Simple spread models for conifer surface fires

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## 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 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. 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 (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]; FCFDG 1992 hereafter]. As with the conifer fuel types, surface ROS (sROS) equations are based on the sigmoidal Chapman-Richards function [8]:

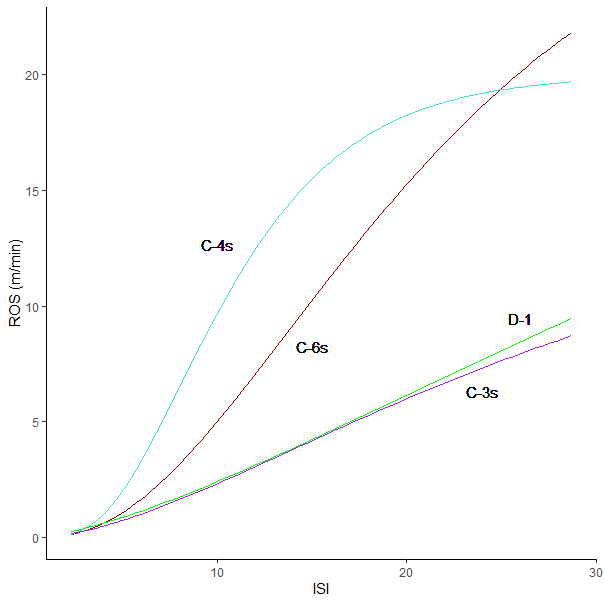
[1],

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 [13,14] and Atlantic shrublands [15]. A few older sROS models were previously published based on individual field experiments [e.g., 16], 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 [17]. 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 [18]. The immature stand was the source of many observations from the C-4 fuel type [19], with the following parameters (“C-4s”): *a*=20, *b*=0.20, *c*=5. Surface fire observations from mature pine stands [C-3; [20]] were used to form another RSS model (“C-3s”): *a*=15, *b*=0.05, *c*=2 [18]. 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 model for comparison (*a*=30, *b*=0.0232, *c*=1.6; FCFDG 1992). As the figure shows, as fire danger levels increase (i.e., higher ISI), predicted surface ROS predictions diverge widely between these models, with C-3S and D-1 curves predicting the lowest and the C-4S predicting the highest values, respectively. These models will be used as familiar benchmarks for the newly fitted models.

### [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 [11,21,22].

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., 23,24,25]. However, this involves detailed studies of wind interactions with fuel structure, including edge effects [26,27], 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 [28]. 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 ground-level winds [29,30].

## 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. 31,32,33], 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 [34], featuring 6 fires in aspen stands from the US lake states; Quintilio et al. [35: 14 aspen stands near Hondo, Alberta]; and Van Wagner [36 : 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.

### Modelling and spread indices

Consistent with longstanding theoretical understanding of fire processes [23,37,38] and the majority of existing empirical models [39,40], 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 (FCFDG 1992). 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 [41,see also 33]. 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 mcFFMC [estimated fine fuel moisture content based on the FFMC; [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 [41]); 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 [42]. 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 [43,44]. This involved normalizing all observations, following Cheney and Gould [45], 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 [46]. 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 [47]. *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.

