Modeling the Likelihood of Crown Fire Occurrence in Conifer Forest Stands

Miguel G. Cruz, Martin E. Alexander, and Ronald H. Wakimoto

ABSTRACT. The unknowns in wildland fire phenomenology lead to a simplified empirical model approach for predicting the onset of crown fires in live coniferous forests on level terrain. Model parameterization is based on a data set (n = 71) generated from conducting outdoor experimental fires covering a significant portion of the spectrum of burning conditions associated with the initiation of crown fires. A logistic model is developed to predict the likelihood of crown fire occurrence based on three fire environment variables, namely the 10-m open wind speed, fuel strata gap (equivalent to live crown base height in some stands), estimated moisture content of fine dead fuels, and one fire-behavior descriptor—surface fuel consumption. The model correctly predicts 85% of the cases in the data set used in its development, and the receiver operating characteristic statistic is 0.94. The model is evaluated for its sensitivity to its inputs, and its behavior is compared with other models used in decision support systems to operationally predict crown fire initiation. The results of a limited test of the model against two independent experimental fire data sets for distinctly different fuel complexes is encouraging. FOR. SCI. 50(5):640–658.

Key Words: Forest fires, crown fire, crown fire initiation, crowning, experimental fire, fire behavior, fire-behavior prediction, logistic model.

A FOREST FIRE IS in essence the result of fire behavior. Its spread, its effects on soil and vegetation properties, and the difficulty of controlling the fire depend mostly on the fire behavior exhibited. The estimation of fire behavior is of utmost importance in any fire management approach, allowing for the determination of the impacts of fire on ecosystem components and supporting forest fire management decisionmaking. Wildland fire researchers have produced models to predict fundamental fire-behavior characteristics or descriptors, such as rate of fire spread (Rothermel 1972), flame geometry (Albini 1981, Nelson and Adkins 1986), and fuel consumption (Reinhardt et al. 1991, 1997, Albini and Reinhardt 1995), from easily recognized or measured fire environment variables (i.e., fuels, weather, and topographic inputs). These models have been integrated into decision support systems that have found widespread use for management and research activities in the United States (Finney 1998, Scott 1998a, Andrews et al. 2003). Nevertheless, our incomplete understanding of the processes and interactions determining

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crown fire phenomenon, especially with respect to initiation or onset of crowning, severely limits the applicability of such systems to truly forecast the behavior of high-intensity fires. The transition from a surface fire to a crown fire is obviously of great interest and concern to fire managers because crown fires can jeopardize the safety of wildland firefighters (Rothermel 1991) and the public at large (Davis and Mutch 2001). They also represent a level of fire behavior that normally precludes any direct suppression action (Alexander 2000).

Previous Crown Fire Initiation Modeling Approaches

Modeling the initiation of crown fires has followed either a semi-empirical approach or a physically based one, with each focusing on solving different questions. This dichotomy exists in nearly all aspect of wildland fire-behavior research (Van Wagner 1971, 1985). Physical models have been directed mainly at understanding relationships and interactions among variables that determine fire behavior. Semi-empirical models, based to a large extent on experimental or wildfire-behavior data, are designed to predict outcomes or characteristics of fire behavior to directly support fire-management decisionmaking. Physical modeling efforts (e.g., Grishin 1997, Linn 1997, Izbicki and Keane 1989) are presently constrained by limitations in our understanding of several processes, namely, the characterization of the chemical processes occurring during combustion, and the resulting flame characteristics, and the isolation and quantification of physical processes governing heat transfer and the contribution of each heat-transfer mechanism to the overall energy transmitted to the unburned fuels (Catchpole and de Mestre 1986).

The semi-empirical approach to crown fire initiation modeling has lead to models suitable for operational implementation (e.g., Van Wagner 1977, Xanthopoulos 1990, Alexander 1998). Van Wagner (1977), through a combination of physical theory and empirical observation, defined quantitative criteria to predict the onset of crowning. His analysis was based on plume theory developed by Yih (1953, 1969) that linked an idealized linear heat source with the maximum temperature attained at a certain height in the buoyant plume above. This relationship, based on dimensional analysis, was rearranged by Van Wagner (1977) to allow for the determination of a critical surface fireline intensity (per Byram 1959) needed to induce crown combustion, as a function of canopy[1] base height, heat required for ignition (as determined by the moisture content of the available canopy fuel), and a proportionality constant, "best regarded as an empirical constant of complex dimensions" (Van Wagner 1977). The proportionality constant was estimated by Van Wagner (1977) to be 0.01, based largely on a single experimental fire conducted in a red pine (*Pinus resinosa*) plantation stand (Alexander 1998).

Although Van Wagner's (1977) formulation is based on convective theory, the proportionality constant was derived from fireline intensity estimated from the total amount of fuel consumed as opposed to just the quantity involved in the active flame front. This measure of fireline intensity reflects the heat or energy release associated with both flaming and smoldering combustion (Rothermel 1994).

