Estimating ladder fuel contributions to crown fire initiation

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Simple solutions for modelling surface fire and ladder fuels in Canadian conifer forests

Abstract

Predicting the onset of conifer crown fires is an uncertain process. Ladder fuels (LF), biomass that act as a bridge between surface and canopy fuel layers, are suspected of being disproportionately important in crown fire initiation, but are difficult to quantify and incorporate into prediction systems. In this study, we show how a simple rearranging of C.E. Van Wagner's classic model (Can. J. For Res. 1977, v7: 23-34) reframes crown fire initiation as a critical fuel consumption threshold-driven process. A new equation is presented for comparing fuel consumption at different vertical positions, which allows a rescaling of LF consumption down to the ground level and corresponding boost in equivalent mass. To test the theoretical model, we used several sources of evidence, primarily from Canadian experimental fires. Incorporating LF into empirical crown fire models improved model predictions, and best results were obtained with a LF multiplier of [??2-3??; draft results]. This suggests that LF consumption is two to three times as influential per unit mass as conifer surface fuel consumption, even accounting for vertical position. The resulting models will be useful for improve fire behaviour predictions as well as for improving the design of hazard reduction treatments.

Introduction

Crown fires, CEVW model and ladder fuels; short lit. review (Stephens' papers, lab studies, etc.) Conifer forests cover most of the circumboreal region of the world and crown fires represent a significant fire-related hazard in these stands (Kneeshaw, Bergeron, and Kuuluvainen 2011; Brian J. Stocks 1991). As noted by Kiil et al. (1976) and quoted by Cruz et al. (2005), surface fires rarely spread > 6 m/min under closed conifer stands, as higher spread rates are usually associated with some degree of crowning or torching. Once flames reach the upper reaches of the canopy, they can be directly influenced by open air winds in the lower atmosphere. The fully developed crowning process has long been known to be associated with a dramatic increase in fire spread rate, due to several processes including flame tilt, increased lee-side wind exposure (Taylor et al. 2004) and vigorous ember spotting .

Stand structure is well-known to influence crown fire occurrence and tendency. The element in fuel complexes that enables crown fires in most tall conifer stands are ladder

fuels. This term refers to any easily-ignited fuels in the mid-canopy space, meaning fine-textured and flammable dead or live biomass above the surface fuel complex but below the live canopy base. In Canada, J.G. Wright first noted that 'crown fires are not likely to occur unless there is a large volume of fuel under the trees' (**wright1932?**). Van Wagner (**vanwagner1977?**), in describing his classic crown fire initiation model based on empirical data and physical convection theory, noted that such 'bridge fuels' consisted of 'combustible matter such as loose bark, dead lower branches, lichen, small conifers, etc.' located above the surface fuel complex, remarking that such fuels needed to be 'present in sufficient quantity to intensify the surface fire appreciably as well as to extend the flame height'. While the paper describing Van Wagner's model has been cited become a classic (> 1500 citations as of 2023), methods for quantifying the effects of ladder fuels are still lacking 45 years later.

Van Wagner's model was originally formulated to solve for critical surface intensity (I_0) as follows:

$$I_0 = (chz)^{1.5}$$

[1],

where h is heat of ignition, z is live crown base height (LCBH), and c is a dimensional constant derived empirically. Most modelling systems have combined I_0 with Byram's (1959) fireline intensity equation in order to solve for critical rate of spread. This combination has allowed for linkages with Rothermel's (1972) semi-physical surface rate of spread model (e.g. **scott2001?**; **andrews2014?**), or with the empirical ROS functions from the FBP System fuel types (**forestrycanadafiredangergroup1992?**). Surprisingly, a simple algebraic rearranging of the terms of Van Wagner's model allows for a useful and powerful estimator applicable to ladder fuels of varying heights.

Objective

The objective of this study was to describe a simple theoretical framework for analyzing ladder fuel influence in crown fire initiation, based on a rearrangement of Van Wagner's (1977) equation. Secondary objectives include calibrations and evaluations of the theoretical equation, as well as refitting empirical crown fire models for use with measured or estimated ladder fuel loadings and structure.

Theoretical model: scaling ladder fuel consumption to the surface

Ladder fuels are defined by their fine texture and intermediate vertical position, by definition (**vanwagner1977?**; **kilgore1975?**). They exist in conifer stands between the surface fuels, at $z = 0$, and canopy fuels, which for our purposes begin at the live canopy base height (LCBH). When connected to the surface fuels and ignited by a proximate source (i.e. an advancing fireline), the heat flux contribution (**melnik2022?**) is much closer to the canopy base, and therefore much more likely to contribute to canopy ignition compared to similar fuel loading at the surface. The structure of the Van Wagner (**vanwagner1977?**) CFI model permits a vertical rescaling that relies on an implied equivalency between SFC and the inverse of z (LCBH).

