Forest Fire Research & Wildland Fire Safety, Viegas (ed.)
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Predicting crown fire behavior to support forest fire management decision-making

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Keywords: fire behavior modeling, crown fire initiation, crown fire spread

ABSTRACT: Fire behavior models are an important component of decision support systems for fire management. This paper describes the modeling of two fundamental crown fire behavior features: the onset of crowning and the spread rate of crown fires. The present study is based largely on the database used in the development of the Canadian Forest Fire Behavior Prediction System. The dataset used in the study consisted of 73 experimental fires in various coniferous forest fuel complexes, 40 of which were classified as crown fires. These fires cover a wide spectrum of fire environment conditions and fire behavior characteristics, with rates of spread ranging from 0.5 - 49.4 m/min, and fireline intensity from 62 – 45,200 kW/m. Crown fire initiation was modeled through a logistic regression approach using 10-m open wind speed, fuel strata gap or height to live crown base, a surface fuel consumption class, and an index of fine dead fuel moisture content as independent variables. Spread rates for active and passive crown fires were modeled through multiple non-linear regression analysis following physical reasoning. Independent variables used in the crown fire spread models were 10-m open wind speed, canopy bulk density and again the index of fine dead fuel moisture content. The crown fire initiation model correctly predicted 85 % of the cases in the dataset used for its construction. The active crown fire spread model yield a R2 of 0.61. The wide variation in fuel complex structure and fire behavior in datasets used to build the crown fire initiation and rate of spread models gives confidence that the models might work well in fuel complexes different from the original ones, given an adequate description of the physical characteristics of the fuel complex.

1 INTRODUCTION

Fire behavior models have been developed mostly with the objective of increasing our understanding of the phenomena driving fire spread and energy release rates in order to produce the tools to support fire management decision making. Throughout the world, various systems have been developed to allow managers to predict fundamental fire behavior characteristics from the information on the state of the fire environment (i.e., fuels, weather and topography). Given the variability inherent in the variables controlling and influencing wildland fire behavior, these systems (e.g., Sneeuwjagt and Peet 1985; Andrews 1986; Cheney 1991; Forestry Canada Fire Danger Group 1992; Finney 1998) have performed adequately and are accepted as valuable tools in support fire

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management decision making activities, such as prescribed fire planning, evaluating fuel treatment effectiveness, and forecasting fire behavior during going wildfires. From the various characteristics that many of these systems attempt to describe, particularily the American and Australian systems, one of the least understood, and consequently the one for which predictions are least reliable, is crown fire behavior. Our increasing understanding of crown fire behavior phenomena has to a certain extent been hindered by several factors that, encompass the advantages and limitations of the experimental versus theoretical study approaches (Van Wagner 1971). Measurements of the extreme fire behavior associated with crowning wildfires is a complex venture and has been mostly limited to observations of rate of fire spread. High-intensity experimental fires, where crown fire behavior can be adequately monitored, are a reliable source of data (Alexander and Quintilio 1990). Nevertheless, the inherent risks associated with the fire weather conditions required to carry out experimental crown fires is certainly a potential limitation in relying solely on this approach. The sensitivity and portability of some instrumentation has also limited the sophisticated measurements being made on experimental crown fires. Only in recent years, have experimental crown fires come to be highly instrumented (Alexander et al. 2001), thus enabling the measurement of such fundamental fire dynamic properties as flame radiometric temperature profiles, heat fluxes, and fluid temperatures and flow velocities. Theoretical analysis and modelling of crown fire phenomena has been restricted by the scarcity of these fundamental measurements on both high-intensity surface and crown fires. The increase in computing power available to researchers has lead to a growing list of models based on numerical methods involving fluid dynamics and heat transfer principles (e.g., Grishin 1997; Linn 1997). Nevertheless, these models at the best are parameterized from laboratory fires (e.g., Dupuy and Larini 1999; Balbi et al. 1999), and consequently may only be applicable to low-intensity fire situations. The small scale at which these models address fire phenomena have not been quantitatively characterized in the field, namely for the energy release levels that characterize the initiation and spread of crown fires (Van Wagner 1971).

