Prediction of crown fire in conifer stands

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Prediction of Crown Fire Behavior in Conifer Stands

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Abstract

A scheme is presented for dealing with the full range of fire behavior in conifer forests. It is based on empirical data from fires in Canadian forests plus a theory to describe the physical conditions for the transition from surface to crown fire. In its ideal form, the model consists of two distinct equations for spread rate in a given forest, one each for surface and crown fire, plus the rules for the transition upward or downward between them. For lack of enough data in some cases, a compromise has been devised that distinguishes between surface and crown fires, but does not provide for complete separation of the spread-rate functions. The scheme will form part of the forthcoming Canadian Forest Fire Behavior Prediction (FBP) system.

Résumé

Nous vous présentons une méthode pour faire face à toute la gamme de comportement du feu dans des forêts de conifères. Elle repose sur des données empiriques compilées lors d'incendies forestiers survenus au Canada ainsi que sur une théorie décrivant les conditions physiques de la transition entre un feu de surface et un feu de cime. Le modèle, dans sa forme idéale, comporte deux équations distinctes sur la vitesse de propagation dans une forêt donnée, l'une pour un feu de surface et l'autre pour un feu de cime ainsi que les règles pour calculer la transition entre eux vers le haut ou vers le bas. Compte tenu de l'insuffisance de données dans certain cas, nous avons trouvé une solution intermédiaire qui établit une distinction entre le feu de surface et le feu de cime, mais qui ne permet pas une séparation totale des fonctions de vitesse de propagation. La méthode fera partie de la Méthode canadienne de prévision du comportement des incendies de forêt qui va bientôt être rendue publique.

Introduction

The prediction of forest fire behavior in Canada is accomplished through the Canadian Forest Fire Behavior Prediction (FBP) System, a division of the larger Canadian Forest Fire Danger Rating System (Canadian Forestry Service 1987, Stocks et al. 1989). The preliminary guide to the FBP System (Alexander et al. 1984) presented, among other things, spread-rate equations for 14 forest or fuel types throughout Canada, all based on the Initial Spread Index (ISI), a component of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), another division of the larger Danger Rating System mentioned above.

At the Eighth Conference in this series, Lawson et al. (1985) described the preliminary version of the FBP System, including its database (now about 360 fires), and covered the general approach to its development.

Since 1984 a more complete version has been under development, which is expected to appear shortly. The purpose of the present paper is to describe the design and structure of the section dealing with fire behavior in conifer stands, especially the transition from surface to crown fire and the distinction between the two.

In the original work on the FBP, the conifer data numbered some 160 fires, both wild and experimental, about half of them crown fires. These were sorted and assigned to seven different conifer forest types and graphed against the ISI. The typical pattern was best suited with the type equation

\[ \text{ROS} = a(1 - e^{-b \text{ISI}})^c \]  

where ROS is spread rate, ISI is Initial Spread Index, and a, b, and c are constants for the fuel type. As described by Lawson et al. (1985), this equation produces an S-shaped curve whose lower section (at low ISI) represents surface fires, the upper flattening section (at high ISI) represents crown fires, and the steep intermediate section a transition zone.

A modern system for explaining and predicting fire behavior in conifer forest should, in addition, account for

- the effect of variable fuel consumption on spread rate,
fuel consumption itself, to permit computation of intensity,
- the transition from surface to crown, and
- the behavior of the crown fire.

The "ideal" crown fire model should comprise separate equations for surface and crown fire spread, plus the rules for transition upwards or downwards between them. It might also include means of varying the stand height and stand density. Such a nearly complete model has been designed for one conifer type, namely red pine plantation. For the others, however, a compromise has been adopted. The single ISI-based equation for the full range of behavior is retained, but the model provides some variation about the basic equation plus an estimate of the degree of crown engagement.

A full account of the entire new FBP System, with all equations and rules for procedure will eventually be published elsewhere. So, because the scope of this paper is limited to fire in conifer forest, some subsidiary sections of the whole system will be here described in brief only. A list of the symbols used appears at the end of the text.

**Model Structure**

### 1 FUEL-WEIGHT EFFECT ON SPREAD RATE

The first new problem to be addressed was the effect of fuel weight on surface spread. Because the ISI is based on the Fine Fuel Moisture Code (FFMC) whose timelag in practice is only a day or so, the computed spread rates would apparently apply in given daily weather regardless of the further length of time since heavy rain. The primary indicator of available fuel weight in the FWI System is the Buildup Index (BUI), whose practical timelag extends to two weeks or so.

