Development and testing of models for predicting crown fire rate of spread in conifer forest stands

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Abstract: The rate of spread of crown fires advancing over level to gently undulating terrain was modeled through nonlinear regression analysis based on an experimental data set pertaining primarily to boreal forest fuel types. The data set covered a significant spectrum of fuel complex and fire behavior characteristics. Crown fire rate of spread was modeled separately for fires spreading in active and passive crown fire regimes. The active crown fire rate of spread model encompassing the effects of 10-m open wind speed, estimated fine fuel moisture content, and canopy bulk density explained 61% of the variability in the data set. Passive crown fire spread was modeled through a correction factor based on a criterion for active crowning related to canopy bulk density. The models were evaluated against independent data sets originating from experimental fires. The active crown fire rate of spread model predicted 42% of the independent experimental crown fire data with an error lower then 25% and a mean absolute percent error of 26%. While the models have some shortcomings and areas in need of improvement, they can be readily utilized in support of fire management decision making and other fire research studies.

Résumé : Le taux de propagation des feux de cimes se propageant en terrain plat ou légèrement onduleux a été modélisé en utilisant l'analyse de régression non linéaire à partir d'un ensemble de données expérimentales portant principalement sur les types de combustibles rencontrés en forêt boréale. L'ensemble de données couvrait une importante gamme de complexes de combustibles et de caractéristiques de comportement du feu. Le taux de propagation des feux de cimes a été modélisé séparément pour les feux se propageant selon des régimes de feu de cimes dépendant ou passif. Le modèle du taux de propagation des feux de cimes dépendants qui tient compte des effets de la vitesse du vent à découvert à 10 m, de la teneur en eau estimée des combustibles fins et de la densité apparente de la canopée expliquait 61 % de la variation dans le jeu de données. La propagation des feux de cimes passifs a été modélisée en appliquant un facteur de correction basé sur un critère des feux de cimes dépendants relié à la densité apparente de la canopée. Les modèles ont été testés avec un ensemble de données indépendantes provenant de feux expérimentaux. Le modèle du taux de propagation des feux de cimes dépendants prédisait 42 % des données indépendantes provenant des feux de cimes expérimentaux avec une erreur inférieure à 25 % et un pourcentage d'erreur absolue moyenne de 26 %. Bien que les modèles aient certaines lacunes et que certains aspects aient besoin d'être améliorés, ils peuvent facilement être utilisés comme support à la prise de décision dans la gestion des feux de forêt et dans le cadre d'autres travaux de recherche sur le feu.

[Traduit par la Rédaction]

Introduction

Advances in our knowledge of the role of fire in ecosystem dynamics demand that land management practices be supported by sound scientific principles and, in turn, reliable information about the prediction of fire impacts and effects (Schmoldt et al. 1999). The application of fire behavior models takes on even greater importance in fire management decision making because the spectrum of fire effects at a local scale depends primarily on burning conditions at the time and the resulting fire behavior characteristics. Among the various types of forest fire propagation, crown fire spread has been of the one more challenging aspects of wildland fire behavior to understand and model (Van Wagner 1977), although it could be argued that in some respects "the prediction of surface fire behavior is, in fact, probably more difficult than the prediction of crowning potential, because of the multiplicity of possible forest floor and understory fuel complexes" (Van Wagner 1979). Our present understanding of crown fire dynamics is mainly of a qualitative nature. This can be partially explained by the inherent difficulty in carrying out and adequately instrumenting full-scale experimental fires designed to simulate their "wild" counterparts in the field. Very few studies have attempted to experimentally quantify some of the basic physical characteristics of crown fires, namely heat fluxes released by the fire, and the gas temperatures and velocities within and above the

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combustion zone (Butler et al. 2004). As a result of this lack of fundamental data, our description of crown fire phenomena, including the importance of the various underlying heat transfer processes involved, is based largely on field observations and theoretical considerations.

Surface fires spreading beneath closed-canopy conifer stands seldom exceed approximately 6 m·min^{-1} without the onset of crowning (Kiil 1976). Following the establishment of full-fledged crowning, fires at a minimum double their rate of spread (Rothermel 1983, 1991; Alexander 1998). Based on the analysis of a simplified heat balance model for fire spread (Thomas and Simms 1964), Van Wagner (1977) hypothesized that the vast majority of crowning forest fires spread either as passive or active crown fires, each controlled by a different set of processes. Passive crown fires cover a relatively wide range in observed fire behavior — from moderately vigorous surface fires with isolated tree torching up to high-intensity surface fires spreading with an almost solid flame front occupying the canopy and subcanopy space that have nearly achieved the critical spread rate for crowning (see Alexander and De Groot 1988; Alexander and Lanoville 1989).

Passive crown fires can occur under two broad situations. First, the canopy base height and canopy bulk density are considered optimum, but fuel moisture and wind conditions are not quite severe enough to induce full-fledged crowning (Lawson 1973; Dyrness and Norum 1983). Second, the canopy base height and canopy bulk density are, respectively, above and below the thresholds generally considered necessary for crowning (e.g., tall and (or) open-forest stand types), so that even under severe burning conditions (i.e., critically dry fuels and strong surface winds), active crown fire spread is not possible, although vigorous, high-intensity fire behavior can occur (Dieterich 1979; NFPA 1990; Alexander 1998). Spread rates of up to approximately 15–25 m·min^{-1} are possible in such cases. Maximum sustained spread rates of active crown fires generally range between approximately 25 and 100 m·min^{-1} and occasionally higher for brief intervals.

The various approaches used to model wildland fire behavior have been empirical or physical in nature or a combination of both (Catchpole and de Mestre 1986). The empirical approach has produced several models and systems for predicting crown fire rate of spread that have found widespread use in operational fire management applications. These include the Rothermel (1991) crown fire rate of spread model, the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Taylor et al. 1997), and the Australian Forest Fire Danger Meter (Luke and McArthur 1978). The Rothermel (1991) crown fire spread model has been implemented in computerized decision-support systems (Scott and Reinhardt 2001; Finney 2004). The FBP system is also the basis for PROMETHEUS, the Canadian wildland fire growth model (Tymstra 2002), and the equations associated with the Australian Forest Fire Danger Meter are a component of the CSIRO Bushfire Spread Simulator (Coleman and Sullivan 1996).

The objective of this study was to develop empirically based models for predicting crown fire rate of spread that would be robust enough to be applicable to a variety of conifer fuel complexes prone to crowning. The models were evaluated against independent data sets to judge their predictive capability and provide insight into their limitations. Symbols used in the equations are identified throughout the text and summarized at the end of the paper.

Methods

Database compilation

For the present study, a suitable fire behavior database was found in the form of published and some unpublished data used in the development of the Canadian FBP System by the Forestry Canada Fire Danger Group (1992).[3] The compiled database (n = 37) consisted of experimental crown fires conducted with the specific objective of studying fire behavior in relation to fuel and weather conditions (Cruz 1999; Cruz et al. 2002). The experimental database consisted of both active (n = 24) and passive (n = 13) crown fires based on visual observations and photographic evidence, involving several coniferous forest fuel types (Table 1): natural stands of immature jack pine (*Pinus banksiana* Lamb.) (Stocks 1987*a*), mature jack pine (Quintilio et al. 1977; Weber et al. 1987; Alexander and De Groot 1988; Stocks 1989), black spruce (*Picea mariana* (Mill.) BSP) (Kiil 1975; Newstead and Alexander 1983; Alexander and Lanoville 1989; Alexander and Quintilio 1990; Alexander et al. 1991), and plantation stands of red pine (*Pinus resinosa* Ait.) (Van Wagner 1964, 1968, 1977). Fire rates of spread and intensity varied between 3.4 and 51.4 m·min^{-1} and 1698 and 45 200 kW·m^{-1}, respectively (Table 1). All of the experimental fires occurred on level terrain, thereby eliminating slope steepness as a variable influencing fire behavior.