Van Wagner's (1977) model is presently used in whole or in part for predicting crown fire initiation in several North American fire-behavior prediction (FBP) systems (Van Wagner 1989, Forestry Canada Fire Danger Group 1992, Finney 1998, Scott and Reinhart 2001). Several research studies have also used this model to carry out simulations and develop operationally oriented guides (e.g., Alexander 1988, Bessie and Johnson 1995, Stephens 1998, Scott 1998b, Graham et al. 1999, Fulé, et al. 2001a, Scott and Reinhardt 2001, Keyes and O'Hara 2002). The main theoretical limitations of the Van Wagner (1977) model are: (1) the original Yih (1953) formulation is related to a maximum temperature, whereas, when considering the ignition process of fuels containing significant quantities of moisture, it would be more appropriate to integrate a temperature–time profile curve and consider a heat balance equation (Dickinson and Johnson 2001) and the relation to the desiccation and ignition of canopy fuels (Albini 1985, de Mestre et al. 1989); (2) the wind flow effect on tilting the buoyant plume and increasing air entrainment in the plume violates several fundamental assumptions (Thomas 1964, Mercer and Weber 1994); and (3) the model relies solely on convective theory and disregards the contribution of upward radiative heat fluxes in determining canopy fuel ignition. According to the fire behavior conditions required to achieve the critical surface fireline intensity as idealized by Van Wagner (1977), flame depth increases to a size where the heat source is no longer a line source, but as an area as viewed by the canopy fuel particles (Van Wagner 1964). Under these conditions, the radiative contribution should be a significant component of the heat flux absorbed by the canopy fuels. The proportionality constant accounts for most of the limitations described above, being dependent on fuel-complex characteristics and the amount of fuel available for flaming combustion in the surface strata. Several authors (e.g., Alexander 1998, Mercer and Weber 2001) have emphasized the nonuniversality nature of the proportionality constant.

To overcome some of limitations evident in the Van Wagner (1977) model, Xanthopoulos (1990) approached the development of a crown fire initiation model by deriving separate equations to (1) predict time–temperature profiles at different heights in the convection plume above a fire, and (2) predict the time to ignition for foliage of three different conifer species (Xanthopoulos and Wakimoto 1993). The coupling of these equations with the output from the surface fire spread model of Rothermel (1972) and Albini's (1976) refinements as embodied in the BEHAVE system (Andrews 1986, Andrews and Chase 1989) would, according to Xanthopoulos (1990), presumably overcome some of the Van Wagner (1977) model limitations. Nevertheless, scale effects from the experimental laboratory set-up (i.e., small fire-front width, no free convection, and low wind velocities) would likely limit model application to real-world crown fires (Alexander 1998). By combining and refining elements of the approaches taken by previous fire-behavior modelers coupled with new insights, Alexander (1998) was able to develop a simple algorithm to predict the onset of crowning. His model, which exemplifies both the art and science of fire-behavior modeling (Van Wagner 1985), integrates the ignition requirements as defined by Xanthopoulos and Wakimoto's (1993) time-to-ignition equations with the convection plume thermal structure, which is, in turn, deemed a function of fireline intensity, plume angle (as dictated by fireline intensity and wind speed), a proportionality constant, and the flame-front residence time of a surface fire. The proportionality constant was assumed to be broadly fuel-complex structure specific.

The objective of the present study is to develop a probabilistic model for the prediction of crown fire occurrence based on fire environment and fire-behavior variables that are normally available to support fire management decision-making (Cruz et al. 2002). It is appropriate to make a distinction between the intent of the model sought in the present study and other approaches to modeling crown fire initiation. The aim of the previously described crown fire initiation models was to define the threshold conditions for the onset of crowning given certain surface fire-behavior characteristics and heat requirements for canopy ignition. In the present study, the focus is on modeling the likelihood of crown fire occurrence on a probabilistic basis. The attempt is not to model crown fire initiation per se, but rather to determine what the chances are of a crown fire occurring given certain burning conditions. Finally, we compare our model with other published models to better understand the model's behavior and its limitations. In addition, a limited test of the model developed in the present study is also undertaken against two independent data sets.

Pertinent Variables Determining Crown Fire Initiation

Based on a literature review of the fundamental processes involved in combustion and heat transfer (Cruz 1999) the following variables were identified as being the main determinants influencing crown fire initiation on level terrain: foliar moisture content (FMC), vertical continuity in the fuel complex, the amount of fuel available for flaming combustion in the surface fuelbed, and wind speed.

Foliar Moisture Content

Moisture content of forest fuels affects fire behavior in several ways. It 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 in the fuel, as described, for example, by Van Wagner (1967b, 1972). The release of moisture from the surface of canopy fuels affects (1) the convective heating by reducing the convective heat transfer coefficient resulting from changes in the fuel particle boundary layer, (2) the incident radiative heat flux resulting from the interception of radiation by water vapor, and (3) the development of flame resulting from the dilution of the available oxygen with water vapor that surrounds the fuel (Simard 1968). The effect of FMC on ignition, combustion, and the resultant fire behavior has been difficult to understand (Weise et al. 1998). Reasoning based on theoretical analyses (e.g., Van Wagner 1967b, 1972) and laboratory experiments involving coniferous tree foliage (e.g., Van Wagner 1967a, Quintilio 1977, Fuglem and Murphy 1979, Bunting et al. 1983, Cohen et al. 1990, Xanthopoulos and Wakimoto 1993) indicates that the moisture content of conifer needle foliage does influence the heat or energy requirements for ignition. Nevertheless, none of these studies were believed to truly replicate the thermal environment (i.e., radiative and convective heat flux conditions) associated with crowning wildfires.