When we replace I_0 (Equation 1) with Byram's (1959) fireline intensity, we get the following equation, a much-used equivalency (e.g. FCFDG 1992, Scott and Reinhardt 2001):

$$H \cdot SFC \cdot ROS = (c \cdot h)^{1.5} z^{1.5}$$

[2]

where H is the heat of combustion, SFC is surface fuel consumption, ROS is rate of forward spread, and the right side is as in Equation 1.

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

$$SFC_0 = \frac{(ch)^{1.5} z^{1.5}}{h \cdot ROS}$$

[3]

Critical SFC for crown fire initiation can then be compared between LCBH levels, e.g. z_1 and z_2.

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

[4]

This also assumes no change in ROS with varying LCBH. Holding all other terms constant, we can simplify this to yield a basic relationship between SFC and LCBH (z) at different heights:

$$SFC_2 = \left(\frac{z_2}{z_1}\right)^{1.5} \cdot SFC_1$$

[5].

A practical example helps illustrate the logic of comparing SFC_0 at two different z values (equation 3). Using Van Wagner's own empirical heat of ignition function (**vanwagner1968?**), at 90% foliar moisture content (FMC) and LCBH=2 m, Equation 1 suggests I_0 of about 417 kW/m, the intensity of a low to moderate intensity surface fire. At some moderate surface ROS value, e.g. 3 m/min, Equation 3 predicts SFC_0 of 0.463 $kg \cdot m^{-2}$. Using Equation 5, increasing LCBH to 5 m without altering other inputs would raise SFC_0 to 1.83 $kg \cdot m^{-2}$; thus, a 2.5 times increase in LCBH would result in a fourfold increase in fuel consumption needed for crowning as a consequence of the much higher surface fire intensity required.

In the case of the consumption of an elevated ladder fuel quantity FC_L positioned at height above ground z_L (such as the centroid of a standing dead sapling, or sapling cohort, beneath a live conifer canopy), finding the equivalent surface-equivalent FC value (FC_{SE}) is then a matter of inflating its influence due to its elevated position. In this case, z remains the normal LCBH for the live canopy and $z - z_L$ can also be considered the fuel strata gap between ladder fuel elements and the LCBH:

$$FC_{SE} = \left(\frac{z}{z - z_L}\right)^{1.5} \cdot FC_L \ , \qquad z_L > z$$

[6]. Using Equation 6, it becomes possible to estimate the contribution of canopy fuel elements and compare them with the surface fuel complex.

We note immediately two fire-related qualifiers. First, this theoretical relationship does not account for the obvious structural differences between the surface and crown fuel complexes. In particular, surface fuelbeds are much more compact (higher bulk density and packing ratio) than crown fuel complexes, including ladder fuels, with a much more aeration-limited combustion environment (Rothermel 1972; **keane2015?**; Schwilk 2015). The general FBP System approach to SFC, where all consumed surface and ground fuels are assumed to contribute to surface fire intensity (**vanwagner1977?**; **fcfdg1992?**), may overemphasize dense duff fuels that burn in post-frontal combustion and ignores factors such as residence time (**nelson1988?**; **wotton2012?**). In contrast, fine crown and ladder fuel strata are much more aerated (more porous) but also vertically and horizontally discontinuous (refs and explanation#). This difference could be addressed theoretically or, as in the present investigation, empirically.

Second, while equation 6 specifies that the ladder fuel height cannot exceed the LCBH, it is apparent that as the difference between them ($z - z_L$) diminishes, FC_G can grow to extreme levels, eventually producing a division by zero problem at $z = z_L$. Thus, $0.1 \ kg \cdot m^{-2}$ of fuel consumption 1 m below a 5 m tall canopy base scales to equate to ground-level SFC of $1.12 \ kg \cdot m^{-2}$, but the same fuel consumption 0.2 m below the same canopy scales to $FC_G = 12.5 \ kg \cdot m^{-2}$. This logic holds in a theoretical sense – a fire is much more likely to ignite the lower live canopy if the burning fuel is immediately beneath, and a 0.2 m separation is essentially showing negligible separation at the fuel particle scale; however, this suggests that caution is needed to utilize equation 6 in a practical sense to avoid inflating the ladder fuel effect to illogical levels.

Ladder fuel multiplier

One simple approach to the challenge of comparing high porosity ladder fuels with low porosity surface fuels is to evaluate the use of a multiplier. This would be, in the simplest sense, a value that could be used to inflate the value of FC_L in order to bring it closer to comparable SFC values. Thus, we might expect $SFC = FC_{SE} \cdot M$ [7], with FC_{SE} being the surface-equivalent ladder fuel consumption value from eq. 6 and M being the appropriate multiplier for converting FC_L to FC_{SE}.