Crown fire classification criteria

As discussed earlier, Van Wagner's (1977) theory of crown fire propagation suggests that the mechanisms controlling passive and active fire spread are quite distinct. It was therefore decided to model these distinctly different forms of crown fire spread as separate entities using Van Wagner's (1977, 1993) criterion for active crowning.

The criterion for active crowning (CAC) is the ratio of the observed or predicted crown fire rate of spread (R_c) and the critical minimum rate of spread (R_o) for active crowning (m·min^{-1}):

$$\text{CAC} = \frac{R_c}{R_o} \quad [1]$$

R_o is the spread rate associated with a minimum mass flow rate for the development of a continuous flame front in both the subcanopy and canopy spaces as given by the following equation (Van Wagner 1977):

$$R_o = \frac{\text{MFR}_o}{\text{CBD}} \quad [2]$$

where CBD is the canopy bulk density (kg·m^{-3}) for the stand, and MFR_o is the critical mass flow rate (kg·m^{-2}·min^{-1}). Van Wagner (1977) has empirically determined from experi-

[3] One of the authors (M.E. Alexander), as a "core" member of the Forestry Canada Fire Danger Group from 1981 until the termination of the group in 1995, was a contributor to the database used in the development of the FBP System and thus had access to the database.

Table 1. Basic descriptive statistics associated with the data set used in the development and evaluation of the crown fire rate of spread models.

	Active crown fires (n = 24)				Passive crown fires (n = 13)			
Variable	Min.	Max.	Mean	Std. dev.	Min.	Max.	Mean	Std. dev.
Stand basal area ($m^2 \cdot ha^{-1}$)	3.35	50	26.8	16.3	4.14	35.2	18.4	10.4
Stand density (trees$\cdot ha^{-1}$)	887	6750	3561	1454	597	9276	3656	3481
Stand height (m)	2.9	14	7.9	3.8	4.1	19	11.7	6.6
Crown ratio (fraction)	0.5	0.88	0.78	0.12	0.37	0.9	0.74	0.15
Canopy base height (m)	0.4	7	2.1	2	0.8	12	3	3.2
Canopy bulk density ($kg \cdot m^{-3}$)	0.12	0.48	0.27	0.09	0.05	0.37	0.16	0.1
10-m open wind speed ($km \cdot h^{-1}$)	5	32.1	15.8	6.7	5	29	16.3	6.3
Estimated fine fuel moisture content (%)	7	12	8.8	1.3	7	11	8.6	1.2
Surface fuel consumption ($kg \cdot m^{-2}$)	0.66	2.4	1.6	0.5	0.9	3.2	1.7	0.7
Foliar moisture content (%)	78	135	107	11.5	75	118	102	15.4
Rate of fire spread ($m \cdot min^{-1}$)	7.5	51.4	22.6	12.6	3.35	15.4	7.1	4
Fireline intensity ($kW \cdot m^{-1}$)	4230	45 200	16 918	10 746	1698	17 000	5127	4239

Note: The 24 experimental active crown fires used in the present study included the following: fires 2, 3, 4, 5, 6, 11a, 11b, 12, 13, and 14 in Stocks (1987*a*); fire 3/91 in Stocks and Hartley (1995); fires L2, L5, and L5A in Alexander et al. (1991); fires C4, C6, and R1 in Van Wagner (1968, 1977); "water" treatment fire in Newstead and Alexander (1983); and the fires carried out in the Big Fish Lake experimental burning plots (Alexander and Quintilio 1990) 1, 9, 11, 12, 17, and 21 (M.E. Alexander, unpublished data). The 13 experimental passive crown fires used in the present study included the following: fire 17 in Stocks (1987*a*); fires 5, 9, and 12 in Stocks (1989); fires 4b and 6 in Quintilio et al. (1977); fires L1, L3, and L4 in Alexander et al. (1991); the "tenogum" treatment fire in Newstead and Alexander (1983); the Steen River experimental fire (Kiil 1975); fires 5 and 7 in Weber et al. (1987). Note that fire 7 in Weber et al. (1987) is referred to as fire SC in Van Wagner (1977).

mental fires carried out in a red pine plantation that MFR_o equals approximately 3.0 $kg \cdot m^{-2} \cdot min^{-1}$. Albini (1993) viewed the R_o criterion as a "lean flammability limit" for active crown fires; in other words, a fully developed or active crown fire cannot occur if it cannot spread rapidly enough.

All of the active crown fires in the experimental database had a CBD above approximately 0.1 $kg \cdot m^{-3}$, a value suggested by Agee (1996) as the approximate threshold necessary to support active crowning based on wildfires in the forest types he studied in the Pacific Northwest. This threshold is also, at least partially, supported by Alexander (1998) in a detailed wildfire case study analysis. Johnson (1992), on the other hand, considered a CBD of 0.05 $kg \cdot m^{-3}$ to be a critical threshold value for active crown fire development. It should be expected that other fuel-complex variables (e.g., canopy base height, ladder or bridge fuels, and surface fuelbed structure) and burning conditions control the development of flame characteristics within the subcanopy and canopy spaces that determine the passive and active crown fire spread regimes as defined by Van Wagner (1977). Nevertheless, the assumption that CBD is one of the governing fuel-complex variables controlling the type of crown fire spread regime has practical value and was therefore used in the present study.

Model building

To the extent possible, our approach to modeling active crown fire rate of spread was based on simple physical theory (Thomas and Simms 1964), attempting to incorporate as many variables and processes believed to be most influential. After considering the various factors controlling or influencing crown fire rate of spread and given the available information in the experimental crown fire data set, the following independent variables, in addition to CBD, were selected for exploratory statistical analyses (Cruz 1999): 10-m open wind speed, U_{10} ($km \cdot h^{-1}$); canopy base height, CBH (m) — a measure of the distance between the ground surface and the canopy fuel layer; canopy fuel load, CFL ($kg \cdot m^{-2}$); stand height, SH (m); crown ratio, i.e., the ratio between crown length and tree height, CR (fraction); surface fuel consumption, SFC ($kg \cdot m^{-2}$); foliar moisture content, FMC (% ovendry mass basis); and the estimated fine fuel moisture content, EFFM (% ovendry mass basis). The EFFM is dictated by air temperature (T_a), relative humidity (RH), time of year and day, and degree of shading (based on cloud cover and canopy coverage) as per the manual procedure of Rothermel (1983); software is now available for making computations (Andrews et al. 2003).

Model testing

Independent data derived from the experimental crown fires carried out during the International Crown Fire Modeling Experiment (ICFME) (Stocks et al. 2004) were sought for modeling evaluation purposes. The ICFME data set, comprising 11 experimental crown fire observations in a conifer fuel type distinctly different from the ones used in model development (Alexander et al. 2004), allows for the evaluation of model behavior using highly reliable fire behavior data. We applied the same evaluation tests to the Rothermel (1991) crown fire rate of spread model to better understand the characteristics of the models developed in this study. This model was also compared with the experimental fire data used to develop the crown fire rate of spread models. The Rothermel (1991) model is based on a correlation developed between the predicted surface fire rate of spread for Fuel Model 10 (Anderson 1982) in the BEHAVE system (Andrews 1986) and eight observations of crown fire rate of spread garnered from wildfires in the western United States in several distinctly different fuel types (e.g., Rothermel 1983; NFPA 1990). In addition to slope steepness (assumed to be zero in the present case), the BEHAVE system predictions are in this particular application based on wind speed and four different fuel moistures as described below. Wind speed measured at a height of 6.1 m (i.e., 20 ft), as is the practice in the United States (Finklin and Fischer

Table 2. Simple correlation coefficient (r) matrix for the fire environment and fire behavior variables associated with active crown fires in the experimental data set (n = 24).