It is worth noting that several studies have attempted to relate crown fire activity with the seasonal variation in FMC of several North American tree species with conflicting results. Hough (1973) and Fuglem (1979), for example, found some relationship between crown fire activity and the period of low FMC levels, whereas others did not (e.g., Johnson 1966, Philpot and Mutch 1971). The lack of empirical evidence confirming an FMC effect on crown fire occurrence may arise from the restricted variability in older conifer foliage during the summer (Philpot 1963, Johnson 1966, Philpot and Mutch 1971, Chrosciewicz 1986, Viegas et al. 1992, Pook and Gill 1993, Agee et al. 2002), which translates into a small variation in the heat sink (Williamson and Agee 2002).

Vertical Fuel Continuity

The importance of the distance between the surface fuels and canopy fuel strata is reasonably well understood from the standpoint of crown fire initiation. Several theoretical and empirical studies (e.g., Van Wagner 1975, Xanthopoulos 1990, Carrier et al. 1991, Mercer and Weber 2001) have quantitatively characterized the variation in ambient air temperature with height above surface fires. One of the main problems with the estimation of the vertical fuel gap is the lack of a universally accepted definition for the lower limit of the aerial fuel stratum. Several authors (e.g., Kilgore and Sando 1975, Van Wagner 1977, McAlpine and Hobbs 1994, Cruz et al. 2003a, 2003c) equated the vertical fuel gap to the live canopy base height (CBH), although even this parameter lacks a precise definition. For example, CBH has been defined as the lower insertion point of live branches on a tree (Maguire and Hann 1990). Sando and Wick (1972) arbitrarily defined CBH as the lower vertical 0.3-m (1.0-ft.) section with a weight greater than 112.4 kg ha^{-1} (i.e., 100 lbs ac^{-1}), based on the reasoning that there is a critical fuelbed bulk density required to support combustion vertically. Ottmar et al. (1998, 2000, 2002) defined CBH as "the height of the lowest continuous branches of the tree canopy" and refined their description of the canopy fuel strata by identifying ladder fuels as "the height of the lowest live or dead branch material that could carry fire into the crown." Other definitions have been proposed (e.g., Hummel and Agee 2003).

Scott and Reinhardt (2001) defined CBH as "the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy" incorporating ladder fuels such as lichen and dead branches. Sufficient canopy fuel was arbitrarily defined by these authors as 0.011 kg m^{-3}, a value that has no theoretical or empirical basis (Hummel and Agee 2003). This definition of CBH could possibly lead to misinterpretations regarding the meaning of CBH. Crown and canopy concepts are associated with live foliage (Helms 1998) and are important silvicultural descriptors used to describe tree vigor, photosynthetic potential, and competition for growing space. Scott and Reinhardt's (2001) definition of CBH leads to the application of the same term to two distinct situations: a silvicultural definition comprising just live foliage and a fire-modeling definition incorporating ladder fuels. However, current crown fire initiation models base their canopy ignition requirements almost solely on the presence of live fuels (Van Wagner 1977, Alexander 1998). The existence of substantial quantities of lichens or dead fuels such as bark flakes and fine twigs would introduce an error term in these models, because their contribution to a heat balance calculation are quite distinct from live fuels. In the present study, we have elected to use the term fuel strata gap (FSG) to define the distance from the top of the surface fuelbed to the lower limit of the aerial fuel stratum constituted by the ladder and live canopy fuels that can sustain vertical fire propagation (Cruz 1999).

Fuel Available for Flaming Combustion

The amount of fuel consumed within the active combustion phase, as defined by a solid flaming zone (Alexander 1982), is expected to have a strong influence on flame characteristics (i.e., length, height, tilt angle, depth, and emissivity), and on the upward velocity and temperature of the buoyant gases in the convection plume, and consequently on the heat flux reaching the base of the canopy fuels. For a particular fuelbed, the amount of available fuel to be consumed during the active or flaming combustion stage is mainly a function of the fuelbed structure (i.e., load, bulk density, and fuel particle size distribution) and fuel moisture content by fuelbed depth and fuel particle size classes (Anderson 1969, Rothermel 1972, Wilson 1982, 1990, Gill and Moore 1990). The amount of fuel available for flaming combustion has been an elusive parameter to estimate because of the complexity of combustion processes, especially in heterogeneous fuelbeds involving intermediate- and large-size woody fuels and the duff layer, which do influence the propensity for crowning (Rothermel 1994). Hence, in this study, total surface fuel consumption (SFC), which integrates the amount of forest floor and dead-down roundwood fuel consumed, will be used as a surrogate for the amount of available fuel consumed during flaming combustion. This assumption is limited because the relationship between these two variables is known to be changeable. In other words, the proportion of fuels consumed during flaming combustion compared to the total surface fuel consumption could easily change depending on the characteristics of the fuel complex and the prevailing burning conditions (e.g., the drier the fuelbed, the higher the proportion of large fuels that are consumed during the active flaming combustion phase).