Despite the fact that crown fires are responsible for a large proportion of the annual area burned in certain fire-prone ecosystems, our knowledge of the phenomena is lacking and the tools available for managers to incorporate an assessment of crown fire potential into their land management planning or fire behavior forecasting must be considered inadequate. There exist a very small number of models for predicting the initiation and spread of crown fires in conifer forests that can be incorporated into decision support systems. Models to predict the onset of crowning include Van Wagner (1977), Xanthopoulos (1990) and Alexander (1998). Models to predict the rate of spread of crown fire include those of Rothermel (1991) and the Forestry Canada Fire Danger Group (1992). The Van Wagner (1977), Rothermel (1991) and Forestry Canada Fire Danger Group (1992) models have been implemented in various decision support systems to predict fire behavior. Although these three models suffer from scant data (i.e., Van Wagner 1971; Rothermel 1991) and/or weak theoretical basis (i.e., Rothermel 1991; Forestry Canada Fire Danger Group 1992) they are the models that underpin the crown fire component of widely used fire behavior prediction systems in North America (Andrews 1986; Finney 1998; Andrews and Bevins 1999; Scott 1999; Lee et al. 2000). The discussion of the conceptual validity of these models is outside the scope of this paper, but some limiting assumptions are worth describing given their remarkable character and implications. Van Wagner (1977) developed his crown fire initiation model based on plume theory of convective heating (cf. Yih 1953), theoretical reasoning and a single experimental fire to derive a needed empirical constant. The constant of proportionality derived from experimental fire R1 (Van Wagner 1968) was regarded by Van Wagner (1977) as an “empirical constant of complex dimensions”. In earlier papers dealing with the convective heating above surface fires, Van Wagner (1973, 1975) may have inadvertently implied that the proportionality constant associated with plume theory can be regarded more or less as a universal constant. However, recent research (Alexander 1998) indicates that it is indeed not the case. Van Wagner’s (1977) crown fire initiation model does not incorporate the effect of radiant heat transfer on the onset of crowning. Furthermore, its dependence on fireline intensity, a output of other models, makes it prone to error propagation due to the need to estimate two quantities in advance of a fire’s occurrence, namely rate of fire spread and the amount of fuel consumed during the flaming combustion stage. The Rothermel (1991) crown fire spread model is based on the relation between predicted surface fire spread rate for

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U.S. Fuel Model 10 (Anderson 1982) and observed average crown fire rates of spread from eight western U.S. wildfires that exhibited sustained runs (i.e., typically greater than two hours duration). A ratio between observed and predicted spread rates yielded an average value of 3.34. This value is used as a multiplier to obtain the predicted crown fire spread rate based on the predicted surface fire rate of spread from the BEHAVE fire behavior prediction system (Andrews 1986). Rothermel's (1991) model assumes that the crown fuel characteristics, such as vertical stratification between fuel layers, fuel load, bulk density, and foliar moisture content have no appreciable influence on crown fire spread rates and that the main drivers are wind speed and dead fine fuel moisture content. Many of the fuel type specific models comprising the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) are based on extensive field data collected from experimental fires and documented wildfires (e.g. Van Wagner 1968; 1977; Stocks 1987, 1989; Alexander and Lanoville 1987; Alexander et al. 1991). The FBP System considers both surface and crown fire spread for several fuel types judged susceptible to crowning. The FBP System is generally regarded by Canadian fire managers as producing good results in the past for the fuel types that it presently considers. However, its performance in other distinctly different fuel complexes is limited (Pearce and Alexander 1994).

Some of the limitations in the models described above not only become more noteworthy when they are used in the context of operational fire behavior prediction systems, but also when such systems are used to answer research questions (e.g., van Wagtendonk 1996; Stephens 1998; Hirsch and Pengelly 2000; Keyes and O'Hara 2002; Fulé et al. 2001) and influence policy directions (Fiedler et al. 2001). The result could conceivably be misguided management with large scale and long-term consequences.

It's believed that the existence of an extensive dataset covering a wide spectrum of fuel complex structures and fire behavior would allow for the development of empirically-based models for predicting crown fire initiation and spread without biasing the results to any specific fuel complex structure or other fire environment variable. Based on this premise, the objective of the present study as reported on by Cruz (1999) was to develop empirically based models for the prediction of the onset of crowning and crown fire rate of spread. Secondly, the resulting models to be constructed should be based on highly reliable experimental data on surface and crown fires, and incorporate physical descriptors of the canopy structure, so that the models can be applied to distinct fuel complexes based on the physical description of the relevant fuel characteristics.