	R_c	U_{10}	EFFM	CBD	FMC	CFL	SFC	CR	CBH	SH
R_c	1.000	0.689**	–0.389*	–0.382*	–0.350	–0.217	–0.147	0.120	–0.079	0.045
U_{10}		1.000	–0.043	–0.490*	–0.463*	–0.023	–0.075	–0.165	0.173	0.135
EFFM			1.000	0.060	0.196	0.626*	0.698**	–0.751**	0.771**	0.578*
CBD				1.000	0.160	0.440*	0.168	0.145	–0.234	–0.478*
FMC					1.000	0.317	0.182	–0.03	0.105	0.208
CFL						1.000	0.212	–0.760**	0.729**	0.346
SFC							1.000	–0.258	0.171	0.034
CR								1.000	–0.952**	–0.702**
CBH									1.000	0.836**
SH										1.000

Note: See the List of symbols for definitions of the variables. *, correlation is significant at the 0.05 level (two-tailed); **, correlation is significant at the 0.01 level (two-tailed).

Table 3. Simple correlation coefficient (r) matrix for the fire environment and fire behavior variables associated with passive crown fires in the experimental data set (n = 13).

	R_c	SH	CBD	U_{10}	CR	CFL	FMC	SFC	EFFM	CBH
R_c	1.000	0.498	–0.334	0.300	0.218	–0.214	0.120	–0.103	0.087	0.043
SH		1.000	–0.636*	0.409	–0.035	–0.254	0.654*	0.256	0.505	0.553*
CBD			1.000	–0.456	0.082	0.851**	–0.106	–0.315	–0.081	–0.368
U_{10}				1.000	0.029	–0.330	–0.193	–0.168	0.145	0.220
CR					1.000	–0.054	–0.050	–0.742**	–0.182	–0.821**
CFL						1.000	0.217	–0.123	–0.018	–0.049
FMC							1.000	0.334	0.294	0.351
SFC								1.000	0.012	0.744**
EFFM									1.000	0.445
CBH										1.000

Note: See the List of symbols for definitions of the variables. *, correlation is significant at the 0.05 level (two-tailed); **, correlation is significant at the 0.01 level (two-tailed).

1990),[4] was reduced by a factor of 0.4 to approximate the midflame wind per Rothermel's (1991) original formulation. The EFFM was equated to the 1-h time lag dead fuel moisture content, and the 10- and 100-h time lag values were in turn estimated by adding 1.0% and 2.0%, respectively, to the 1-h value per Rothermel (1983, 1991). The live fuel moisture content was assumed to be 75% as a "near-worst-case" scenario (Rothermel 1983, 1991).

The principal statistics used to quantify model adequacy were modeling efficiency (EF) (Mayer and Butler 1993) and the mean absolute error (MAE) (Schaeffer 1980). The y intercept and slope of regression analysis from observed versus predicted rates of spread were also calculated (Vanclay and Skovsgaard 1997).

Results and discussion

Model development

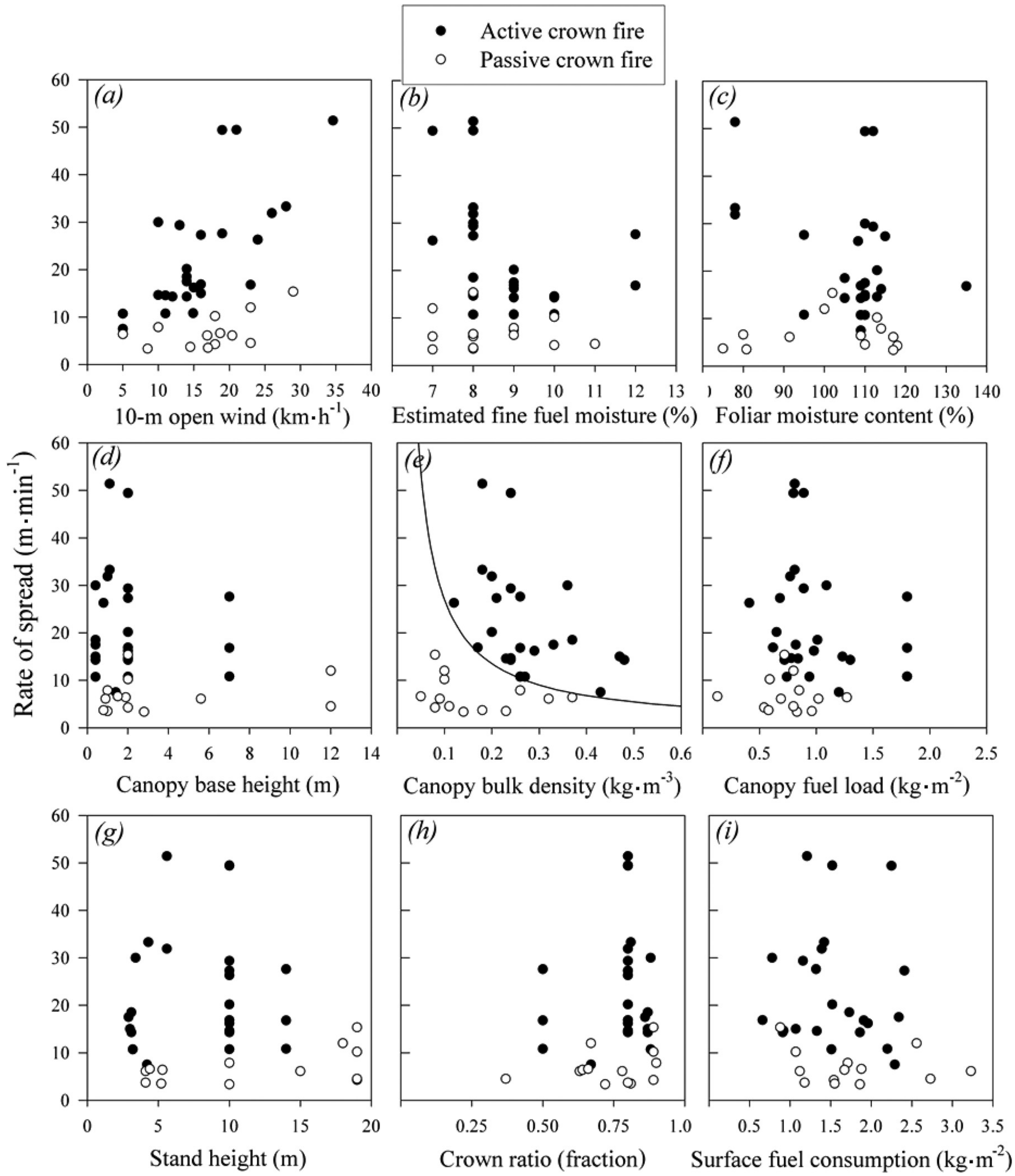
Active crown fire rate of spread

Active crown fire spread rates were found to be significantly correlated with U_{10}, EFFM, and CBD as judged by the Pearson's correlation coefficient (r) (Table 2). U_{10} was also significantly correlated with CBD and FMC (Table 2). None of the explanatory variables were, however, significantly correlated with the rate of spread of the passive crown fires (Table 3). Figure 1 shows the relationships between the most relevant independent variables considered in the analysis and the crown fire rate of spread by type of spread regime (i.e., passive or active crowning). It is worth noting that Van Wagner's (1977) criterion for active crowning appears to do a good job of distinguishing between active and passive crown fire spread (Fig. 1e).