Although the correlations of spread rate with ISI were generally very good, no amount of statistical analysis could show any secondary dependence of spread rate on the BUI. In fact, given the empirical nature of the fire data, collected without specific concern for the full range of BUI, it was probably unreasonable to expect anything more than a good correlation with the primary variable. Nevertheless, because all physical logic points to a real effect of available fuel weight on the spread rate, and to avoid over-estimating spread rate very soon after rain, it was decided to include a BUI function, called \( f(U) \), as a modifier to the main ISI-based equation. It is based on the assumption that spread rate must be zero at BUI zero, rise quickly with increasing BUI, then finally level off at a maximum for the given value of ISI. Here is a brief description of the result:

First, the assumption above was expressed as

\[
f(U) = f(U_\infty) e^{-\frac{U}{U_\infty}}
\]  

(2)

where \( U \) is BUI and \( U_\infty \) is BUI\(_\infty\). The concept "\( q \)" was then introduced, defined as the proportion of maximum possible spread rate (for a given ISI) that is reached at a standard BUI called \( U_\infty \). Somewhat subjectively, each fuel type was assigned a \( q \)-value, ranging from 0.70 to 1.00 depending on the rate at which dryness in depth might affect spread rate. But the fires within each fuel-type data set have their own particular average BUI, to which the empirical ISI-based spread equation should presumably best apply; at such a value, called \( U_\infty \), \( f(U) \) should equal 1. Several algebraic steps then produced the equation

\[
f(U) = \exp \left[ \frac{\ln q}{1 - \frac{U}{U_\infty}} \right]
\]  

(3)

The values of \( q \) and \( U_\infty \) are listed for each fuel type, and the normal standard BUI was set at 50. The function \( f(U) \) could then be readily calculated for any BUI and applied as a multiplier on the result of the basic ISI spread equation. Three examples are shown in Figure 1.

**Figure 1.** Graphs illustrating the form of the Buildup Function, \( f(U) \), at three combinations of \( q \) and \( U_\infty \). \( f(U) = 1 \) when BUI = \( U_\infty \). Also \( U_\infty = 50 \).

### II FOLIAR MOISTURE CONTENT

Foliar Moisture Content (FMC) has an important bearing on two features of the fire behavior model, namely the initiation of crowning and the crown spread rate. Because it is out of the question to require every region to be continuously aware of the current FMCs in its conifer forests, a scheme was required for est-
imating FMC on demand from simple information such as location and date.

The basis of the scheme is the known seasonal variation in the FMC of old conifer foliage, especially a period of relatively low values in the spring and early summer, referred to here as the "spring dip". Its mechanism is mainly physiological, being due rather to a temporary increase in dry weight than to a real decrease in cellular water content (Little 1970, Gary 1971). For practical purposes, it was therefore assumed that its date is fairly constant from year to year, and not much affected by annual trends of soil and air temperature.

As field data for the scheme, nine Canadian foliar-moisture trends were available, ranging in location from longitude 67° to 124°, and as far north as latitude 59°. A more complete account of its design and structure will be published elsewhere, but the main steps were, in brief, as follows.

1) A "standard spring dip" was designed in terms of duration and amplitude, to represent all conifer species. It is constructed of two linked parabolas, and the limiting values are 85% and 120%. Given the date of its minimum plus the date of the fire in question, an FMC could then be estimated.

2) Analysis of the dates of minimum FMC, namely DO, among the nine sources eventually yielded a model in terms of latitude, longitude, and elevation. The key to this analysis was that, according to the nature of climatic isotherms in Canada, the isoline for a given DO should form a curve of decreasing slope from northwestern Canada, gradually becoming parallel to latitude in the east. The final equation for DO is thus a semi-log function of longitude, plus normalizing functions to accommodate elevation and latitude.

The FMC for any hypothetical fire can now be estimated entirely from its location, elevation, and date. It is then used as required in further sections of the crown fire model.