2 METHODS

For the present study, a suitable fire behavior database was found in the form of the published and unpublished data used in the development of the Canadian FBP System by the Forestry Canada Fire Danger Group (1992)[2]. The compiled surface and crown fire behavior database (n = 73) consisted almost solely of experimental fires conducted with the specific objective of studying fire behavior in relation to fuel and weather conditions. The resulting dataset thus offers a high degree of reliability. No fire behavior data derived from the wildfire case studies used by Forestry Canada Fire Danger Group (1992) in the development of the FBP System were used in the present study mainly due to the fact that circumstances do not often permit the opportunity to secure detailed preburn information on the fuel complex characteristics and localized measurement of fire weather conditions during the various phases of the fire. The experimental fire database involved several coniferous forest fuel types: natural stands of immature jack pine [*Pinus banksiana*] (Stocks 1987), mature jack pine (Quintilio et al. 1977; Weber et al. 1987; Stocks 1989), lodgepole pine [*Pinus contorta*] (Lawson 1972), and black spruce [*Picea mariana*] (Kiil 1975; Newstead and Alexander 1983; Alexander et al. 1991), and red pine [*Pinus resinosa*] plantations (Van Wagner 1968, 1977). The FBP System database was supplemented with a few observations from Australian slash pine (Pinus elliottii) and maritime pine (*Pinus pinaster*) plantations (Van Loon and Love 1973; Burrows et al. 1988). Figure 1 presents the distribution of some of the relevant independent vari-

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[2] One of us (MEA), as a "core" member of the Forestry Canada Fire Danger Group from 1981 until the termination of the group in 1995 as a result of restructuring by the Government of Canada, was responsible for the creation of the database that used in the development of the FBP System.

ables. The distribution of these variables does not show any particular bias, with their distribution covering well the expected range for which the models are intended to be used. Exceptions to this are the lack of data for estimated fine dead fuel moisture contents (as per Rothermel 1983) less than 6 % and 10-m open wind speeds greater than 30 km/h. This is to a certain extent a reflection of the operational and social constrains that are normally imposed to outdoor experimental fire programs, in which ignition may not be allowed under extreme fire weather conditions which of course do not tend to occur that often as well. The dataset also shows a moderate variability in foliar moisture content. The dataset assembled covers a wide spectrum of fire behavior characteristics, with fireline intensities as defined by (Byram 1959) ranging from 64 to 45,200 kW/m and spread rates from 0.4 to 49.4 m/min. A more complete quantitative description of the dataset is given in Cruz (1999).