Recall that SFC values in Canadian experimental fires ranged from 0.2 to 3.8 kg m^{-2} (Perrakis et al. 2023). The value of this multiplier, M, could range from 1 (no effect) to 10

or more in the event that ladder fuel biomass and arrangement appeared to have more than an order of magnitude greater effect than surface biomass on upward heat flux and crown fire initiation.

The remainder of the study tests and discusses empirical evidence for equations 5 –7, using ananlyses on previously documented Canadian experimental fire data.

Methods

Three separate validation methods were used to evaluate the theoretical ladder fuel scaling relationship and estimate the value and significance of the multiplier M: 1) an expert opinion assessment; 2) a crown fire threshold model between three treatment types; and 3) modifications of an empirical crown fire model using the Canadian experimental fire dataset. All of these relate to stand level estimates of fuel structure using mean values, which is simple and operationally practical, but may mask significant impacts of within-stand heterogeneity and spatial pattern of fuel arrangement (e.g. clumping, proximity to overstory trees).

Study area: Sharpsand Creek, Ontario

The first two validation methods used data from the fire experiments at Sharpsand Creek, Ontario. Stand and fuel measurements were initiated in the early 1970's at this site north of Thessalon, Ontario, in advance of experimental burns conducted over a 15-year period. This resulted in 27 separate and independent experimental fire observations in three distinct structure classes. The original unaltered stand (immature: IM) consisted of densely stocked jack pine natural regenerated on gravelly soil (**walker1975a?**) following the spring 1948 Mississagi fire (**stocks1973?**). The dense stands in the earliest burns featured over 9000 live stems/ha and over 10,000 dead stems/ha as the stand underwent rapid stem-exclusion. Results from the earlier fires (1975-1981) were published in Stocks (**stocks1987a?**) and included in the empirical derivation of the C-4 fuel type model (**fcfdg1992?**); these were also analyzed separately by Van Wagner (Van Wagner 1993) and discussed in several other fire behaviour studies (**call1997?**; **cruz2003?**; **albini1986?**).

Results from the later fires (1988-1991) were not included in the FBP System analyses and were fully documented only recently (**mcrae2017a?**). The stand characteristics associated with the later experimental fires highlighted significant structural and successional changes underway as stands evolved: the dense immature forest was rapidly self-thinning, from 9,276 live stems/ha at the time of the original experiments (measured in 1973) to less than half the live density (4,375 stems/ha) as well as 53% more basal area in 1984. These were termed 'semi-mature' (SM), and estimated to also have average LCBH of 5.3 m, about 1 m higher than the IM stands. During the course of the earlier burn experiments, it was discovered that 6 of the plots had been hand-thinned (TH) in 1960, removing most of the live stems and resulting in much less dense stands compared with the IM plots [(**stocks1987a?**); B. J. Stocks, personal communication, Jan. 2020]. While these thinned stands were the same age and site characteristics as the denser IM (C-4 fuel type) stands, the burns in the thinned plots had been deemed more representative of mature pine stands and previously included in the FBP System C-3 fuel type dataset (**degroot2022?**).

Burning years ranged from in 1974-1976, 1981, 1988, 1990-1991; thus, at post-fire ages 26-43. As discussed in a previous analysis (**Perrakis2023?**), earlier studies handled these three treatments in different ways, but mainly by estimating the ladder fuel influence as a modification of the LCBH in a subjective sense, using an expert judgment adjustment and defining the fuel strata gap (FSG) as the net distance between surface and fuel strata, including the effects of standing dead ladder fuels Perrakis et al. (2023).

Crowning behaviour and ladder fuel consumption

There is a question of which plots experienced crown fire vs surface fire or transitional torching behaviour. In the original Sharpsand experiments (1974-1981; Stocks 1987; Cruz 1999), fire type was identified as 'surface' or 'crown'. In the latter experiments, however, fire type was identified as 'surface', 'some torching', 'torching', and 'crown' (**mcrae2017?**). Descriptions in the latter text make it clear that 'torching' fires experienced behaviour akin to passive crowning, while those described as 'some torching' appeared to be near the crowning threshold (i.e., ~5-15% crown fraction burned). Following discussions with experimental leaders (BJ Stocks, pers. comm.), the two fires described as 'some torching' were split, with fire #16 (ISI=8.1, ROS=3.5 m/min) was considered a vigorous surface fire, while fire #18 (ISI=9.4, ROS=5.1 m/min) was considered a marginal passive crown fire. As noted in a previous study, as surface fires begin to involve more canopy fuels and transition to passive crown fire, ROS is observed to increase beyond the baseline for true surface fires (i.e., no crown fuel involvement).