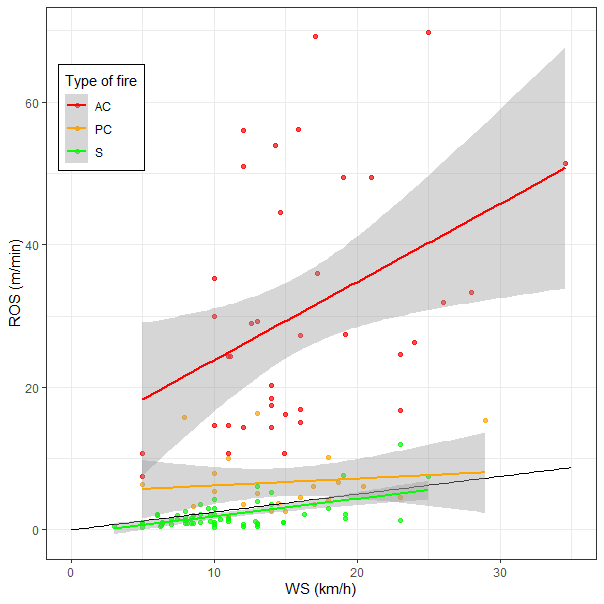
## 4. Results

#### Dataset and fire types

An initial exploratory analysis of our fire database revealed some obvious patterns. 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. 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 (see Appendix 1 for all model formulas and statistics). Due to the negative y-intecept, this model is limited to conditions where *WS10* > 2.38 km h-1. In addition, simple inspection suggested that a very simple arithmetic model, similar to Model 1 but forced through the intercept, would result from the 0.25 *WS10* function (Figure 2, black line; ‘25 % model’ hereafter).

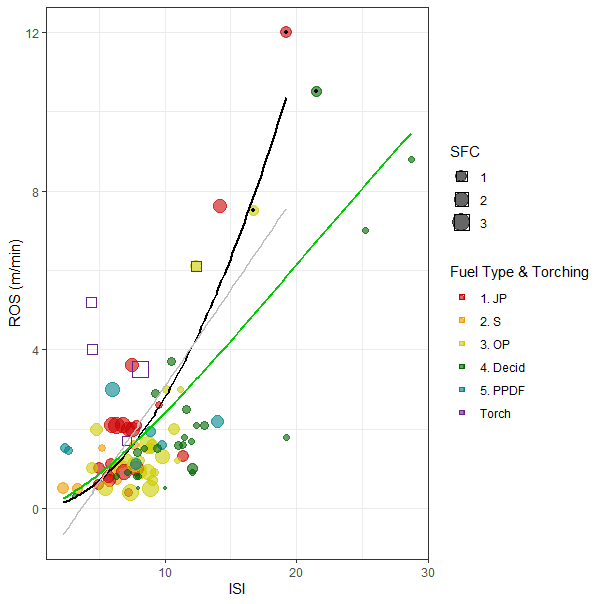
### Initial data exploration and model building

As expected, the extensive search revealed ISI and ISIsa to be strong predictors of ROS. 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 (see below). 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; highlighted in Figure 3) were then removed from the dataset as these were considered transitional to crown fire. Other possible outliers included PPDF fires and wildfires.

While a linear sROS model based on ISI was statistically significant (Model 2), the model forced through the origin using *ISI2* gave a much better fit (Model 3).

### [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; Decid: deciduous; PPDF: ponderosa pine-Douglas-fir; Torch: torching or passive crown fire behaviour (removed from surface model analysis). Size indicates relative surface fuel consumption (SFC). The lines represent linear (Model 2: gray) and quadratic (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) only emerged as a significant predictor when combined with *ISI2* or *ISIsa2* in the conifer-only dataset. 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 stand observations. There were 19 fires in jack pine (JP), and 26 in stands dominated by other pine species (OP), including lodgepole (*P. contorta*), red (*P. resinosa*), and white pine (*P. strobus*)-red pine stands. Although FT was significant in this model, 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).

As we refined the list of potentially usable models, variables were only retained when statistically significant () in order to reduce overfitting concerns. 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 as a standalone variable 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[48] and Smaill [49], while summary information and photos were incorporated into the FBP System C-7 fuel type [50,51]. 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 improve the fire 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 (Nyberg 1979).

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), 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 % (cf. Stocks 1987, 1989), 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 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 sites (e.g., ~ 1 % of trees in the ‘> 23 cm’ DBH class at Kenshoe Lake (‘White River’); [52]).

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 [53–55]. 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 [48], 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 [47,56]:

[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 [49] 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. [57], 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: Model summary]