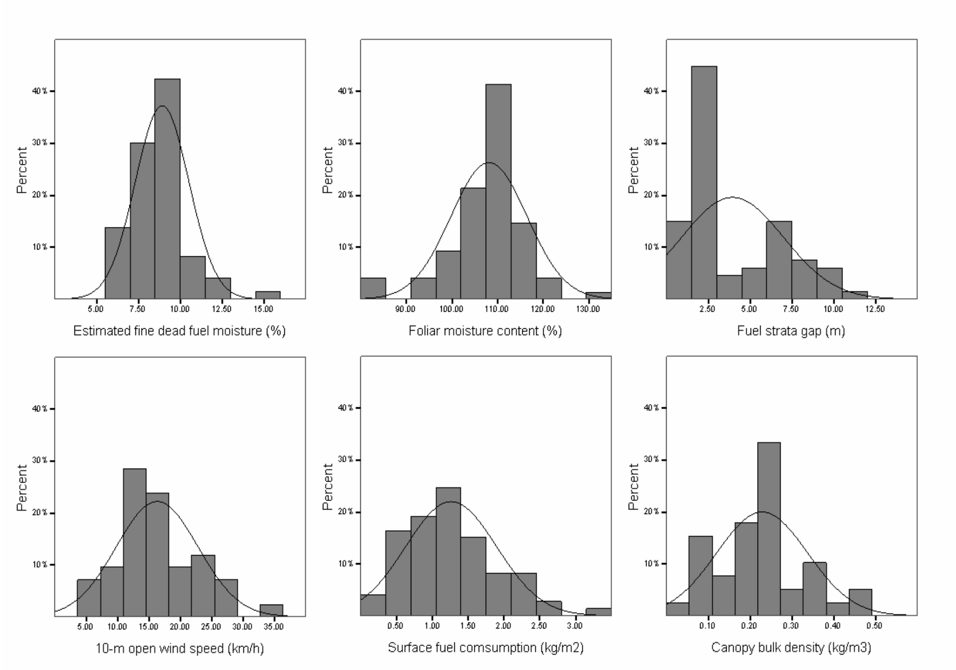

Figure 1: Distribution of relevant explanatory variables in the database used in the present study.

The characteristics of the two distinct phenomena underlying the analysis in the present study (i.e., crown fire initiation and crown fire rate of spread), lead to two different modeling approaches. In regards to the onset of crowning model development, due to the fact that the dependent variable has a dichotomous outcome (i.e., there is crowning or there is no crown fire occurrence), a logistic regression approach was followed. This allowed for the estimation of the probability of a crown fire event occurring based on a combination of environment factors chosen as inputs. For the crown fire spread model, in order to produce a robust model applicable to different fuel complexes over as wide a wide spectrum of fire weather conditions as possible, the modeling approach used was based on non-linear regression analysis incorporating the pertinent driving variables in a physically realistic form. With this in mind, Thomas and Simms'(1964) simple heat balance equation was selected as the general model form. This equation links the rate of spread with fuel bulk density (a variable fuel complex descriptor) and the heat of ignition (which is in turn a function of foliar moisture content, fine dead fuel moisture content and amount of fuel) as a function of the net horizontal heat flux to unburned fuels ahead of the advancing flame front. The crown fires included in the dataset were further classified as either "active" or "passive" using Van Wagner's (1977) criteria for active crowning:

$$R_0 = \frac{3.0}{CBD} \qquad [1]$$

where, R_0 is the critical minimum spread rate for active crown fire (m/min) and CBD is the canopy bulk density (kg/m^3).

3 RESULTS

3.1 *Crown fire initiation modeling*

Following a theoretical analysis of the processes involved in the crown fire initiation and the determinant variables controlling crown fire initiation in relation to the database characteristics, the variables selected to test their influence in the crown fire initiation model were: (1) wind speed measured at a 10 m height in the open, U_{10} (km/h); (2) fuel strata gap (FSG) (m); (3) surface fuel consumption, SFC (kg/m$^{2)}$; (3) foliar moisture content, FMC (% ovendry weight basis); and (4) estimated fine fuel moisture content, EFFM (% ovendry weight basis) as per Rothermel (1983). Since the SFC reflects a post-fire condition and because of some of the inherent difficulties in estimating available fuel for combustion, it was decided to use the SFC as a categorical variable in order to simplify its use. Three classes encompassing broad ranges of SFC were accordingly defined, namely <1 kg/m^2, 1-2 kg/m^2, and SF >2 kg/m^2. The limits of these classes were based on trends of the influence of this variable on crown fire initiation evident in the dataset. Since the SFC classes are broad and might not reflect a physical reality, it was decided to use it as a coded variable. The newly created categorical variable SFC (SFC_CAT) was coded through two design variables (D1 and D2). Since the values of the design variables are assumed to be nominally scaled as opposed to interval scaled, the logit equation is given by (Hosmer and Lemeshow 1989):

$$g(x) = \beta_0 + \beta_1 x_1 + \ldots + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_i x_i \qquad [2]$$