The most challenging value for the analysis is the fuel consumption of ladder fuels, as this is seldom measured (though sometimes estimated indirectly) in experimental studies. Stocks (1987) presented estimated dead roundwood fuel consumption for the original Sharpsand Creek exprerimental fires, and these values are used in the present analysis.

For the calculations, ladder fuel influence was incorporated into certain models using equation 6 to scale the fine dead ladder fuels (fine snags and dead crown fuel < 1 cm; Stocks 1987) into an equivalent SFC contribution value, SFC_L. The vertical position of fine standing ladder fuels was assumed to be the crown centroid of the mean dead snag height [LCBH+(height-LCBH)/2; Perrakis et al. (2023)] in an experimental plot (Figure X#snag diagram). SFC_L was then added to the actual (measured) SFC for modelling. Additional tests were completed where the elevated fuel contribution was increased using a multiplier, discussed further below.

Estimation 1 - expert opinion

The first method involved expert opinion from previous studies. Cruz et al. (2004) noted that the abundant ladder fuels characterizing the IM stands, in the form of standing dead trees (including dead branches, bark flakes, and fine stemwood) amounted to a reduced FSG of 2 m, compared to approximately 4 m for the actual LCBH (or z). We used those values as a first estimate along with equation 5 to investigate a potential value for multiplier M.

For the second estimation method, we used the Sharpsand Creek, Ontario experiments once again, including the full complement of immature, thinned, and semi-mature stands in our analysis (B. J. Stocks 1987; **mcrae2017?**; Perrakis et al. 2023). This site, with many fires in stands that differed primarily by age and treatment, provided the ideal test case for assessing threshold crown fire conditions and ladder fuel effects. We first used logistic regression to compare the crown fire thresholds between treatments [in terms of ISI, the Initial Spread Index; Van Wagner (1987)]. We then evaluated the crowning thresholds in terms of critical FC to solve for the multiplier effect (M). This involved using Byram's (1959) fireline intensity along with predicted ROS using fitted surface ROS models, and solving for M using the threshold values.

Estimation 3 - empirical fitting using a crown fire model

For the third and final method of examining the theoretical relationships, we returned to a recent crown fire analysis and attemped to refit the relationship between fire environment variables and crown fire occurrence. As in Perrakis et al. (2023), we used 10 m open wind speed, estimated litter and fine dead surface fuel moisture (as represented by either the FFMC or the stand-adjusted moisture content, mc_{SA}). This time, rather than subjectively estimating the FSG adjustments to LCBH in certain stands, we used eq. 7 to estimate the ladder fuel contributions of standing dead fuels, based on the measured or estimated < 1 cm elevated roundwood (dead) consumption values. We tested only the best-performing model forms for this purpose, which had log-transformed SFC values and a 3/2 exponent for the LCBH term. The multiplier M in this case was held inside the log-transformed SFC term; thus, the respective coefficient was fitted to $log(SFC + FC_{SE} \cdot M)$. The initial value of M in this fitted model was taken from the previous estimates, but a sensitivity analysis step also tested other values of M, from 1 to 20.

Results

Expert opinion [delete?? – incorrect as written]

The first estimation method for the multiplier M was based on solving eq. 5 using the expert opinion values given in Cruz et al. (Cruz, Alexander, and Wakimoto 2004; Cruz, Alexander, and Wakimoto 2005) to account for ladder fuels.

From eq. 5, we can easily rearrange as follows:

$$\frac{SFC_2}{SFC_1} = \left(\frac{z_2}{z_1}\right)^{1.5} = M$$

Starting with the approximate LCBH values originally reported for the Sharpsand IM stands (4 m), this value was reduced by 2 m to produce the FSG estimate. Therefore, using a slight modification of equation 5, we can easil $z_2 = 4$ m and $z_1 = 2$ m, producing our first estimate for M:

$$M = \left(\frac{4}{2}\right)^{1.5}$$
$$M = 2.828$$

[7]. Instead of those approximate values, we could also use values derived from the more precise estimates from original stand data (Walker and Stocks 1975). As previously described (Perrakis et al. 2023), detailed stand survey analysis produced mean treatment-level LCBH values of about 4.36 m in the IM plots (4.45 m in the TH plots). If we assume that the 2 m reduction in FSG due to ladder fuels holds true (Cruz, Alexander, and Wakimoto 2004), we get the following values for equation 6:

$$M = \left(\frac{4.36}{2.36}\right)^{1.5}$$
$$M = 2.511$$

[8]. The estimate for M based on this logic appears to be in the order of ~2.5 – 3.0.

```
##
## Call:
## glm(formula = CFI1 ~ ISI + ExpF, family = "binomial", data = fires.stat)
##
## Deviance Residuals:
##      Min        1Q    Median        3Q       Max
## -1.9835   -0.1781    0.1236    0.4290    1.1171
##
## Coefficients:
##               Estimate Std. Error z value Pr(>|z|)
## (Intercept) -10.0947      4.6458  -2.173   0.0298 *
## ISI           1.5271      0.6451   2.367   0.0179 *
## ExpFThin     -5.6434      2.7891  -2.023   0.0430 *
## ExpFSemi-M   -3.0644      1.9572  -1.566   0.1174
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##     Null deviance: 34.372  on 26  degrees of freedom
## Residual deviance: 15.114  on 23  degrees of freedom
## AIC: 23.114
##
## Number of Fisher Scoring iterations: 7


##
##   Simultaneous Tests for General Linear Hypotheses
##
## Multiple Comparisons of Means: Tukey Contrasts
##
##
## Fit: glm(formula = CFI1 ~ ISI + ExpF, family = "binomial", data =
## fires.stat)
```

```
## 
## Linear Hypotheses:
##                    Estimate Std. Error z value Pr(>|z|)
## Thin - Imm == 0      -5.643      2.789  -2.023    0.102
## Semi-M - Imm == 0    -3.064      1.957  -1.566    0.252
## Semi-M - Thin == 0    2.579      2.184   1.181    0.454
## (Adjusted p values reported -- single-step method)
```

*Crowning thresholds and critical FC, Sharpsand Creek*

For the second multiplier estimation method, we first tested the ISI crowning threshold between treatments (comparing IM, TH, and SM stands as treatments).

Based on the logistic regression model, ISI and treatment both appeared to be significant predictors of crown fire success at the α=0.05 level, with the Immature treatment as the base case. Note that a post-hoc Tukey multiple comparison test revealed that apparent difference between IM and TH treatments was marginal at best (p=0.102), which is not unexpected with such small treatment group sizes; other pairwise contrasts were non-significant (p>0.2 for all other pairs). Nonetheless, at this point we are not testing the hypothesis of treatment effects, but rather identifying the most likely crowning threshold between the treatment groups. Thus, we used this model to identify the most likely ISI crowning thresholds between treatments (Figure XX). This produced the three logistic curves shown in Figure X. By solving for p=0.5 (50% probability), we calculated the crown fire transition thresholds based on ISI or stand-adjusted ISI (ISI.sa), simply a renewed calculation of the ISI based on the FWI System equations, using the stand-adjusted moisture content estimate (from Wotton and Beverly 2007) in place of the FFMC-based moisture content estimate ('m' in Van Wagner 1987).
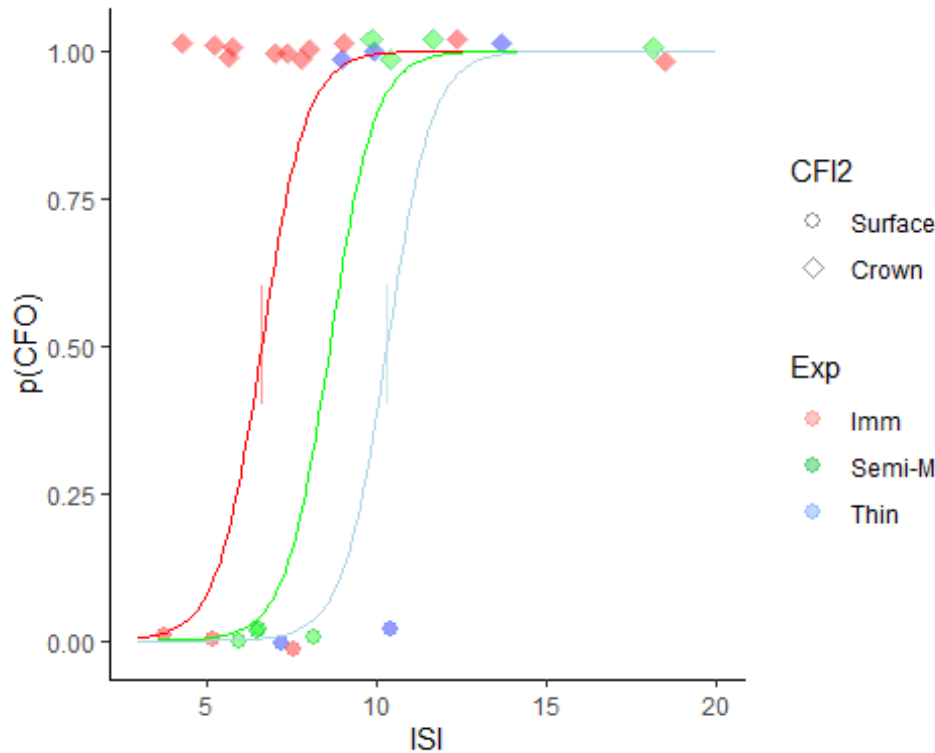
Crowning thresholds, as shown in the figure, were 6.61 and 10.31 for immature controls and thinned stands, respectively. In terms of ISI.sa, the MC_{SA}-based spread index, the respective thresholds were 4.7 and 9.19 for unthinned controls and thinned stands (not shown). Given identical ignition patterns and stand origin, the difference between these values, therefore, represents the increased crowning threshold achieved by reducing ladder fuels, counteracted somewhat by reduced stand density (from 'dense' to 'moderate', based on Wotton and Beverly's (2007) stand-adjusted model).