Initially we relied on multiple regression analysis to model the rate of spread of active crown fires. The results obtained were not considered satisfactory. The variables found to have the most significant effect were U_{10} ($p < 0.0005$), EFFM (p = 0.006), and ln(CBD) (p = 0.11). The model produced an adjusted R^2 of 0.53. Preliminary analysis of model behavior revealed that the model tended to predict unreasonably low rates of spread for low EFFM values and high rates of spread for high EFFM values. The response to changes in U_{10} was also considered weak. Inclusion of second-order terms resulted in high variance inflation factors. Transformation of variables also failed to improve results. Nonlinear regression analysis was pursued as an alternative method to develop a

[4] In Canada, the practice is to measure wind speed at a height of 10 m in the open per the World Meteorological Organization standard (Turner and Lawson 1978). In this paper, wind speeds measured at 6.1 m were increased by 15% to approximate the U_{10} standard, or conversely, U_{10} values were decreased by 15% to approximate the United States standard (Finklin and Fisher 1990).

Fig. 1. Scatterplots of experimental crown fire rates of spread by type of spread regime versus the major explanatory fire environment variables analyzed in the present study. The curve in Fig. 1*e* represents Van Wagner's (1977) criterion for active crowning represented by eq. 2, assuming a critical mass flow rate (MFR_o) of 3.0 $kg \cdot m^{-2} \cdot min^{-1}$.



predictive model. Model form for nonlinear regression analysis was based on findings from laboratory and field studies in fire behavior, namely the relative effects of environmental variables on fire rate of spread (e.g., Catchpole et al. 1998; Cheney et al. 1998; Fernandes 2001).

The optimum model fit selected for predicting active crown fire rate of spread was based on the following equation form:

$$[3] \qquad CROS_A = \beta_1 U_{10}^{\beta_2} \times CBD^{\beta_3} \times e^{(-\beta_4 EFFM)}, \quad U_{10} > 0.0$$

where $CROS_A$ is the active crown fire rate of spread ($m \cdot min^{-1}$), as dictated by the three inputs. The resulting coefficients β_1, …, β_4 derived from the assembled data set of experimental crown fires are as follows (with asymptotic standard errors in parentheses): 11.02 (9.77), 0.90 (0.23), 0.19 (0.25), and 0.17 (0.07), respectively. The restriction that the model is not applicable for zero wind speed, which probably does not occur in nature in any event, was considered of minor importance from a practical standpoint.

This model for predicting active crown fire rate of spread represented by eq. 3 will produce results very similar to the one presented earlier by Cruz et al. (2002). Equation 3 constitutes a reanalysis of the same experimental data set as the one used in the development of the Cruz et al. (2002) model following a revision of certain data entries.

The model for predicting the rate of spread of active crown fires represented by eq. 3 accounted for 61% of the variability in observed rate of fire spread within the data set. The proportion of variation in the data set not explained by the model can be attributed to the absence of other variables in the model (not included because of the nature of the database, such as CBH, FMC, and SFC), to the influence of possibly other factors (e.g., ladder fuel characteristics), and to considerations such as fire – convection column interactions that are difficult to integrate under the modeling approach used in this analysis (Cheney et al. 1998). The uncertainty associated with eq. 3 is comparable to results obtained by others in developing empirically based models from experimental fires carried out under field conditions for a single distinct fuel type (Stocks 1987*a*, 1989; Cheney et al. 1998; Marsden-Smedley and Catchpole 1995; Fernandes 2001). The amount of variability explained by these models typically varies between 60% and 90%, largely as a result of the variability in the fuel and weather variables in the data sets. Data sets covering a wide spectrum of fuel moisture and wind conditions usually resulted in lower coefficients of determination. The model represented by eq. 3 is intended to apply to a wide range of conifer forest fuel complexes. Even with laboratory fires involving so-called replicated fuelbeds (e.g., Catchpole et al. 1998) there is generally an inherent degree of variability. For replicated laboratory fires, Catchpole et al. (1998) has indicated an among-fire coefficient of variation in rate of spread of 12%.

Wind speed is the variable with the strongest effect on the spread rate of active crown fires. The 0.86 coefficient in the power function expressing the effect of wind is similar to the value determined by Cheney et al. (1998) for grasslands (0.84), but lower than the ones derived by Fernandes et al. (2000) (1.79) and Marsden-Smedley and Catchpole (1995) (1.32) for shrubland fuels. It is expected that in empirical field studies, this coefficient would vary within a limited range, as a function of 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 moisture term used in eq. 3 follows the results of the damping effect of fine fuel moisture content found in the spread rate of laboratory fires (e.g., Van Wagner 1968; Catchpole et al. 1998).

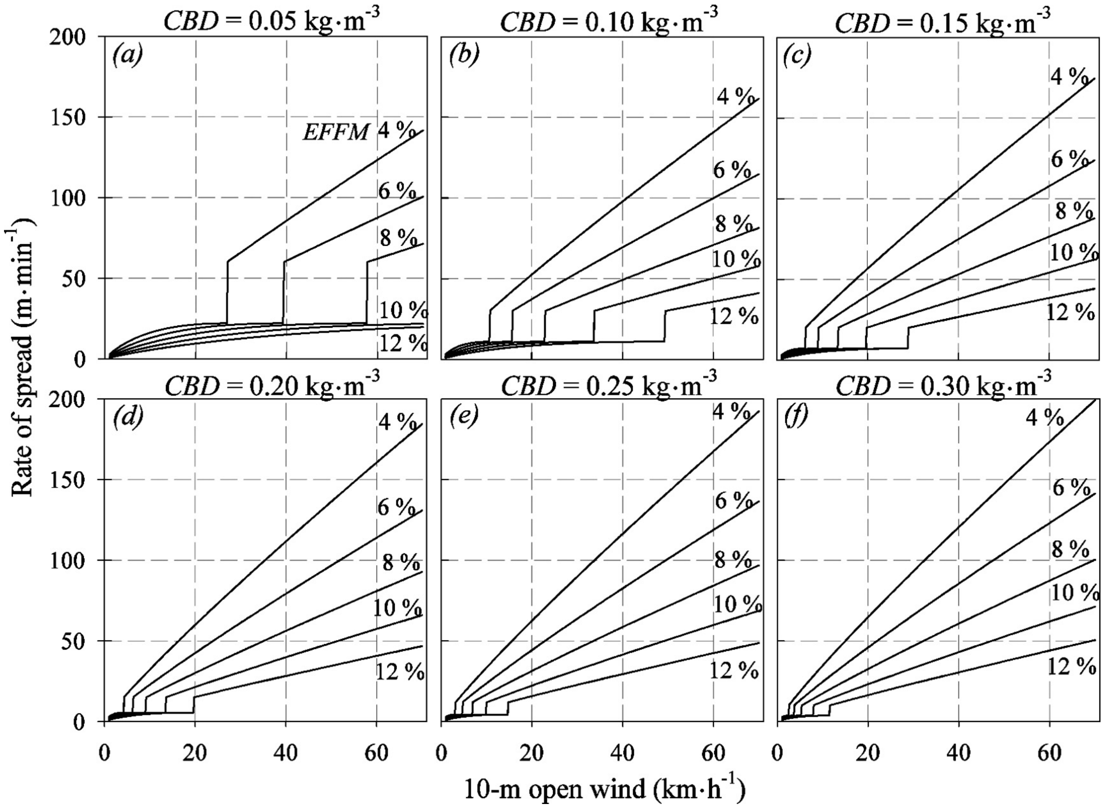
The CBD has the smallest influence of the three variables in the model. The model suggests a proportional increase in rate of spread with CBD. Grishin (1997) concluded from an analysis of his mechanistic model that an increase in canopy fuel bulk density would actually decrease the crown fire spread rate because of the additional heat energy required to preheat the additional unburned fuel. Catchpole et al. (1998) determined an inversely proportional effect of fuelbed bulk density on rate of fire spread from experimental fires carried out in the laboratory. This finding is also supported by theoretical analyses (Thomas 1971; Van Wagner 1974). Nevertheless, it should be noted that physiological constraints limit the amount of foliage within a forest canopy (McAlpine and Hobbs 1994). The packing ratio (i.e., the ratio of fuelbed bulk density to the fuel particle density as defined by Rothermel 1972) of overstory crown or canopy fuelbeds associated with conifer forest stands are three to four orders of magnitude lower than those of surface fuelbeds. This places the characteristic bulk density of canopies within a range for which an increase in its quantity will result in higher amounts of fuel available for combustion and consequently higher mass flow rates within the combustion zone. This agrees with Rothermel's (1972) laboratory results that showed an increase in packing ratio will result in an increase in the propagating heat flux until an optimum packing ratio is reached. Further increases in the fuelbed packing ratio above the optimum will result in a decrease in the propagating heat flux and consequently in the rate of spread according to the Rothermel (1972) model.