where j^{th} variable is SFC, with k_j levels (two in the present formulation), and D_{ju} are the design variables. The method of estimation of the parameters in Equation [2] is the maximum likelihood, which will produce coefficients that maximize the probability density as function of the original set of data. Several possible model solutions were analyzed, with various combinations of the independent variables. The best model fit and behavior was obtained using the following variables (model parameter, standard error): U_{10} (0.370, 0.123); FSG (-0.664, 0.222); SFC_CATD1 (-4.354, 1.575); SFC_CATD2 (-1.787, 1,387); EFFM (-0.286, 0.342) and constant (3.397, 3.406). The model yields a goodness of fit statistic of 36.98 and a Nalgelkerke R^2 (similar interpretation to coefficient of determination in linear regression) of 0.72. The EFFM variable coefficient was not significantly different from 0 (based on the Wald statistic) but was still included in the model due to its influence in determining the peak burning period throughout the diurnal cycle. Overall, the model correctly predicted 85 % of the situations in the dataset (i.e, 80 % and 89 % of the surface fires and crown fires were correctly predicted, respectively). Most of the incorrect scores were in the middle section of the probability scale, where a naturally higher level of uncertainty is to be expected relative to the occurrence or not of crown fire initiation.

3.2 *Crown fire spread modeling*

In order to model the spread rate of crown fires it was acknowledge that crowning forest fires can spread either as passive or active crown fires (Van Wagner 1977). The different processes that control fires spreading under these two distinct regimes justified this subdivision of crown fires. Passive crown fires are largely controlled by the surface phase whereas active crown fire behavior should be largely controlled by the crown phase. The criterion used to divide the dataset into active (*n*=25) and passive (*n*=14) crown fires was the achievement of a crown fire spread criterion (Van Wagner 1977) above 0.9 (i.e., ratio of observed crown fire rate of spread to $R_O > 0.9$) After reasoning on the effect of the various independent variables controlling crown fire rate of spread and given the constraints of available information in the dataset, the following independent variables were selected for exploratory statistical analyses: U_{10}, EFFM, CBD, FMC, crown or canopy fuel load, CFL (kg/m^2), SFC, and FSG. Active crown fire spread rates were significantly correlated (Pearson correlation coefficient) with U_{10}, EFFM and CBD. U_{10} was also significantly correlated with CBD and FMC, which might create some autocorrelation problems in the intended regression analysis begin sought. Interestingly enough, no explanatory variables were significantly correlated with the rate of spread of passive crown fires.

The modeling approach followed for the modeling of active crown fire spread rate, $CROS_A$ (m/min), was based as much as possible on the physical relationships between the variables and the processes they influence. Thomas and Simms (1964) simplified form of an heat balance equation for forward or heading rate of fire spread was selected as baseline model form to proceed with non-linear regression analysis. The optimum model fit was:

$$CROS_A = 11.76 \cdot {U_{10}}^{0.86} \cdot CBD^{0.18} \cdot e^{(-0.17 \cdot EFFM)} \qquad [3]$$

The model accounted for 61 % of the variability in rate of spread in the dataset. Although this model produced an R^2 a little lower than other models forms, the model behavior was in better agreement with expected behavior under very low fine fuel moisture content values. The proportion of variation in the dataset explained by the model can be attributed to the absence of other variables in the model (not included due to the nature of the database) and the influence of other phenomena, such as, convection plume interaction, that are difficult to integrate under the present modeling approach. Wind speed is the variable with the strongest effect on spread rate of active crown fires. The 0.86 coefficient in the power function expressing the effect of wind is very similar to the value determined by Cheney et al. (1998) for grasslands (0.84), but lower than the one found by Marsden-Smedley and Catchpole (1995) for shrublands (1.32). It is expected that in empirical studies this coefficient would vary within a certain limited range, a function of the representativeness of the dataset, namely the spectrum covered by wind speed, and the interaction between fire behavior and the wind field in a particular fuel complex. The exponential decay function of the fine fuel moisture term used in Equation [3] agrees with findings on the damping effect of fine fuel moisture found in the spread rate of laboratory fires (Wilson 1990; Catchpole *et al.* 1998).

Passive crown fires can be regarded as spanning a wide range in observable fire behavior – i.e., from moderately vigorous surface fires with single tree torching to high intensity surface fires spreading with an almost solid flame front occupying the canopy and sub-canopy space that have nearly achieved the R_O as defined by Equation 1. Building an empirically-based regression model to predict the spread rate of passive crown fires was not deemed viable given the limited number of passive crown fires in the dataset and the enormous range in fire behavior associated with passive crown fires as described above. Given this restriction it was decided to model passive crown fire spread rates based on the output of the $CROS_A$ model represented by Equation [3] with an adjustment term that would reduce the predicted fire rate of spread according to the degree of crown fuel involvement. By assuming that there exists a continuous gradient in spread rate between the passive and active crown fire spread regimes, a crown fire burning below the critical criteria for active crowning under increasingly favorable conditions would cover that gradient and reach an active crown fire-spreading regime. Assuming canopy bulk density to be the fuel complex characteristic determining the crown fire spread regime, passive crown fire spread rate was modeled as:

$$CROS_P = CROS_A \cdot CAC \qquad [4]$$

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where, $CROS_P$ is the passive crown fire rate of spread (m/min) $CROS_A$ is the active crown fire rate of spread according to Equation [3], and CAC is the criteria for active crowning as defined by the ratio of $CROS_A$ to R_O as specified by Equation [1]. The approach yielded coherent results, with much of the predicted fire spread rates closely following a line of perfect agreement. Regression analysis (linear regression with y-intercept forced through origin) between predicted versus observed rates of spread yielded an R^2 of 0.76, and a slope of 0.82 (standard error of 0.13). The slope of the regression equation reveals a slight bias towards over-prediction.

4 MANAGEMENT IMPLICATIONS

The models developed in the present study were designed to support decision making as it relates appraising crown fire potential in various fire management activities. Fire managers in crown fire prone forest environments need quantitative information on crown fire potential for a given stand in order to evaluate various activities such as high-intensity prescribed fire planning for ecosystem health purposes, effectiveness of fuel treatments aimed at reducing crown fire hazard, or site specific prediction of wildfire behavior. The models will also allow a fire manager to assess to a certain extent the impact of various silvicultural treatments, such as thinning and pruning, on crown fire potential. The models will allow for quantitative answers to questions about (i) the effect of the reduction in canopy cover, and consequently reduction in canopy bulk density, on the potential for the occurrence of active crown fires; (ii) the effect of leaving thinning or pruning residues within the stand on subsequent crown fire initiation; and (iii) the effect of increasing the vertical separation through pruning in a stand in order to decrease the likelihood for crown fire formation.

The crown fire initiation and spread models developed in this study constitute a system to predict crown fire behavior in fuel complexes that sustain such phenomena. Figure 2 illustrates how the information flows between the models. The process can be summarized as follows:

- Step 1. Compute the probability of crown fire initiation from Equation [2]. Required inputs are 10- m open wind speed (U_{10}), fuel strata gap (FSG), estimated surface fuel consumption (SFC) and estimated fine fuel moisture content (EFFM);

- Step 2. If the probability is < 0.5, the fire should spread as a surface fire, and Step 1 should be repeated when there are changes in the input variables;

- Step 3. If probability is > 0.5, the fire should spread as a crown fire;

- Step 4. Compute crown fire rate of spread from Equation [3]. Required inputs are U_{10}, canopy bulk density (CBD), and EFFM;

- Step 5. Compute the criteria for active crowning (CAC) based on the CBD, R_0 and the crown fire rate of spread from Step 4;

- Step 6. If the CAC is > 1, the fire is judged to be spreading as an active crown fire and final rate of spread is the one computed at Step 4;

- Step 7. If the CAC is < 1, then the fire is expected to spread as a passive crown fire, and hence the final rate of fire spread is judged to that produced by [Equation 4].