## Loading required package: gt

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 | I(ISI^2) | 56 | 0.7 | 2.8 | 6.3 | 1.30 | 0.940 | 0.668 | 0.613 | 192.7 |
| 4 | I(isi.m^2) | 56 | 0.6 | 2.3 | 5.3 | 1.39 | 0.984 | 0.639 | 0.560 | 199.8 |
| 5 | I(ws^2) | 91 | 0.0 | 2.0 | 4.9 | 1.92 | 1.250 | 0.660 | 0.258 | 381.4 |
| 6 | I(ISI^2) | 91 | 0.4 | 1.6 | 3.7 | 1.79 | 1.190 | 0.566 | 0.361 | 367.8 |
| 7 | I(ISI^2) + sqrt(SFC) | 84 | 1.5 | 2.5 | 4.1 | 1.58 | 1.110 | 0.734 | 0.516 | 321.2 |
| 8 | I(isi.m^2) | 91 | 0.4 | 1.8 | 4.0 | 1.47 | 1.060 | 0.562 | 0.564 | 332.9 |
| 9 | I(isi.m^2) + sqrt(SFC) | 84 | 1.1 | 2.3 | 4.2 | 1.32 | 0.957 | 0.602 | 0.662 | 291.0 |
| 10 | a.value \* (1 - exp(-b \* ISI))^c | 91 | 0.7 | 2.4 | 4.4 | 1.62 | 1.160 | 0.732 | 0.474 | 352.2 |
| 11 | a.value \* (1 - exp(-b \* isi.m))^c | 91 | 0.6 | 2.3 | 4.4 | 1.43 | 1.050 | 0.659 | 0.590 | 329.3 |
| 12 | b0 +a \* ISI^b | 91 | 0.9 | 2.4 | 4.2 | 1.62 | 1.170 | 0.750 | 0.471 | 352.6 |
| 13 | a.value \* (1 - exp(-b \* ISI))^c | 51 | 0.2 | 2.5 | 6.8 | 1.00 | 0.797 | 0.612 | 0.772 | 150.7 |
| 14 | a.value \* (1 - exp(-b \* isi.m))^c | 51 | 0.3 | 2.2 | 5.5 | 1.10 | 0.875 | 0.660 | 0.723 | 160.7 |
| 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 |
| Your source note or additional information here | | | | | | | | | | |

*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 includes fires in deciduous stands and PPDF fires (Box 1); three wildfires observations were also retained. Boreal conifer models used only the aforementioned fires in spruce, pine-spruce, or boreal/sub-boreal pine [for site and experimental descriptions see 33]. 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) values selected by previous researchers. 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. Notably, refitting this model using [1] produced a slightly improved model:

### [Table 2: Extended SFC predictions]

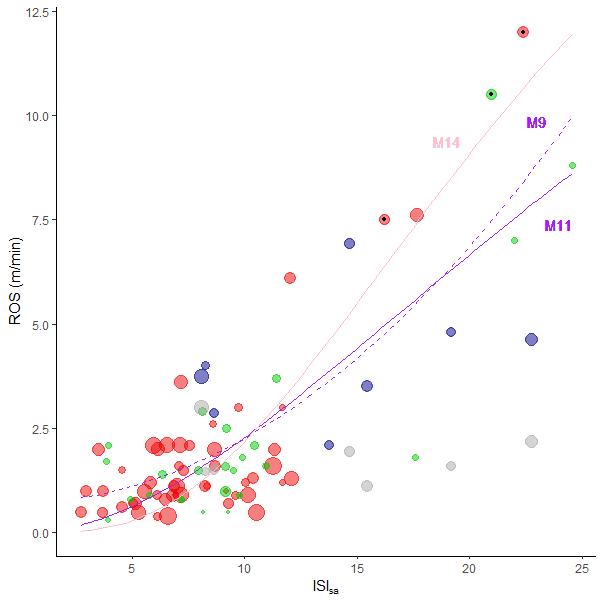
Table 1: Extended prediction table for multivariate models

|  |  |  | 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. The Model 15 predictions show the slowest ROS for deciduous fuel type (FT), following by conifer, and the fastest for the transformed PPDF fuel type. While FT was a significant factor in this model (Appendix 1), a Tukey’s HSD test showed that only the PPDF-Conifer and PPDF-Deciduous differences were significant at the level.