Wind Speed

Wind affects fire behavior by increasing (1) the rate of energy production and (2) the propagating heat flux by exposing the unburned fuel to additional radiative and convective heating (Rothermel 1972). The increase in flame depth associated with a faster spreading surface fire will enhance upward heat fluxes because of (1) the enlargement of the radiating surface as viewed by the canopy fuel elements and (2) the increase in the buoyant plume depth and consequently its integrity. However, this effect is counteracted by plume tilting and an increase in air entrainment (Alexander 1998). The spatial and temporal nature of wind data makes it one of the most difficult variables to quantify and integrate in any fire behavior-modeling exercise. The effect of turbulent wind flow on fire behavior is weakly understood and the effect of wind velocity on the rate of fire spread is introduced by assuming an average scalar wind speed at a specified height. In accordance with most outdoor experimental fire-behavior studies, wind speed in the present study follows the international exposure standard—i.e., the wind measured at a height of 10 m above the open ground (Turner and Lawson 1978). Much of the variability in the structure of the wind field is not quantified in fire-behavior studies, with the time interval used to average wind properties being related to the duration of active fire spread (Cheney et al. 1993, Sullivan and Knight 2001), although even this is not normally reported. Only a few fire-behavior studies report both the 10-m open wind speed (U_{10}) and the within-stand wind speed (e.g., Van Loon and Love 1973, Nicholls and Cheney 1974). This information would allow for a better understanding of the wind effects on fire spread and plume structure.

Methodology

Nature of the Experimental Database

The aim of the modeling approach taken in the present study is to predict the occurrence of crown fires. The prediction is based on the premise that there exists an available experimental fire-behavior database (Table 1) encompassing a relative wide variety of fuel and weather conditions (Table 2) that would allow for the modeling of this phenomenon without biasing the results to certain fuel characteristics and other fire environment factors.

An experimental fire-behavior database was compiled from existing data used in the development of the Canadian Forest FBP System (Forestry Canada Fire Danger Group 1992)[2] and from other published sources (Table 1). The assembled database (Cruz 1999) consists of experimental fires burning under surface and crown-spread regimes ignited with the objective of quantifying fire behavior in relation to the prevailing burning conditions. Most fire environment and fire-behavior variables were comprehensively sampled and monitored during these fires (Alexander and Quintilio 1990). No wildfire case study data were used because of a lack of specific quantitative information on the

Table 1. Fuel complexes and type of fire distribution in the database used for building the logistic model for predicting the probability of crown fire occurrence.

Fuel complex	Surface fires	Crown fires	Sources
Immature jack pine *(Pinus banksiana)* stand	2	12	[1]
Mature jack pine stand	16	8	[2]
Red pine (*Pinus resinosa*) plantation	2	4	[3]
Maritime pine (*Pinus pinaster*) plantation	4	3	[4]
Mature lodgepole pine (*Pinus contorta*) stand	8	0	[5]
Lowland black spruce (*Picea mariana*) stand	2	9	[6]
Slash pine (*Pinus elliottii*) plantation	0	1	[7]
Total	34	37	

[1] Stocks (1987); [2] Quintilio et al. (1977), Weber et al. (1987), Stocks (1989), Stocks and Hartley (1995), B.J. Stocks (unpublished data); [3] Van Wagner (1968, 1977); [4] Burrows et al. (1988), Cruz and Viegas (1998); [5] Lawson (1972); [6] Kiil (1975), Newstead and Alexander (1983), M.E. Alexander (unpublished data); [7] Van Loon and Love 1973.

fuel-complex characteristics during the transition phase from surface to crown fire.

Within the data set, some fires ($n = 37$) had incomplete information regarding the moisture content of the fine, dead surface fuels. Hence we used Rothermel's (1983) estimated fine fuel moisture (EFFM) as a surrogate for the moisture content of the fine, dead fuels controlling surface fire spread for all of the fires in the assembled database. This measure of dead fine fuel moisture content, based on Rothermel's (1983) tables should be perceived, for the purposes of the present study, as an index. The EFFM tables are based on work by Fosberg and Deeming (1971) for mid-afternoon fuel moisture content and include the effect of slope, aspect, season, and time of day on fine fuel moisture content. Reliability of these estimates of dead fine fuel moisture content has been assessed by several authors with acceptable results (Rothermel et al. 1986, Burgan 1987a, Hartford and Rothermel 1991).

For all the fires in the data set, except the immature jack pine experimental fires (Stocks 1987), FSG equates to CBH. In the immature jack pine stands, the presence of ladder fuels constituted by bark flakes and the abundance of fine dead twigs attached the lower boles of both live and dead tree stems (see photos in Walker and Stocks 1975, Stocks 1987, Stocks and Hartley 1995) made the specified 4.0-m CBH (Stocks 1987, Van Wagner 1993) unrealistic given the FSG concept. Following the judgment of one of the present study authors (MEA), who directly observed many of the Sharpsand Creek experimental fires reported on by Stocks (1987), an FSG of 2.0 m was assigned to the experimental fires associated with this fuel complex (i.e., half of the distance to the CBH).

Model Building

Given the binary nature of the dependent variable (i.e., the occurrence or not of crowning), logistic regression analysis (Walker and Duncan 1967) was identified has an appropriate method to model the probability or likelihood of crown fire occurrence (Alexander 1998). The multiple logistic regression model has the form (Hosmer and Lemeshow 2000),

$$P(Y = 1)\ \frac{e^{g(x)}}{1 + e^{g(x)}}, \qquad (1)$$

being the logit given by the equation,

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i, \qquad (2)$$

where $P(y_i = 1)$ is the probability that a crown fire will occur, x_i are the independent variables, and β_i are coefficients estimated through the maximum likelihood method, which will produce coefficients that maximize the probability density as function of the original data set (Hosmer and Lemeshow 2000).

The fire environment variables previously discussed were selected to test their influence in the proposed model. Because the pre and postfire measurements of surface fuels

Table 2. Basic descriptive statistics associated with the data set used in the development of the logistic crown fire occurrence model.