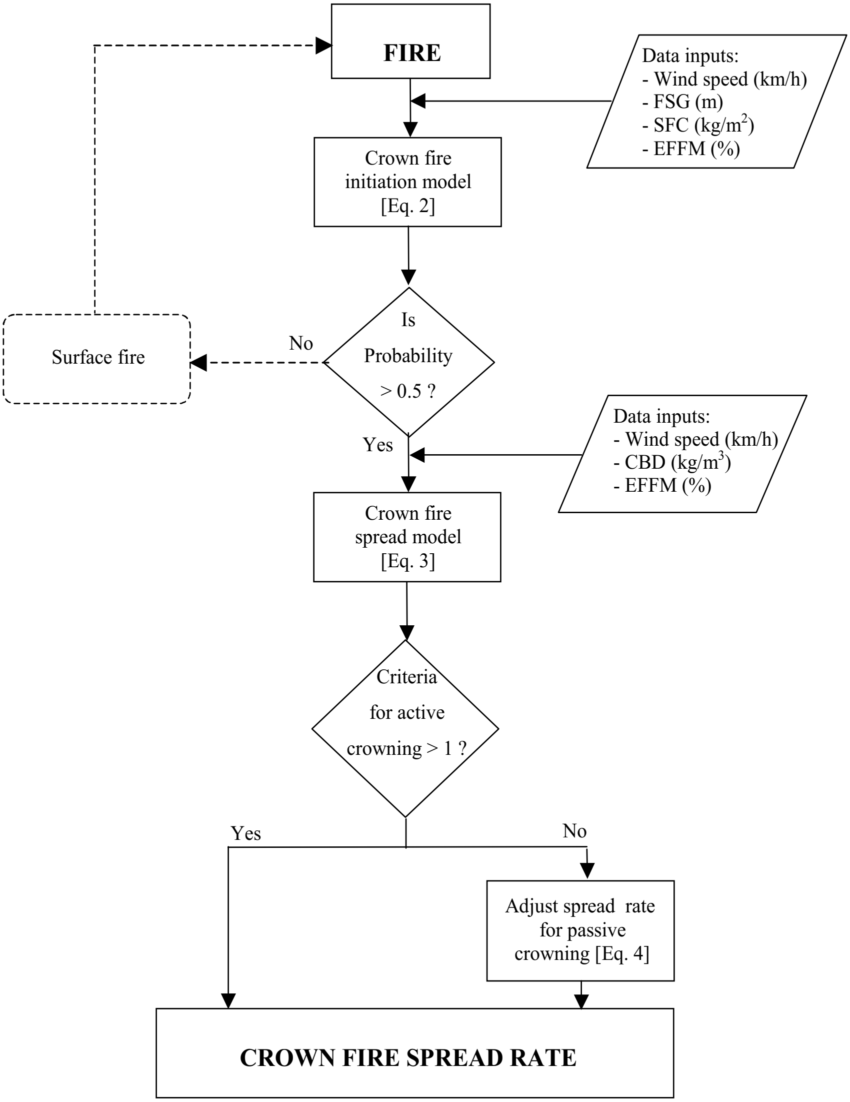

Figure 2: Diagram of information flow for the prediction of crown fire behavior.

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5 CONCLUDING REMARKS

The models developed in the present study are believed to include the most significant variables influencing crown fire initiation and spread. Other theoretically important variables identified as important controls on crown fire behavior, namely, FMC for both models, and FSG, CFL, and SFC in the crown fire rate of spread model, did not produce meaningful results in the models' performances no doubt due in part to the lack of range and incompleteness in the dataset. s. The crown fire initiation and rate of spread models developed in the present study do not incorporate the effect of slope steepness. The effect of slope of fire spread rate has generally been difficult to quantify under field conditions due to the non-independence and interactions of wind and slope in certain situations. A possible approximation for the slope effect would be the calculation of a wind equivalency-based slope effect (Rothermel 1972; Forestry Canada Fire Danger Group 1992).

The fact that the models developed in this study were based on data originating mainly from Canada may raise questions as to their applicability elsewhere. The fact that the modeling approach followed utilized physical fuel quantities to a large extent gives confidence that the models can be applied to other structurally similar yet distinctly different fuel types regardless of geographical location. The variety of fuel complex structures incorporated in the dataset used to derive the models is believed to support such a claim. However, the models as presented here should be submitted to a thorough evaluation as Cruz (1999) has done. This will allow a better understanding of the models behavior and capacities. This evaluation should comprise several aspects, such as, (1) model conceptual validity, (2) data requirements for model validation, (3) sensitivity analysis, (4) predictive and statistical validation, and (5) inter-model comparison (Cruz et al. 2002). Inter-model comparison will allow recognizing distinct behavior between models and raising questions relative to modeling assumptions. This will allow identifying future research needs. Some of those were patent in the results obtained here, namely the non-significance of the FMC effect either on crown fire initiation and spread. Two papers dealing with the specifics of the models and their performance have been submitted for publication in scientific peer-review journals.

ACKNOWLEDGEMENTS

We would like to thank the Canadian Forest Service for making available its Canadian Forest Fire Behavior Prediction System database for the present study and its staff for the collection and safekeeping of such unique data through the years.

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