We then needed a model to predict surface ROS values near the crowning threshold in the Sharpsand stands. This resulted in the empirical analysis of Canadian surface fire ROS data described in Appendix 1. The best surface fire models were obtained using the combination of ISI or ISI.sa and SFC, with adjusted R^2 values of 0.747 and 0.807, respectively. Notably, these models produce lower ROS predictions than Van Wagner's surface fire model (VW93), a model he suggested 'to define the spread rate of all possible surface fires' in the Sharpsand stands (Van Wagner 1993). While the aggregated sROS predictions appear more scattered above ISI 12 or so, conditions favoring crown fire in many conifer stands, the observations are closer to the model under lower danger conditions. Based on the estimated crowning thresholds, representing ISI (or ISI.sa) values of ~5-10, approximate surface fire spread rates of 0.7 – 2.5 m min^{-1} are expected.
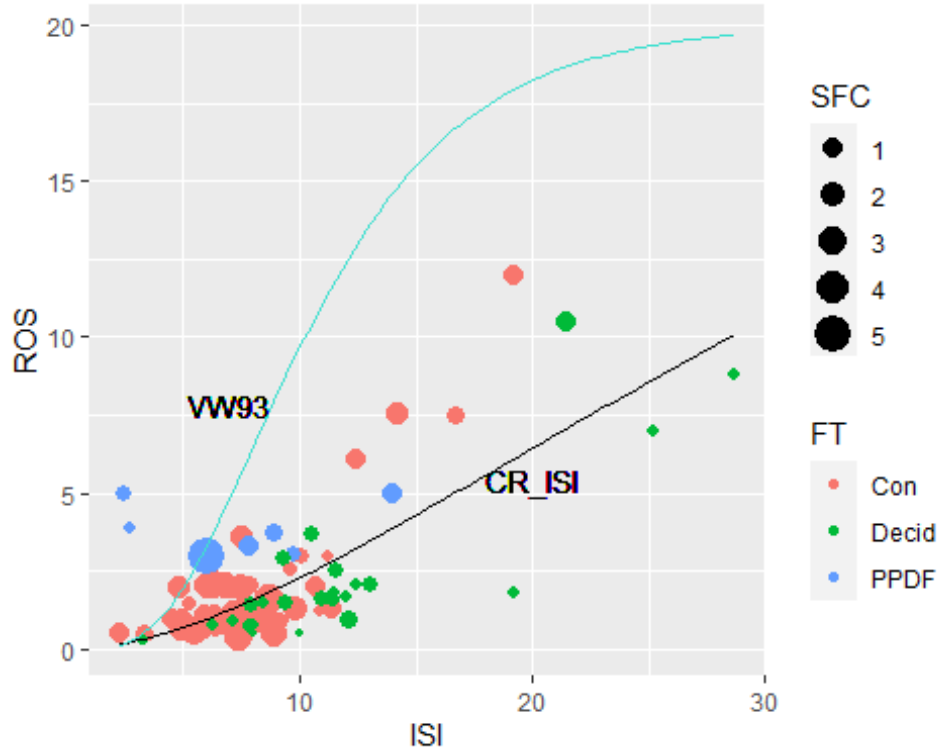
Byram's intensity and estimating M

We can finally use our scaled ladder fuel equation [7] along with Byram's equation (Byram 1959) and our empirical surface ROS models, and calculate the most likely M value. This calculation assumes that equivalent critical surface intensity values (I_0) are required for crowning in the control and thinned stands, both with LCBH of 4.4 m.