Neither FMC nor CBH was found to be a significant predictor of crown fire rate of spread. It is unknown if these results arise from a possible limited effect of these variables on the phenomena under study or from the characteristics of the database, namely the large concentration of data in a restricted range of FMC and CBH (Figs. 1*c* and 1*d*).

The effect of FMC as a determining factor in the rate of spread of crown fires is arguable because the effect of live fuel moisture content on fire dynamics is not well understood (Weise et al. 1998). As Van Wagner (1974) notes, "Ideal evidence to substantiate this theory would be a set of crown fire spread data in some uniform conifer fuel types under similar conditions of weather and surface fuel, foliar moisture content being the only variable. This is a very tall order." Fuel moisture acts as a heat sink in the ignition process because of the need to raise the temperature of the water in the fuel to the boiling point, vaporize it, and give up the heat of desorption of the water (Van Wagner 1967). The release of moisture from the surface of canopy fuels affects (1) the convective heating by reducing the convective heat transfer coefficient because of changes in the fuel particle boundary layer; (2) the incident radiative heat flux because of the interception of radiation by water vapor; and (3) the development of flame because of the dilution of the available oxygen with water vapor that surrounds the fuel.

Several empirical studies of fire behavior in shrubland fuel complexes (e.g., Marsden-Smedley and Catchpole 1995; Fernandes 2001) have also failed to show a significant effect of live fuel moisture content on the rate of fire spread (Alexander 1998; Cruz 1999). Nor did Van Wagner (1998) find any empirical evidence for such an effect within the database used to develop the FBP System fuel type specific models. On the other hand, some theoretical (e.g., Van Wagner 1974, 1993) and laboratory (e.g., Van Wagner 1967; Xanthopoulos and Wakimoto 1993) studies have indicated a strong effect of moisture content on the ignition and combustion characteristics of live fuels. However, none of these studies have truly replicated the thermal environment (i.e., radiative and convective heat flux conditions) found in crowning wildfires. Thus, caution is advised when extrapolating results of these studies to describe the effect of live fuel moisture content in full-scale crown fires.

Fig. 2. Crown fire rate of spread as a function of wind and estimated fine fuel moisture (EFFM) for various levels of canopy bulk density (CBD) based on the models represented by eqs. 3 and 4 developed in the present study.



If it is assumed that active crown fires rely on the upward heat flux from the surface phase to meet the heat requirements for a certain steady-state spread rate (Van Wagner 1977), the higher the vertical stratification in the fuel complex (i.e., the higher the CBH), the smaller will be the convective heat energy reaching the canopy space because of plume tilt and air entrainment (Alexander 1998). All conditions being the same, this would result in slower rates of spread. In the data set used herein, the distribution of CBH is somewhat limited (Fig. 1*d*), negating the possibility of finding a conclusive effect of CBH on crown fire rate of spread.

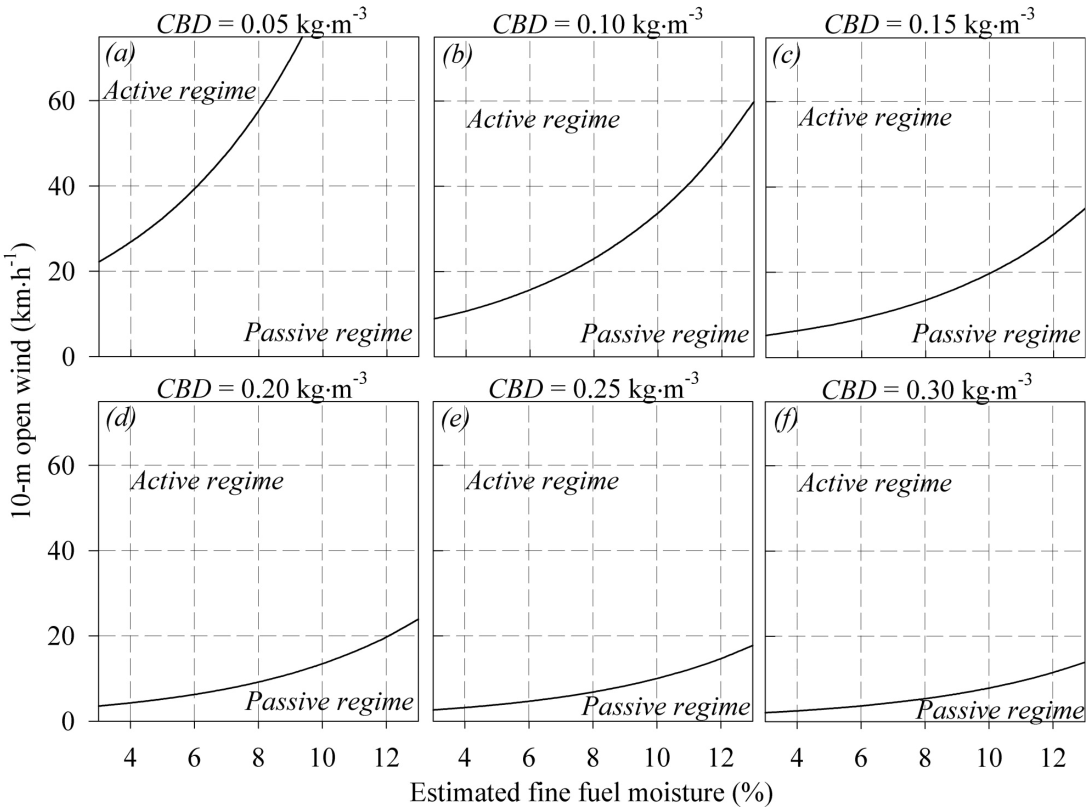
Graphical representations of $CROS_A$ for six categories of CBD as a function of U_{10} for various levels of EFFM using eq. 3 are presented in Fig. 2. The lower portion of each EFFM curve in these graphs constitutes passive crown fire spread, and the upper region is associated with active crown fire spread. The vertical "kinks" in the EFFM curves are considered to represent the wind speed thresholds for full-fledged crown fire development for a given EFFM and CBD combination (i.e., the transition point between passive and active crowning). Thus, eq. 3 also allows one to define the threshold conditions for active versus passive crown fire spread in terms of fuel moisture and wind speed for broad categories of CBD (Fig. 3). The notion of a critical CBD threshold value of around 0.1 $kg \cdot m^{-3}$ for active crowning mentioned earlier on is quite evident in Fig. 2.