Independent variables	n	Minimum	Maximum	Mean	SD
Stand basal area ($m^2\ ha^{-1}$)	55	4.3	50.0	23.7	11.2
Stand density (trees ha^{-1})	64	532	9,276	3,952	3,076
Stand height (m)	69	2.9	20	13.1	5.6
Fuel strata gap (m)	71	0.4	12.0	4.3	3.4
10-m open wind speed ($km\ h^{-1}$)	71	3.0	32.1	12.5	6.0
Estimated fine fuel moisture content (%)	71	6.0	15.6	9.1	1.7
Surface fuel consumption ($kg\ m^{-2}$)	71	0.19	3.23	1.26	0.64
Foliar moisture content (%)	41	80.0	168.0	114.6	19.4
Rate of fire spread ($m\ min^{-1}$)	71	0.4	49.4	8.1	10.0
Fireline intensity ($kW\ m^{-1}$)	71	62	45,200	5,903	9,180

reflects the overall amount of fuel consumed in both the flaming and glowing combustion stages, its use as an absolute quantity is limited in this model. SFC is an ex post facto measure of fire behavior, but there exist models that predict total fuel consumption (e.g., Reinhardt et al. 1997) or fractional fuel consumption by size classes (e.g., Call and Albini 1997). Because of the difficulty of estimating the amount of fuel available for flaming combustion and possible errors introduced in the model system by the use of outputs from a subsystem as inputs to others, SFC was coded as a categorical variable. Three classes encompassing broad ranges of SFC were defined, and SFC entered the model as two design variables, $D1$ and $D2$. The classes and the design variable values were: SFC < 1.0 kg m^{-2} [$D1 = 1$, $D2 = 0$]; $1.0 <$ SFC < 2.0 kg m^{-2} [$D1 = 0$, $D2 = 1$]; SFC > 2.0 kg m^{-2} [$D1 = 0$, $D2 = 0$]. Because the values of the design variables are assumed to be nominally scaled as opposed to interval scaled, the logit in Equation 2 is changed to

$$g(x) = \beta_0 + \beta_1 x_1 + \cdots + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_i x_i \tag{3}$$

where jth variable is SFC, with k_j levels (two in the present formulation), and D_{ju} are the design variables.

The decision criteria (i.e., the probability threshold value that separates surface from crown fire occurrence) was based on the rule that would maximize both sensitivity and specificity (Hosmer and Lemeshow 2000). These two measures arise from cross-classifying and examining the agreement between the observed outcomes and the predicted probabilities. For the present case, sensitivity is the percentage of correct classification of crown fire occurrences, and specificity is the correct classification of surface fire occurrences.

The model was analyzed through the rationality of the explanatory variables, the significance of the regression coefficients, and several statistical indicators characterizing model performance. These indicators were the Nagelkerke R^2 (Nagelkerke 1991) and the discrimination capacity as measured by the area under a relative operating characteristic (ROC) curve (Hanley and McNeil 1982, Wilson 1987, Saveland and Neuenschwander 1990). The ROC curve plots the probability of detecting a hit (i.e., sensitivity) and a false alarm (i.e., 1 – specificity) independent of the decision criteria (Pearce and Ferrier 2000). This statistic can be interpreted as the probability that a random surface fire–crown fire pair is correctly ranked as to their category (Hanley and McNeil 1982). SPSS software (Norušis 1997) was used in data analysis and model development.

Model Behavior and Testing

Testing and evaluation of models is a fundamental component of model development, leading to model understanding and increased credibility (e.g., Andrews 1980, Albini and Stocks 1986, Cruz et al. 2003b). An important aspect to consider in model evaluation is the definition of the criteria that should be applied, which will depend on the type of model being evaluated and its potential application. A large number of different tests have been applied to evaluate models—see, for example, Sargent (1984) and Rykiel (1996) for review of model evaluation approaches. The model represented by Equation 4 was evaluated using sensitivity analysis tests and comparisons with the behavior of other similar models.

An evaluation of the logistic model's predictive capacity was also undertaken against two independent experimental fire data sets. The Porter Lake Project data set comprises eight experimental crown fires in a black spruce–lichen woodland fuel type (Alexander and Lanoville 1989, Alexander et al. 1991), and the International Crown Fire Modeling Experiment (ICFME) data set includes 11 experimental crown fire observations in a mature jack pine stand possessing a substantial black spruce understory (Alexander et al. 2004, Stocks et al. 2004). These two fuel complexes exhibit distinctly different characteristics. The Porter Lake fuel complex would be characterized as a very open stand with low FSG (averages 0.8 m). The ICFME fuel complex would be characterized as closed forest stand with an average FSG of ≈6.6 m.

Results and Discussion

Variables Analyses

To evaluate relationships between variables, correlation matrices using the Pearson correlation coefficient were computed for the various variables identified as pertinent (Table 3). Histograms of variable distributions and scatter

Table 3. Simple correlation coefficient (r) matrix for the fire-environment and fire-behavior variables in the experimental fire data set.

	R	I_B	U_{10}	SFC	FSG	FMC	EFFM
R	1	0.974**	0.393**	0.308*	0.307**	−0.237	−0.215
I_B		1	0.357**	0.408**	0.288*	−0.224	−0.177
U_{10}			1	0.243*	0.067	0.145	−0.063
SFC				1	−0.111	0.034	0.002.
FSG					1	0.458**	0.334**
FMC							0.377*
EFFM							1

R, rate of fire spread; I_B, fireline intensity; U_{10}, 10-m open wind; SFC, surface fuel consumption; FSG, fuel strata gap; EFFM, estimated fine fuel moisture; FMC, foliar moisture content.