### [Figure 4]



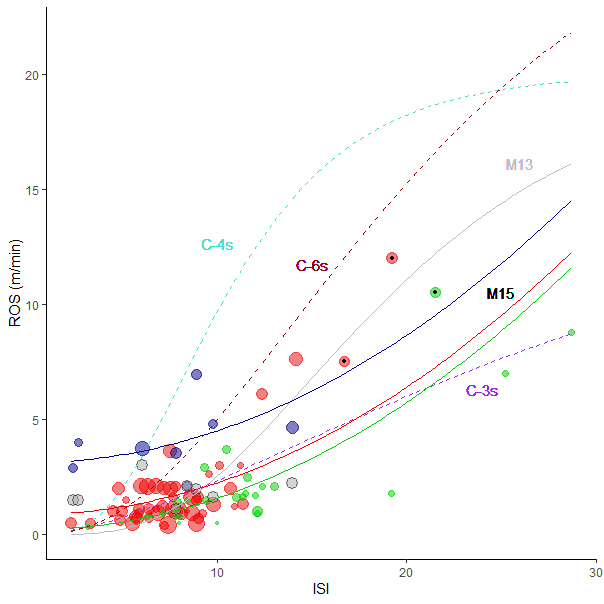
*Caption: Figure 4. Surface fire rate of spread (ROS) observations and selected fitted models, using the stand-adjusted initial spread index (ISIsa). Colours indicate fuel type as follows: red: boreal conifer; blue: ponderosa pine-Douglas-fir (PPDF) adjusted to seasonally cured condition; green: deciduous; 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: 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. Fuel type (Con, PPDF, or Decid) was not significant in any form of model using ISIsa

#### 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; [58]). 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 [58]. 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., 59] suggest low confidence in these observations, unsurprisingly.

### [Fig 5]



*Caption: Figure 5. Surface fire observations by ISI and ROS (m min-1), along with ‘aggregated data’ model M13, fuel type (FT) category model M15 (Conifer, Deciduous and PPDF), and FBP-era surface fire models (C-3s, C-4s, C-6s). 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.*

Figure 5 shows the observations and selected model predictions based on the ISI, along with certain FBP models. Model 15 also provided a valuable option, with FT comprising boreal conifer (Con), PPDF (95% cured), or deciduous (Decid) categories. For ROS prediction purposes, Decid < Con < PPDF (see Appendix 1), but only the Con-PPDF and Decid-PPDF differences were significant. There were no advantages to the model (Model 12) over other model forms.

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. Also evident from this Figure 5 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 [17,60,61], 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 [33,62], 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 [e.g., 63,64], there is a need to estimate sROS under higher danger conditions.

While the ISI is old and familiar, it was the strongest ROS predictor, performing better than other combinations of weather or moisture index variables. 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 on Wotton and Beverly’s (2007) stand-adjusted moisture estimate models. The ISI was recently found to be the variable most closely correlated to area burned during the record-breaking 2023 Canadian wildfire season [66].

##Indeed, some of the observations classed as surface fires clearly had some canopy fuel involvement, based on photographic evidence [see, e.g., 67,68] 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 [69,70]. 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 [71,e.g., **Thompson.etal2020?**] may support surface fire at higher danger levels than suggested by the best FBP System categorical fuel type (i.e., C-2; [6]). 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 [22], 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 [e.g., 38,72]. 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 [21,73]. 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 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 [41] 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., 74,75]. 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 [36,59,76] 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 [20]; [77]] than in any surface fire.

Finally, the 25% model is presented in the same vein as the Cruz and Alexander ‘10% rule’ [78] and ‘20% rule’ [79] 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 [78].

## `summarise()` has grouped output by 'ISI\_sa'. You can override using the  
## `.groups` argument.  
## `summarise()` has grouped output by 'ISI\_sa'. You can override using the  
## `.groups` argument.  
## Joining with `by = join\_by(ISI\_sa, Prediction)`

| 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. Since there appeared to be a difference between the over- and under-prediction error potential at lower versus higher fire danger levels (Fig. 4), these categories are shown separately. Thus, Surface ROS errors of 1-2 m min-1 (mean and Q90 absolute error of 0.6 – 1.7) 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. Use of these models above ISI 25 involves extrapolation and should be undertaken only with great caution; in such cases the sigmoidal models (Models r

acc.tab4 %>% select(Model, Num) %>% filter(str\_detect(Model, 'cr')) %>% pull(Num)

) are recommended to avoid more extreme overprediction problems, since the ‘levelling off’ factor limits the ROS at extreme ISI or ISIsa levels.

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.

Under very low danger conditions (e.g., FFMC < 75 or ISI < 1), ignition in needle fuel substrates becomes highly unlikely [80,81], 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., 25,72]. 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