Judging from the graphs in Fig. 2, the model for predicting active crown fire rate of spread represented by eq. 3 appears to produce realistic results according to our present knowledge of the characteristics of crown fire behavior. The "near" maximum rate of spread predicted by eq. 3 is of considerable interest. For an EFFM of 4%, a CBD of 0.2 $kg \cdot m^{-3}$, and U_{10} levels of 50 and 75 $km \cdot h^{-1}$, the $CROS_A$ would be 137 and 196 $m \cdot min^{-1}$, respectively. These predictions appear reasonable on the basis of the observed rate of spread (~200 $m \cdot min^{-1}$) during the initial run of the 16 February 1983 Mount Muirhead Fire in South Australia (Keeves and Douglas 1983), which occurred in radiata pine (*Pinus radiata* D. Don) plantations under extreme burning conditions (T_a = 40–44 °C; RH = 10%–12%) with winds in excess of 80 $km \cdot h^{-1}$ reported (Bureau of Meteorology 1984).

Passive crown fire rate of spread

Building an empirically based regression model to predict the spread rate of passive crown fires proved difficult given the limited number of passive crown fires in the data set (n = 13). It was therefore decided to model passive crown fire spread rates based on the output of eq. 3 with an adjustment factor that would reduce the predicted rate of fire spread according to the degree of canopy fuel involvement. If it is assumed that a continuous gradient in rate of spread exists between the passive and active crown fire spread regimes, a crown fire burning below the critical CAC under increasingly favorable conditions will eventually exceed the threshold and assume an active crown fire type of spread regime. If CBD is assumed to be the fuel-complex characteristic that determines the type of crown fire spread regime, passive crown fire rate of spread resulting in the best correlation with the experimental data was as follows:

Fig. 3. Graphical representation of the threshold conditions for passive versus active crown fire spread in terms of fuel moisture and wind for various levels of canopy bulk density (CBD) according to the active crown fire rate of spread model developed in the present study (eq. 3) and Van Wagner's (1977) criterion for active crowning.



$$[4] \qquad \mathrm{CROS_P} = \mathrm{CROS_A} \times e^{(-\mathrm{CAC})}$$

where $CROS_P$ is the passive crown fire rate of spread (m·min^{-1}), and CAC is the criterion for active crowning as defined by the ratio of $CROS_A$ to R_o, as given by eq. 1. Equation 4 differs from a previous model given by Cruz et al. (2002). Again, judging from the outputs displayed in Fig. 2, the proposed model for predicting passive crown fire rate of spread represented by eq. 4 also appears to produce realistic spread rates relative to the specified environmental conditions.

The model for predicting $CROS_P$ given in Cruz et al. (2002) was based on the use of CAC as a multiplicative correction factor. This model was initially deemed acceptable in part because of a misinterpretation of the evaluation data by the authors.

Model testing

Active crown fire rates of spread

The predictive capacity of the active crown fire rate of spread model was evaluated against the ICFME data set. This data set comprises observations from 11 experimental crown fires in a mature jack pine stand with a substantial black spruce understory. Detailed characterizations of the fuel complex (Alexander et al. 2004), burning conditions (Stocks et al. 2004), and fire spread dynamics (Taylor et al. 2004) associated with these experimental crown fires exist. Through the use of eqs. 1 and 2, the ICFME experimental fire in plot 2 (Stocks et al. 2004) was classified as a passive crown fire for model evaluation purposes. Figure 4*a* displays the agreement between eq. 3 predictions and the data used in its parameterization. The application of this model to the ICFME experimental crown fire data set (Fig. 4*b*, Table 4) resulted in a low EF (0.05) and a mean absolute error of 11.4 m·min^{-1} (MA%E = 26%). Fourty percent of the predictions were within an error of ±25%.

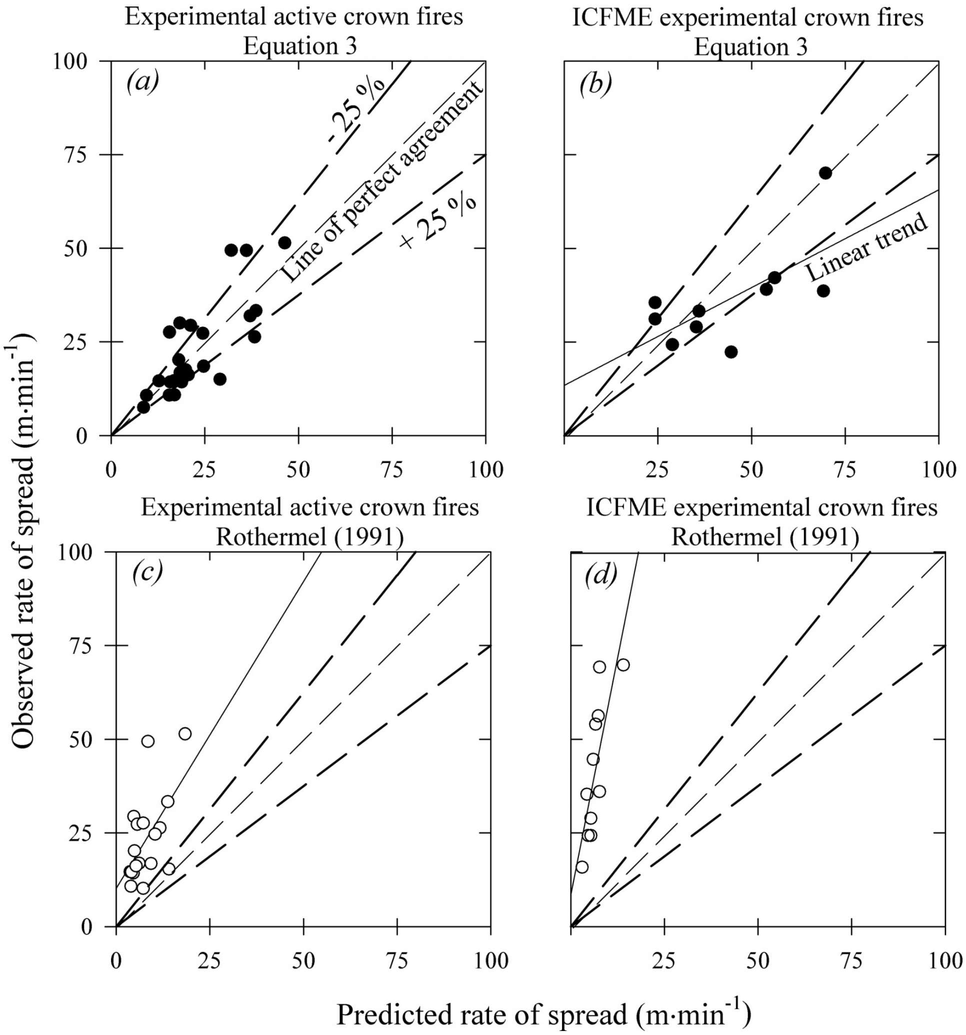
The Rothermel (1991) crown fire rate of spread model underpredicted the spread rates of the experimental fires used in the development of the active crown rate of spread model (Fig. 4*c*, Table 4). For this data set the model produced a MA%E of 66%. For the ICFME experimental crown fire data set (Fig. 4*d*, Table 4), this model produced a MA%E of 84%.

Passive crown fire rates of spread

The predictive capacity of eq. 4 was evaluated against the passive experimental crown fires described previously. Against this data set the passive crown fire spread model produced a MA%E of 177% and an EF of –6.58 (Fig. 5*a*, Table 4). The Rothermel (1991) crown fire rate of spread model produced a MA%E of 53% and an EF of –0.43 (Fig. 5*b*, Table 4).