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

plots were examined to evaluate the representative coverage of the data and to identify apparent relationships among the various variables.

U_{10} was significantly correlated with the observed rate of fire spread. The scatter plot of U_{10} versus rate of spread (Figure 1a) shows that this variable covers a significant portion of the spectrum of fire behavior associated with the onset of crowning. The data show a strong effect of U_{10} on the type of fire (i.e., surface or crown fire). Only one out of the 34 surface fires in the experimental database had wind speeds above 15 km h^{-1}.

FSG was significantly correlated with rate of fire spread (Table 3), which is expected from the effect of this variable on transitional fire behavior, and consequently on overall rate of fire spread. From a visual analysis of the scatter in Figure 1b, it can be seen that, although FSG values cover the range where crown fire initiation is expected to occur, they are not evenly distributed. The scatter plot does however give some insight relative to a FSG threshold value for crown fire occurrence. Above an FSG of ~7.0 m, the incidence of crown fire drops considerably because of the higher energy requirements needed to ignite the canopy fuels. This is in contrast to cases of an FSG below ~2.0 m, were the incidence of crown fire activity is commonplace.

SFC was significantly correlated with U_{10} and rate of fire spread (Table 3). Figure 1c displays the scatter associated with rate of fire spread versus SFC as categorized by the type of fire-spread regime. A differentiation between surface and crown fires can be readily identified, with the crown fires occupying the upper spectrum of the surface fuel consumption.

The EFFM was not significantly correlated with rate of fire spread or any other fire environmental variable (Table 3). This is undoubtedly the result of the limited range in the EFFM (Figure 1d) with 90% of the data lying within the 6–11% range. The lack of experimental fires possessing an EFFM lower than 6% is explained by the inherent difficulties of conducting experimental fires under extreme fire weather conditions resulting from operational and safety constraints (Stocks 1987, 1989, Alexander and Quintilio

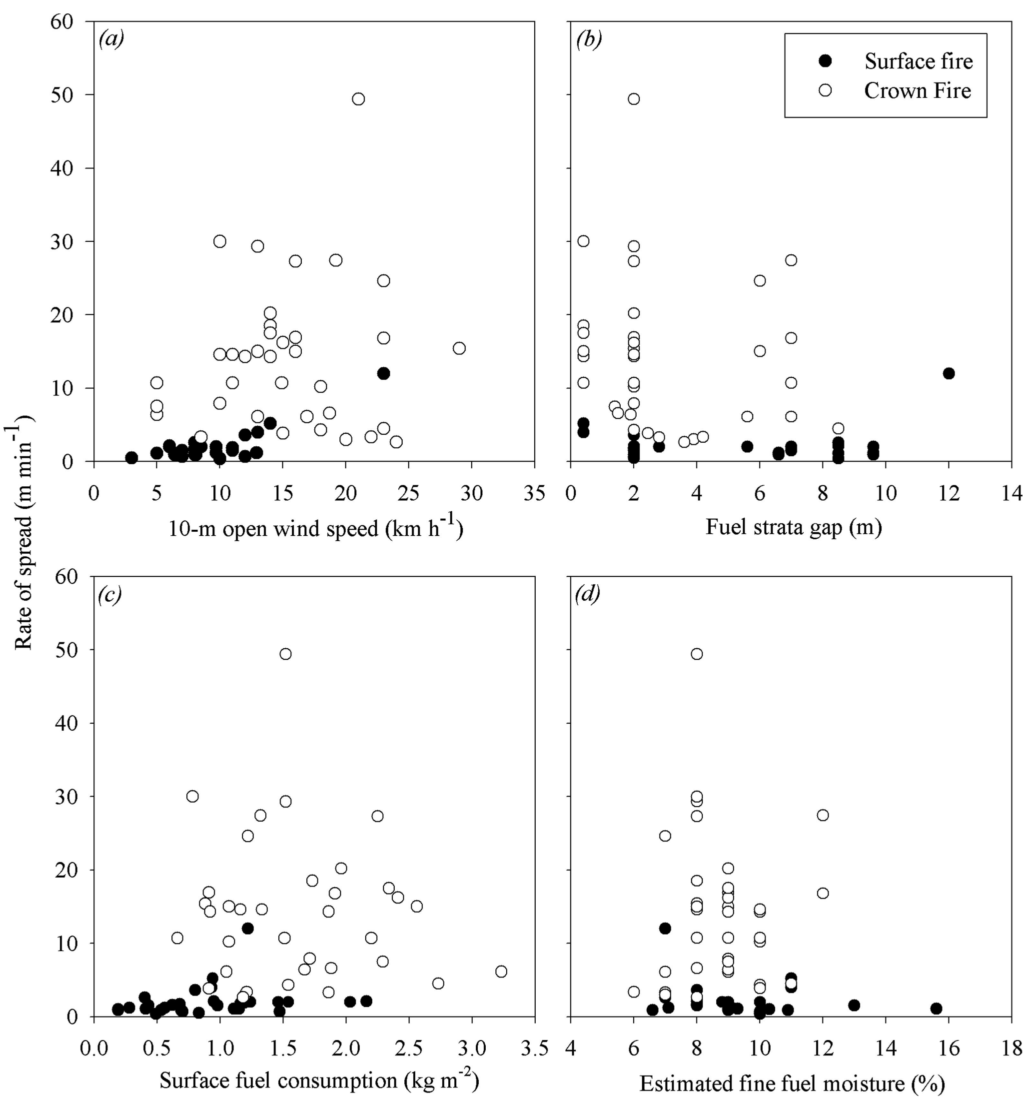

Figure 1. Scatterplots of rate of fire spread by principal type of fire versus the main determinants influencing the likelihood of a crown fire occurrence.