III CRITERION FOR THE START OF CROWNING

As spread rate increases, a point is eventually reached at which the crowns become engaged. In the new FBP System this point is judged by the intensity criterion of Van Wagner (1977), namely his Equation (4), which defines the critical surface intensity for crowning in terms of the Crown Base Height (CBH) and the Foliar Moisture Content (FMC). Called CSI, it is given in terms of the FBP symbols as

\[
CSI = 0.001 \times (CBH)^{1.5} \times (460 + 25.9 \times FMC)^{1.5}
\]  

(4)

Next, a prediction of the actual surface frontal intensity was needed. The function for spread rate has already been covered, and equations for Surface Fuel Consumption (SFC) based on correlation with the BUI for the individual fuel types have been developed. Assigning a constant 18 000 kJ/kg for heat of combustion, surface frontal intensity (SFI) is then given by

\[ SFI = 300 \times (RSS \times SFC) \]  

(5)

where SFI is in kW/m, RSS is surface spread rate in m/min, and SFC is in kg/m². SFI and CSI are then compared. If SFI is the lesser, the fire is classed as Surface; if SFI is the greater, then as Crown, and the computation proceeds to the next step.

It is obvious that the Crown Base Height (CBH) is a critical factor in the crowning criterion. Because the theory on which the criterion is based was itself dependent on empirical data for its final form, it was inevitable that the CBH assigned to each fuel type description incorporates some indication of CBH; on the other hand, the assigned value had to match the general crowning pattern embedded in each fuel type's data set. The final assigned CBHs, with this reservation, represent the real forest structure as well as possible.

IV TRANSITION FROM SURFACE TO CROWN

Although a given surface fire when, say, the wind increases, may appear to rise quickly into the crowns and assume more or less instantly a new high-intensity state, there are two reasons for adopting a gradual transition for purposes of the FBP System.

First, wind in the FWI System is single-valued, whereas in reality it varies erratically around its mean. This means that within a certain range of mean wind speeds, the fire should be alternately on the surface during the lulls and in the crowns during the gusts, on a scale of a few minutes. In this state, it would presumably spread at a rate between that of pure surface and pure crown fire. Such behavior may indeed be observed on occasion. The second argument is statistical. With all the variability in fuel type, plus the inaccuracies in any empirical data set, it seemed safer to attempt prediction of a degree of crowning than to try to identify each fire as pure Surface or pure Crown.

Accordingly, a transition function was designed to accomplish this concept. It was assumed that the degree of crowning would depend on the amount by which the predicted surface intensity (SFI) exceeded the critical intensity (CSI). In practice, the concept is more easily handled in terms of spread rate; in other works, the amount by which the predicted surface spread rate (RSS) exceeded the spread rate (RSO) associated with the critical intensity. The practical yardstick chosen was that crowning should be 90% complete when (RSS) exceeded (RSO) by 10 m/min.

First, RSO is readily found by putting CSI for SFI in (5) and working backwards. The desired transition function, called the Crown Fraction Burned (CFB) becomes, then,

\[ CFB = 1 - \text{Exp}[-a(RSS - RSO)] \]  

(6)
where \( a = 0.23 \) in order to accomplish the transition at the rate specified above. This function is applied in determining both the resultant crown-fire spread rate and the degree of crown consumption, leading finally to the frontal fire intensity.

Two different models of crown-fire behavior are used in the new FBP System. Before presenting them, however, the role of foliar moisture content is first described.

V FOLIAR MOISTURE EFFECT

Foliar Moisture Content (FMC) has already appeared as part of the criterion for judging the onset of crown ignition (Section III). By physical logic, it must also have some effect on the rate of fire spread through the crown layer. Because FMC in Canadian conifer forest exhibits a strong seasonal trend (e.g., Van Wagner 1967), with distinctly lower values during spring, the implication is that crown fires should start more easily and spread faster during that season. Again, as with the BUI effect, analysis of the fire data failed to yield any statistical evidence, probably owing to the various empirical limitations in the data. The physical argument was then applied, as adapted for crown fire by Van Wagner (1974) from original arguments by Thomas et al. (1964), that spread rate should be

a) proportional to the horizontal radiant heat flux through the crown layer
b) inversely proportional to the foliar ignition energy, and
c) inversely proportional to the foliar bulk density.