The large errors resulting from the application of eq. 4 to the experimental data set arise from the overprediction for the three experimental fires carried out in the black spruce – lichen woodland fuel type (Alexander and Lanoville 1989; Alexander et al. 1991). The spatial distribution of canopy fuel in these stands is highly heterogeneous, generally consisting of dense clumps of trees and low horizontal fuel continuity. Nevertheless, the stands associated with these three

Fig. 4. Plot of observed versus predicted rates of spread of active crown fire from various models based on experimental fire and wildfire data sources. Information on the International Crown Fire Modeling Experiment (ICFME) experimental crown fires is based, in part, on Stocks et al. (2004). The broken lines around the line of perfect agreement indicate the ±25% error interval.



experimental fires exhibit some of the largest CBD values in the data set (i.e., 0.18 to 0.32 kg·m^{-3}), which, in turn, result in low R_o values. According to eq. 3, such low R_o values are attained under moderate burning conditions (Figs. 2*f* and 3*f*) and result in these fires being classified as active crown fires, thereby leading to large overpredictions in rate of fire spread (Fig. 5*a*). If the three experimental fires in the black spruce – lichen woodland fuel type are excluded from the data set, it would result in an EF of 0.17 and a MA%E of 80% for eq. 4 (Fig. 5*a*) and an EF of 0.47 and a MA%E of 44% for the Rothermel (1991) model (Fig. 5*b*). The predictions of the Cruz et al. (2002) passive crown fire model are given in Fig. 5*c*, illustrating the poor performance of that model in predicting the rate of spread of passive crown fires. In general terms, the model represented by eq. 4 proved to be a significant improvement in the capability to predict $CROS_P$ over the Cruz et al. (2002) passive crown fire rate of spread model.

Not included in Fig. 5 is a relatively well-documented operational prescribed fire that took place 11 May 1993, in a sand pine (*Pinus clausa* (Chapm.) Vasey) stand on the Ocala National Forest in central Florida as described by Custer and Thorsen (1996). During the final stages, this prescribed fire exhibited the behavior of a passive crown fire with a reported observed spread rate of 12 m·min^{-1} (Outcalt and Greenberg 1998). The pertinent environmental conditions at the time were as follows: T_a = 28 °C; RH = 46%; EFFM = 10%; U_{10} = 21 km·h^{-1}; and CBD = 0.1 kg·m^{-3}. The $CROS_P$ predicted by the eq. 4 model was 10.2 m·min^{-1}. In comparison, the predicted spread rates for the Rothermel (1991) and Cruz et al. (2002) models were 8.7 and 12.9 m·min^{-1}, respectively.

Applications, limitations, and possible improvements

Simply stated, the purpose of developing any fire behavior model is to predict or forecast the outcome of some phenomenon before it happens (Van Wagner 1985). This study developed a set of models to predict crown fire rate of spread in conifer forest stands involving a minimal number of model inputs. The overriding aim was to develop simplistic models that could be used operationally to support decision making in fire management related issues (e.g., near-real-time fire behavior prediction for tactical decision making, hazard assessment, prescribed fire planning) either as a stand-alone guide or incorporated into computerized decision-support sys-

Table 4. Statistics associated with the evaluations of the models for predicting crown fire rate of spread developed in the present study and in Rothermel (1991).

	This study		
Statistic	Eq. 3	Eq. 4	Rothermel 1991
Experimental crown fires, active spread regime (*n* = 24)			
EF	na	na	–1.39
MAE (MA%E)	na	na	16.1 (66%)
β_0 (SE)	na	na	6.25 (3.81)
β_1 (SE)	na	na	2.43 (0.48)
Experimental crown fires, passive spread regime (*n* = 14)			
EF	na	–6.58	–0.43
MAE (MA%E)	na	9.0 (177%)	3.9 (53%)
β_0 (SE)	na	9.64 (2.6)	6.78 (2.92)
β_1 (SE)	na	–0.13 (0.16)	0.15 (0.40)
ICFME experimental crown fires, active spread regime (*n* = 10)[a]			
EF	0.05	na	0
MAE (MA%E)	11.4 (26%)	na	33.9 (84%)
β_0 (SE)	12.5 (13.03)	na	12.3 (10.9)
β_1 (SE)	0.87 (0.33)	na	4.61 (1.48)

Note: See the List of symbols for definitions of the statistics. na, not applicable.

[a]Based in part on Stocks et al. (2004). Following the criteria of eqs. 1 and 2, in the International Crown Fire Modeling Experiment (ICFME) data set, one experimental fire was considered to have spread as a passive crown fire.

tems like FARSITE, NEXUS, and BehavePlus (Andrews et al. 2003). The models could also be used to answer research questions, namely to assess the effect of stand-level fuel treatments on crown fire behavior potential (Scott and Reinhardt 2001). The implementation of the models into spatially explicit fire simulation tools would allow one to assess the effectiveness of landscape-scale fuel treatments in reducing the potential for the development of large fires (Finney 2001). In countries that presently have no means of predicting crown fire rate of spread in coniferous fuel types, the models as developed here offer an initial starting point, although we strongly encourage that an evaluation using existing wildfire case study data should be undertaken prior to implementation or, at the very least, a qualitative appraisal.

The three weather elements required of the crown fire rate of spread models (i.e., U_{10} plus T_a and RH to compute the EFFM) can either be measured or estimated (including forecasted) values. The CBD can be calculated directly (Cruz et al. 2003*a*), estimated (i.e., assigned nominal value from local knowledge), or inferred by other means (e.g., Riano et al. 2003; Keane et al. 2005; Scott and Reinhardt 2005).

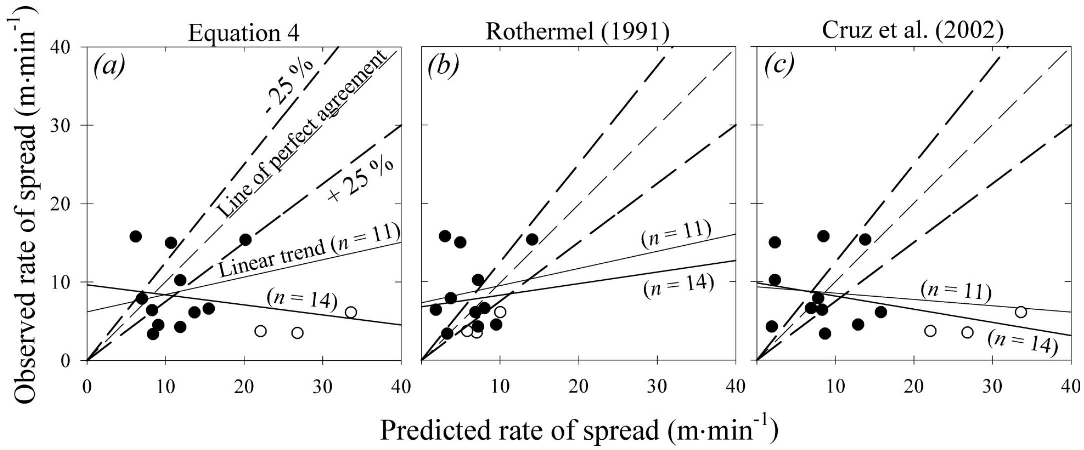
The models for predicting crown fire rate of spread developed here are simplifications of the phenomena they represent. They are not necessarily attempts to explain cause–effect relationships between fire environment and fire behavior variables or to increase our knowledge of poorly understood fire behavior phenomena. Limitations in the experimental crown fire data sets, namely size, distribution of variables, and collinearity, led to some inconclusive results about the effect of certain fire environment variables on crown fire rate of spread. Surface fuel availability, foliar moisture, and vertical stratification of the fuel complex did not have a significant effect on crown fire rate of spread, although theoretically they should have a strong influence on crown fire spread. Nevertheless, the simplifications used to develop the models do not appear to have limited the coherence and applicability of the models, as demonstrated by the results of their evaluation against an independent data set.