1990). Although the overall EFFM content values are not related to rate of fire spread, Figure 1d shows the damping effect of this variable on crown fire rate of spread.

Interestingly, no readily apparent effect of FMC on crown fire occurrence was found. FMC in the data set (n = 41) was not significantly correlated with any of the fire environment or fire-behavior variables under analysis (Table 3). FMC data, like EFFM, showed limited variability, with 80% of the data within a range of 100–120%. The difficulty of finding a distinct FMC effect in the experimental data set is the same problem one faces in trying to conduct outdoor experimental fires in general—i.e., you don't have the luxury of holding everything else constant and varying one parameter, in this case FMC, like you do with indoor laboratory fires (Van Wagner 1971).

Model Development and Performance Measures

Several possible model solutions were analyzed, with various combinations of the independent variables. Because not all of the experimental fires used in this study had an associated sampled FMC value, logistic regression analysis was applied to a subset of the data (i.e., $n = 41$) for which the FMC had been measured. For this model, the FMC coefficient was not significantly different from zero (P = 0.26). Hence, the FMC variable was not considered in any subsequent analyses. Based on the complete data set ($n = 71$), the model considered as most valid was

$$g(x) = \beta_0 + \beta_1 \mathrm{U}_{10} + \beta_2 \mathrm{FSG} + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_5 \mathrm{EFFM}. \quad (4)$$

The estimated parameters for Equation 4, their standard errors, and significance levels are presented in Table 4. The coefficients for U_{10}, FSG, and SFC categories (i.e., SFC_CAT in Table 4) were significant ($\alpha = 0.05$). The relevance of EFFM in the model is open to question, because this variable was not statistically significant. However, EFFM was kept in the model based on simple physical reasoning. Fuel moisture content determines ignitability, the fuel available for combustion, and burning rates. The incorporation of the EFFM variable in the Equation 4 model will presumably help discriminate the peak-burning period, when fine fuel dryness is at its lowest point and the likelihood or potential for crowning is correspondingly at its highest.

Table 4. Estimated parameters and statistics associated with the probabilistic crown fire occurrence logistic model.

Variable	β	S.E.	S.L.
U_{10}	0.357	0.122	0.004
FSG	−0.710	0.218	0.001
SFC_CAT			0.003
SFC_CAT(1)	−4.613	1.566	0.003
SFC_CAT(2)	−1.856	1.390	0.182
EFFM	−0.331	0.336	0.325
Constant	4.236	3.194	0.185

S.E., Standard error; S.L., Significance level.

The selection of the most adequate decision criteria was based on the value that would maximize both sensitivity and specificity (i.e., where the sensitivity and specificity curves intersect (Figure 2). For the present data set, this was attained at a cutoff value of ≈0.5 (Cruz et al. 2003c). Based on this decision criterion, sensitivity and specificity were, respectively, 0.84 and 0.85, for an overall discrimination of 0.85. The Nagelkerke R^2 value associated with Equation 4 is 0.74. The Nagelkerke R^2 value should be interpreted with care, because it is not comparable to the conventional R^2 statistic computed in least squares regression. R^2 measures proposed for logistic regression models rely on comparisons between the fitted model and an intercept only model, rather than comparing model predictions with observed values (Hosmer and Lemeshow 2000). Consequently these measures are better used for model comparison purposes. The logistic model represented by Equation 4 yields an area under the ROC curve of 0.94. Overall, the logistic model correctly predicted type of fire 84.5% of the time in the data set (Table 5). The model equally discriminated between surface and crown fires—85.3% of the surface fires and 83.8% of the crown fires were correctly discriminated by the model.

Figure 3 illustrates the effects of the four logistic model inputs on the probability of crown fire occurrence. Within the range that these variables, one can easily ascertain from Figure 3 that U_{10} has the most effect on the probability of crown fire occurrence given a nominal available fuel load and fuel dryness. This could be expected from the logistic regression coefficients given in Table 4. These graphical representations of the logistic model give insight into its behavior under marginal and severe burning conditions. The model appears to perhaps place too much weight on the effect of U_{10}, especially at the higher levels. For instance, it is difficult to imagine crowning with an FSG of 16 m or when EFFM levels are at 25%, even if winds are exceeding

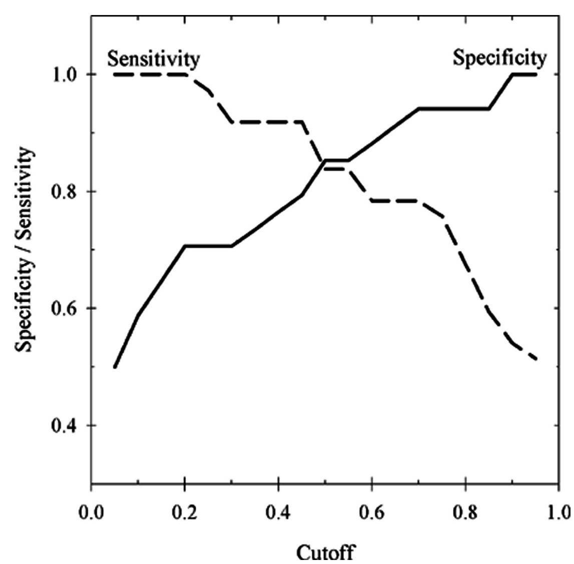

Figure 2. Plot of model sensitivity and specificity for the possible range of cutoff values.