The effect of seasonal variation in foliar bulk density was omitted as a conservative simplification, leaving the first and second effects to be accounted for. Expressions for crown flame temperature \( T \) and heat of ignition \( h \), both in terms of FMC, were first required. A reasonable expression for the first is

\[
T = 1500 - 2.75(\text{FMC}), \text{ in } ^\circ\text{K}, \quad (7)
\]
based on an assumed air supply twice that needed for perfect combustion\(^1\), and for the second,

\[
h = 460 + 25.9(\text{FMC}), \text{ in kJ/kg}, \quad (8)
\]
taken from Van Wagner (1977). Applying Boltzmann's fourth-power law of thermal radiation, and adjusting decimal points for convenience, the desired Foliar Moisture Effect (FME) is given by

\[
\text{FME} = 1000 (1.5 - 0.00275\text{FMC})/(460 + 25.9\text{FMC}) \quad (9)
\]

It must be quickly explained that the FME is always applied in ratio with a normal value \( \text{FME}_{\text{n}} \), which is based on the supposed average FMC (namely, 97%) found in the composite crown-fire data set. Therefore, a real proportionality constant is not required. The value of \( \text{FME}_{\text{n}} \) is 0.778. In practice, FME varies from 0.525 to 0.966 within the standard FMC range of 85% to 120%.

VI TWO-EQUATION CROWN FIRE MODEL

Ideally, it was supposed, any fire in a conifer stand could be visualized mathematically as some point in the space between two bounding curves, a lower one representing pure surface fire and an upper one representing complete crown engagement. This concept is most readily handled in terms of spread rate as dependent primarily on the ISI. Then, if SFI exceeds CSI (see Section III), crown ignition is assumed. The process of determining the final spread rate is best described with the help of a diagram.

In Figure 2, the lower curve represents all possible surface fires, with spread rate RSS; the upper curve represents complete crown fires with spread rate RSC. Obviously, the right end of the RSS curve and the left end of the RSC curve never come into play, but a central range of horizontal overlap does exist, depending on the secondary effects of BUI (Section I) and FMC (Section IV).

The horizontal dashed line in Figure 2 represents RSO, the critical spread rate at which crowning begins. The value of CFB, the Crown Fraction Burned, is first computed (see Section III) from the difference between

![FIG 2. Graph of the two-equation crown-fire model, including a) separate curves of spread rate for surface and crown fires, b) a horizontal line representing RSO, the critical spread rate, and c) three examples of final spread rate.](image)
RSS and RSO. The resultant final spread rate $\text{ROS}$ is then found from

$$\text{ROS} = \text{RSS} + \text{CFB} (\text{RSC} - \text{RSS})$$  \hspace{1cm} (10)

In other words, the amount by which the spread rate rises above RSS depends on the amount by which RSS exceeds RSO; the intermediate function is the CFB. This latter factor is also applied to the Crown Fuel Load CFL to obtain the actual Crown Fuel Consumption CFC. The Frontal Fire Intensity FFI can now be determined.

The crowning process assumed by this model can be further visualized by imagining that the tendency of the crown fire to attain its full potential is somehow hampered by the restraining action of the surface phase as measured by the CFB. With secondary effects operating, actual crown fires will occupy a band of space rising to the right from the region where RSS first exceeds RSO to meet the RSC curve at ISI’s high enough to produce full crowning.

Three examples appear in Figure 2. At ISI, the surface spread rate RSS lies below the critical rate for crowning RSO; the fire therefore remains on the surface. At ISI, RSS exceeds RSO, so the fire crowns, the CFB is appreciable, and the final ROS is somewhere between RSS and RSC. At ISI, the RSS is high enough that CFB approaches 1 and the fire spreads nearly at the RSC value.

The flexibility of this two-equation model allows for variation in the Crown Sase Height (CSH) as it depends on stand height. This feature is particularly desirable for intimately-known areas of flammable plantation forest.

VII SINGLE-EQUATION CROWN FIRE MODEL

For most conifer fuel types, including the major boreal species, it was decided to retain the full-range spread-rate equation, and to design a less complete model around it (see Fig. 3).

A spreadrate is first computed from the basic equation and labelled temporarily RSS, as for surface fire. The routine for judging the onset of crowning (see Section II) is called into play and, if RSS exceeds RSO, the fire is labelled Crown; the Crown Fraction Burned (CFB) is then computed (see Section IV).