In terms of ROS values at the crowning threshold (ROS_0) in the Im and Th stands, the equivalency is expressed as follows:

$$
\begin{aligned}
I_{0 \cdot Im} &= I_{0 \cdot Th} \\
h \cdot w_{Im} \cdot ROS_{Im} &= h \cdot w_{Th} \cdot ROS_{Th} \\
SFC_{Im} \cdot ROS_{0 \cdot Im} &= SFC_{Th} \cdot ROS_{0 \cdot Th} \\
(SFC + FC_{SE \cdot Im} \cdot M) \cdot ROS_{0 \cdot Im} &= SFC_{Th} \cdot ROS_{0 \cdot Th}
\end{aligned}
$$

Based on [7], FC_{SE} is calculated using estimated ladder fuel consumption and structure. In this case, we calculate ladder fuel height (z_L) using an estimated crown ratio of 0.5 and cohort heights from Walker and Stocks (1975) original stand data. Mean dead sapling height and < 1 cm dead roundwood (FC_L) in control stands were 3.49 m and 0.159 kg m-2, resulting in mean z_L = 2.62 m. Scaled surface-equivalent consumption values, calculated using [6], ranged from 0.291 to 1.227 kg m-2, with a mean of 0.658 kg m-2 .

The final solution for estimating M was calculated by solving for M:

$$(SFC + FC_{SE \cdot Im} \cdot M) \cdot ROS_{0 \cdot Im} \quad = SFC \cdot ROS_{0 \cdot Th}$$

$$M \quad = \frac{\dfrac{SFC \cdot ROS_{0 \cdot Th}}{ROS_{0 \cdot Im}} - SFC}{FC_{SE \cdot Im}}$$

Using overall mean SFC values (1.34 kg m^{-2}), this generates estimates of $M = 2.2$ using the ISI-based sROS model and crowning thresholds, and $M = 4.6$ using the ISI.sa-based model and thresholds.[1]

```
##    mean(SFC)
## 1  970.6644
```

```
##    mean(SFC)
## 1  971.3117
```

Empirical crown fire analysis

Finally, we reanalyzed the experimental crown fire dataset using Monte Carlo cross-validation, comparing models with $log(SFC)$, $log(SFC + FC_{SE})$, and $log(SFC + FC_{SE} \cdot M)$. The starting value for M was 3, a rough mean of the previous estimates.

As the table shows, the cross-validation evidence does support the existence of M > 1, but it is perhaps underwhelming. The best model results (highest MCC, lowest AIC) for both FFMC and MC.SA-based models are the versions using the M=3 multiplier for FC_{SE}.

Table

```
##                                                 Model Accuracy    MCC    AIC
## 1  ws + I(FSG^1.5) + I(log(SFC)) + ws:MC.FFMC   0.8781 0.7547 46.19
## 2    ws + I(FSG^1.5) + I(log(SFC)) + ws:MC.SA   0.8635 0.7252 49.88
## 3  ws + I(FSG^1.5) + I(log(SFC)) + ws:MC.FFMC   0.8841 0.7671 43.27
## 4    ws + I(FSG^1.5) + I(log(SFC)) + ws:MC.SA   0.8879 0.7747 42.41
## 5 ws + I(FSG^1.5) + I(log(SFC2)) + ws:MC.FFMC   0.8950 0.7888 43.19
## 6   ws + I(FSG^1.5) + I(log(SFC2)) + ws:MC.SA   0.8742 0.7469 45.94
## 7 ws + I(FSG^1.5) + I(log(SFC3)) + ws:MC.FFMC   0.8963 0.7915 40.75
## 8   ws + I(FSG^1.5) + I(log(SFC3)) + ws:MC.SA   0.8898 0.7785 41.23
##    Dataset.reorder2. MCC.rank AIC.rank
## 1            1.Base         6        7
## 2            1.Base         8        8
## 3         2.FSG Adj.        5        5
## 4         2.FSG Adj.        4        3
## 5        3.LF to SFC        2        4
## 6        3.LF to SFC        7        6
## 7     3.LF x M to SFC        1        1
## 8     3.LF x M to SFC        3        2
```

---

[1] Measured SFC values were not significantly different between treatments (p=0.07), so the mean value between all plots was used.

Discussion

Aside from Van Wagner's equation, this is simply a slightly different representation of Thomas' (**thomas1963?**) equation for flame size under calm conditions.

- Figure showing more complex architecture; 2-story stands, using Eq 2 to estimate contribution of surface fuels to upper stratum crowning - Validation 4. Upper canopy crowning -Scale issues are obvious here. Following the logic and intent of Van Wagner's (1977) model, the scaling equation represents relationships between canopy strata logically in 1-dimensional space, assuming ladder fuels are positioned beneath overstory canopy fuels. They also may hold at the single tree level, where individual ladder fuel elements (saplings, bark flakes, arboreal lichen) are horizontally juxtaposed with overstory fuels. More detailed survey methods (e.g. Alexander et al. 2004; Reinhardt et al. 2006; Arkin et al. 2023) can describe the frequency distributions associated with vertical strata in a stand, while ecologists have described the spatial patterns of overstory trees in stands across various stand types (Kenkel et al. 1997; Larson and Churchill 2012). Future investigations will be needed on how these spatial distribution patterns affect ladder fuel influences near crown fire initiation thresholds.