An important consideration regarding the model predictive capacity is what would constitute a reasonable allowable error and still be useful for fire management applications. The errors obtained in the present study were comparable to those for very uniform fuel complexes involving grasslands and shrublands. Albini (1976) pointed out that for phenomena varying over various orders of magnitude, prediction within a factor of two or three can be considered successful. To our knowledge, no definition exists for acceptable performance for fire behavior model predictions. The difficulty in defining such a threshold includes the unknown error inherent in the estimation of the input variables (Trevitt 1991).

The use of the models represented by eqs. 3 and 4 to predict crown fire rate of spread requires the assumption that crowning has commenced or occurred. Such a decision will require the use of the companion crown fire initiation model that we have developed (Cruz et al. 2002, 2004) or alternatively other methods or models (e.g., Van Wagner 1977; Alexander 1998; Cruz et al. 2003*b*), including expert opinion and experienced judgment on the part of the user (Rothermel 1991). In this regard, several authors have reported cases in which strong surface winds coupled with low amounts of available fuel (because of preburn quantities and (or) fuel moisture conditions) have limited the degree of crowning in spite of the fact that computed fire intensities presumably have exceeded the threshold for crown fire initiation (e.g., Luke and McArthur 1978; NFPA 1992). The major run of the Burnt fire that occurred on the Coconino National Forest in northern Arizona on 2 November 1973 (Dieterich 1979) represents a case in point. The principal fuel type was variable stocked stands of ponderosa pine with much of it open grown and exhibiting low CBH (1.2–1.5 m). The prevailing environmental conditions were as follows: U_{10} = 74 km·h^{-1}; T_a = 10 °C; RH = 25%–35%; and EFFM = 9%. SFC was low (0.56 kg·m^{-2}), and coupled with the observed spread rate (30.2 m·min^{-1}) fire intensity was computed to be 5251 kW·m^{-1} (Alexander 1998). Postfire analysis revealed damage varied from complete crown consumption in patches of saplings to large areas characterized by slight crown scorch "on the lowest portions of the crowns" (Dieterich 1979). The $CROS_A$ predicted by eq. 3 for CBD = 0.05 and 0.1 kg·m^{-3} would be 63.2 and 72.2 m·min^{-1}, respectively.

The empirical approach used in the development process obviously makes the models a reflection of their data sets. In this sense, the models are not considered applicable to disease- or insect-killed stands, and as such they represent a growing research need in North America (Alexander and Stam 2003), although some guidance exists (Stocks 1987*b*). The models should also not be applied to prescribed fire situations that involve strong convective activity as a result of the ignition pattern (Rothermel 1985), thereby resulting in underpredictions of crown fire rate of spread including the type of crown fire. For example, an R_c of 25 m·min^{-1} was recorded in a Scots pine (*Pinus sylvestris* L.) stand that burned as an active crown fire during the Bor Island Fire Experiment (FIRESCAN

Fig. 5. Plot of observed versus predicted rates of spread of passive crown fires from various models based on experimental fire data sources. The linear trend for n = 11 does not include three experimental fires in the black spruce – lichen woodland fuel type (identified by the open circle data points, ○) as described by Alexander et al. (1991) that were classified as passive crown fires. The broken lines around the line of perfect agreement indicate the ±25% error interval.



1996) carried out in the Krasnoyarsk region of the central Russian Federation on the afternoon of 6 July 1993. The $CROS_P$ predicted by eq. 4 was 7.6 m·min^{-1} based on the following burning conditions: T_a = 30.2 °C; RH = 36%; EFFM = 8%; U_{10} = 7 km·h^{-1}; and CBD = 0.08 kg·m^{-3}.

One of the more obvious shortcomings of the models developed in the present study is that they do not incorporate the effect of slope steepness on the resultant crown fire rate of spread. A possible approximation would be the calculation of a slope–wind equivalency approach, as advocated, for example, by Rothermel (1972).

One possible improvement to the present models for predicting the rate of spread of both active and passive crown fires that warrants further investigation is the incorporation of a physical fuel variable in lieu of or as a supplement to CBD. Ideally such a variable would consider the height of the stand as the fuelbed depth and integrate many of the complexities involved in stand structure and morphological tree characteristics associated with various coniferous forest fuel types, in both vertical and horizontal dimensions. Such an approach would avoid the problem of overfitting the model that arises from the attempt to fit too many parameters based on a small data set. For example, the crown volume ratio described by Sando and Wick (1972), i.e., the ratio of the total space from the ground surface to the treetop height actually occupied by tree crowns taking into account crown taper, has been suggested by Van Wagner (1977) as a potentially useful fuel parameter in the prediction of crown fire behavior.

The results of this study have highlighted the limitations of the empirical approach to developing a crown fire rate of spread model based solely on outdoor experimental fire data. Limitations imposed by conducting experimental crown fires (Van Wagner 1985; Alexander and Quintilio 1990) can result in a lack of independence among explanatory variables. This lack of independence and the relatively small sample size constrain analysis results, namely finding a significant effect of certain variables that theoretically should influence the rate of spread of crown fires. Fire is a phenomenon characterized by processes acting at various scales and interacting in complex and poorly understood ways. Further advances in our understanding of the processes determining crown fire behavior will require a fundamental approach linking measurements of physical fire properties (Butler et al. 2004) with theoretical analyses.

The unknowns and the complexity associated with the small-scale processes determining fire behavior suggest that a simplified physically based approach might suffice for describing much of the fuel complex – weather interactions and effects on crown fire behavior. Catchpole et al.'s (2002) model is an example of a robust fire behavior model that incorporates simplified descriptions of heat transfer processes (but still requires a high degree of computation) and empirically derived models to explain weakly understood phenomena, such as combustion processes. The application of this type of modeling approach could provide insights into the effects of certain determinant variables on the mechanisms associated with crown fire spread while bypassing much of the complexity introduced by the need to numerically solve the conservation equations and turbulence phenomena. The computational requirements to run such a model would allow for its use to support decision making in fire management related issues such as described above.

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List of symbols

$\beta_1, \ldots, \beta_4$	regression coefficients
CAC	criteria for active crowning (ratio)
CBD	canopy bulk density ($kg \cdot m^{-3}$)
CBH	canopy base height (m)
CFL	canopy fuel load ($kg \cdot m^{-2}$)
CR	crown ratio (fraction)
$CROS_A$	active crown fire rate of spread ($m \cdot min^{-1}$)
$CROS_P$	passive crown fire rate of spread ($m \cdot min^{-1}$)
EF	modeling efficiency
EFFM	estimated fine fuel moisture content (% ovendry mass basis)
FMC	foliar moisture content (% ovendry mass basis)
MAE	mean absolute error
MA%E	mean absolute percent error
MFR_o	critical mass flow rate ($kg \cdot m^{-2} \cdot min^{-1}$)
R_c	observed or predicted crown fire rate of spread ($m \cdot min^{-1}$)
R_o	critical minimum spread rate for active crowning ($m \cdot min^{-1}$)
RH	relative humidity (%)
SE	standard error
SFC	surface fuel consumption ($kg \cdot m^{-2}$)
SH	stand height (m)
T_a	air temperature (°C)
U_{10}	10-m open wind speed ($km \cdot h^{-1}$)