From the region where crowning begins, the basic curve is then assumed to occupy a vertical range whose upper bound represents fires spreading at minimum FMC, and whose lower bound the case of maximum FMC. The CFB determines the extent to which the predicted resultant ROS departs from the basic curve toward the upper or lower bound. The process is normalized, as before, to the supposed mean FMC of the composite crown-fire data set. The resulting equation for final spread rate is, accordingly,

$$\text{ROS} = \text{RSS} [1 + \text{CFB}(1.285\text{FME} - 1)]$$,  \hspace{1cm} (11)

where 1.285 is the above-mentioned normalizing factor. Thus, if $1.285\text{FME}$ exceeds 1, the fire spreads faster than the basic curve value and vice versa. Because CFB starts at zero just at the point where crowning is first possible, the effect of (11) is to produce a gradually widening band of potential fires that reaches its greatest width as CFB approaches 1.

As before, the CFB is applied to the full Crown Fuel Load (CFL) to yield the actual Crown Fuel Consumption (CFC), permitting a computation of final Frontal Fire Intensity (FFI).

The single-equation model provides for the identification of fires as Surface and Crown, and provides for some variation in spread rate and intensity.

FIG 3. Graphs of the single-equation crown-fire model, built around the standard equation for normal FMC. The curves for high and low FMC start at RSO, the critical spread-rate for crowning. They represent the upper and lower limits of FMC within the standard spring dip.

Conclusion

As with previous work in Canadian forest fire danger rating, the present fire behavior model is an obvious blend of empirical data and physical theory. Because crown fire looms so large in the Canadian forest-fire scene, the model must account for it as logically as possible. But the complete combustion process in heterogeneous natural fuel, especially in distinct surface and crown layers, has so far proven intractable by physics and mathematics alone. The model of Albini and Stocks (1986) has come closest but is not yet in practical form. At the same time, the available empiri-
cal data are still not robust enough to demonstrate statistical evidence of several effects that must, by force of physical logic and indirect evidence, play some part in real fire behavior. Thus the compromise between theory and field data as described previously.

A particular issue is the basic label, Surface or Crown, applied to each fire. At present, only fires whose SFI is less than CSI are classed as Surface; a fire with any degree of crown engagement, no matter how small, is labelled Crown. Van Wagner (1977) classed crown fires as passive, active, or independent, each with a somewhat different mechanism. The crown-fire models described here will, however, not accommodate such distinctions; perhaps some classification according to CFB can be developed.

Failing statistical evidence for each distinct effect or factor, the best evidence of the new FBP System’s credibility must lie in its ability to predict overall fire behavior. Again there is difficulty, because every available documented fire has already been used in deriving the basic empirical rates of spread and fuel consumption. The model can thus be “verified” against its own design data, but not yet “validated” against independent data. In fact, the average R-squares for its own design data, but not yet “validated” against independent data. In fact, the average R-squares for regressions of predicted behavior vs. observed were as follows:

- for spread rate, 0.82,
- for fuel consumption, 0.36,
- for frontal fire intensity, 0.61

Of these 160 conifer fires, 82 were listed as Surface in the original data set, the other 78 as Crown. The model’s predictions as to fire type were correct in 144 (or 90%) of cases.

As time passes, new fire data will become available, and weaknesses in the new FBP System will be exposed. Periodic modifications are to be expected. Meanwhile, for the first time, a more or less comprehensive model of fire behavior in Canadian forests is at the point of release for use in forest fire management.

List of Symbols

FWI - Fire Weather Index (System)
FBP - Fire Behavior Prediction (System)
ISI - Initial Spread Index
BUI - Buildup Index

f(U) - BUI function
U - Standard BUI
U - Average BUI for a fuel type
q - Factor representing fuel buildup with dryness in depth

FMC - Foliar Moisture Content
FME - Foliar Moisture Effect
DO - Date of minimum FMC
CBH - Crown Base Height
CFB - Crown Fraction Burned

ROS - Final spread rate
RSO - Critical spread rate
RSS - Surface spread rate
RSC - Crown spread rate

SFC - Surface Fuel Consumption
CFL - Crown Fuel Load
CFC - Surface Fuel Consumption

SFI - Surface intensity
CSI - Critical Surface Intensity
FFI - Frontal Fire Intensity

Endnotes

1 From an unpublished report on file at the Petawawa National Forestry Institute by C.E. Van Wagner.

References