-For the theoretical relationship to hold for actual ladder fuel elements (flammable shrubs, saplings, bark flakes, hanging lichens, etc.), it is imperative that they be connected to surface fuels, and in actual forest settings

-The concept of a multiplier for comparing elevated fuels to surface fuels is a similar topic to Van Wagner's [-vanwagner1977] 'c' parameter of 0.01, deduced from a comparison of only two experimental fires, as discussed by Alexander (**alexander1998?**). Densely-packed litter fuelbeds have lower spread rate than lower density fuelbeds with the same fuel load (**campbell-lochrie2021?**), although the relationship is likely more complex in canopy fuels (Schwilk 2015).

-As Andrews (**andrews2018?**) noted, Rothermel surface model only applicable to surface fuels, within ~6ft of the ground

-Thinning increases sub-canopy turbulence (**russell2018?**). See also Banerjee et al. (Banerjee 2020)

McAlpine and Xanthopoulos (Mcalpine and Xanthopoulos 1989) also noted that C-6s appeared to overpredict sROS in needle fuelbed experiments. Although they explained it as a difficulty in estimating

Method could also be used to estimate influence of dead branch fuel below LCBH, bark flakes, arboreal lichens, or similar material.

References:

Banerjee, Tirtha. 2020. "Impacts of Forest Thinning on Wildland Fire Behavior." *Forests* 11 (9): 918.

Byram, G. M. 1959. "Combustion of Forest Fuels." In, edited by K. P. Davis, 61–89. New York: McGraw-Hill.

Cruz, Miguel G., Martin E. Alexander, and Ronald H. Wakimoto. 2004. "Modeling the Likelihood of Crown Fire Occurrence in Conifer Forest Stands." *Forest Science* 50 (5): 640–58.

Cruz, Miguel G., Marty E. Alexander, and Ronald H. Wakimoto. 2005. "Development and Testing of Models for Predicting Crown Fire Rate of Spread in Conifer Forest Stands." *Canadian Journal of Forest Research* 35: 1626–39.

Kiil, A D. 1976. "Fire Retardants: Proceedings of the 1975 International Symposium on Flammability and Fire Retardants." In, 175–76. Canadian Forestry Service, Northern Forest Research Centre, Edmonton, Alberta.

Kneeshaw, Daniel, Yves Bergeron, and Timo Kuuluvainen. 2011. "Forest Ecosystem Structure and Disturbance Dynamics Across the Circumboreal Forest." *The Sage Handbook of Biogeography. Sage, Los Angeles*, 263280.

Mcalpine, R S, and G Xanthopoulos. 1989. "Predicted Vs Observed Fire Spread Rates in Ponderosa Pine Fuel Beds: A Test of American and Canadian Systems."

Perrakis, Daniel D. B., Miguel G. Cruz, Martin E. Alexander, Chelene C. Hanes, Dan K. Thompson, Stephen W. Taylor, and Brian J. Stocks. 2023. "Improved Logistic Models of Crown Fire Probability in Canadian Conifer Forests." *International Journal of Wildland Fire* 32 (10): 1455–73. https://doi.org/10.1071/WF23074.

Rothermel, Richard C. 1972. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper RP-INT-115*. Ogden, UT: USDA Forest Service Intermountain Forest; Range Experiment Station.

Schwilk, Dylan W. 2015. "Dimensions of Plant Flammability." *New Phytologist* 206 (2): 486–88.

Stocks, B. J. 1987. "Fire Behavior in Immature Jack Pine." *Canadian Journal of Forest Research* 17 (1): 80–86.

Stocks, Brian J. 1991. "The Extent and Impact of Forest Fires in Northern Circumpolar Countries." In.

Taylor, S. W., B. M. Wotton, M. E. Alexander, and G. N. Dalrymple. 2004. "Variation in Wind and Crown Fire Behaviour in a Northern Jack Pine Black Spruce Forest." *Canadian Journal of Forest Research* 34: 1571–76.

Van Wagner, C. E. 1987. "Development and Structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35." Chalk River, Ontario, Canada.

———. 1993. "Prediction of Crown Fire Behavior in Two Stands of Jack Pine." *Canadian Journal of Forest Research* 23 (3): 442–49.

Walker, John D., and Brian J. Stocks. 1975. "The Fuel Complex of Mature and Immature Jack Pine Stands in Ontario. Report o-x-229." Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, Canada.

Wotton, B. Mike, and Jennifer L. Beverly. 2007. "Stand-Specific Litter Moisture Content Calibrations for the Canadian Fine Fuel Moisture Code." *International Journal of Wildland Fire* 16 (4): 463–72.