps 2-4 m min-1 (mean and Q90 absolute error of 1.7 – 3.5) may be expected in real world use between ISIsa 12 and 25. In approximate percentage terms, underprediction by 30-60 %, and overprediction by 70-170 % is to be expected with these models. Under very low danger conditions (e.g., FFMC < 75 or ISI < 1), ignition in needle fuel substrates becomes highly unlikely [79,80], so ROS is a minimal concern.

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 in real world use (assuming surface fire behaviour is expected) under most conditions, based on the available data.

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. Barring that, gleaning additional data from wildfires [75,81] could provide many additional observations, albeit with challenges to accurately characterize fuel structure and weather.

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## 7. Appendix: Final model coefficients

## # A tibble: 29 × 6  
## Model Term Estimate std.error statistic 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 0.0326 0.00640 5.09 2.01e- 6  
## 15 . c 1.84 0.268 6.86 8.80e-10  
## 16 11. crisim.agg b 0.0373 0.00583 6.40 7.19e- 9  
## 17 . c 2.05 0.266 7.72 1.65e-11  
## 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 0.0924 0.00985 9.38 1.62e-12  
## 21 . c 4.54 0.645 7.04 5.75e- 9  
## 22 14. crisim.con b 0.0710 0.00909 7.81 3.76e-10  
## 23 . c 3.60 0.542 6.65 2.32e- 8  
## 24 15. ftisi ISI 0.556 0.0654 8.51 5.40e-13  
## 25 . FTCon -2.58 0.560 -4.60 1.44e- 5  
## 26 . FTDecid -1.34 0.559 -2.40 1.86e- 2  
## 27 . FTPPDF 3.03 1.16 2.61 1.07e- 2  
## 28 . ISI:FTDecid -0.226 0.0794 -2.85 5.56e- 3  
## 29 . ISI:FTPPDF -0.417 0.154 -2.70 8.42e- 3

1. Note: the dataset for the D-1 model originally described by [39] differs only from present deciduous database by two additional wildfires, excluded here to a lack of documentation. [↑](#footnote-ref-1)