Table 5. Classification table comparing observed and predicted type of fire through the application of the logistic model to the data set used in its development and two independent experimental fire data sets.

Observed	Predicted Surface fire	Predicted Crown fire	Correctly predicted (%)
Data set used in logistic model development			
Surface fire	29	5	85.3
Crown fire	6	31	83.8
Porter Lake experimental fires (Alexander et al. 1991)			
Surface fire	0	0	100
Crown fire	0	8	100
ICFME experimental fires (Stocks et al. 2004)			
Surface fire	0	0	100
Crown fire	0	11	100

35 km h^{-1}. Unfortunately, it has not been possible to conduct experimental fires under strong winds ($U_{10} > 35$ km h^{-1}) coupled with low available fuel quantities (e.g., SFC > 0.5 kg m^{-2}) or high fuel moisture conditions (EFFM $> 12\%$). In this regard, it is worth noting that several authors have reported cases where strong surface winds coupled with low amounts of available fuel (either resulting from preburn quantities 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 crowning (e.g., Luke and McArthur 1978, Buckley 1992, National Fire Protection Association 1992). The major run of the Burnt Fire that occurred on the Coconino National Forest in northern Arizona on Nov. 2, 1973 (Dieterich 1979) represents a case in point. The principal fuel type was variable stocked stands of ponderosa pine (*Pinus ponderosa*) with much of it open-grown and exhibiting low FSG (1.2–1.5 m). Observed rates of fire spread generally averaged 30.2 m min^{-1}. According to Dieterich (1979), "Damage from this fast-spreading fire was extremely variable ranging from complete destruction of crown material in patches of samplings and pole timber and an occasional mature tree, to large areas where the only evidence of fire was a blackened litter layer and slight scorch on the lowest portions of the crowns." The prevailing fuel and weather conditions were as follows: dry-bulb temperature, 10.0° C; relative humidity, 25–35%; U_{10}, 56–74 km h^{-1}; EFFM, 9%; and SFC, −0.56 kg m^{-2}. The computed fire-line intensity was 5251 kW m^{-1} (Alexander 1998). The predicted probability of crown fire occurrence by Equation 4 was 1.0.

Model Evaluations

Sensitivity Analysis

Sensitivity analysis allows the quantification of the degree of sensitivity of model components to changes in input parameters. Model parameters and submodels which, when perturbed, cause the greatest fluctuations in model predictions, can thus be identified (Vanclay and Skovsgaard 1997). For the present analysis, Bartlink's (1998) dimensionless relative sensitivity (RS) criteria was chosen:

$$RS = \frac{V_{+10\%} - V_{-10\%}}{V_{\text{def } 0.2}}, \tag{5}$$

where, $V_{+10\%}$ and $V_{-10\%}$ are the resulting value of the critical parameter when the value of the parameter to be analyzed is increased or decreased by 10%; V_{def} is the resulting value of the critical parameter under default conditions, and the value 0.2 is the relative range (i.e., 1.1–0.9) of the parameter to be analyzed. The RS score reflects the importance of each variable in the model. It indicates the proportional response of the model to changes in an input parameter.

Because of the S-shaped form of the cumulative probability distribution output curve, the sensitivity analysis was conducted where the curve would be at its maximum slope, implying maximum model sensitivity (Figure 3). The selected combination of input variables were thus: U_{10}, 15 km h^{-1}; FSG, 6 m; SFC, between 1.0 and 2.0 kg m^{-2}; and EFFM, 10%.

Computed RS scores were 2.33 for U_{10}, 1.64 for the FSG, and 1.21 for the EFFM. SFC was not subjected to sensitivity analysis because of its categorical nature. The model showed high sensitivity to U_{10}. A change of 10% in the U_{10} input parameter results in a 23% higher probability score. A similar variation in the FSG and EFFM inputs resulted in changes in the probability score of 16 and 12%, respectively. Each of the three variables under analysis induced a proportionally higher response by the model, with errors in the estimation of U_{10} doubling the final error in the system.

Comparison with Other Models

An intercomparison of the behavior of several models describing the same phenomena provides an understanding of possible deficiencies in the models and their limits of applicability. The crown fire initiation models selected for comparison with Equation 4 were those developed by Van Wagner (1977) and Alexander (1998). The nature of the distinct modeling approaches taken in the development of the crown fire initiation models under evaluation, each with its own distinct input requirements, does place some constrains on the type of comparative analysis that can, in fact, be applied. The intermodel comparison approach taken requires the use of an actual forest fire situation where the distinct input variables have been simultaneously measured.

There is a general scarcity of quality data on prescribed or outdoor fires in the published literature. Generally, the limiting factor is having time-specific fuel and weather conditions matched up with the information and data collected on fire behavior. Several of the early experimental crown fires carried out in red pine plantations at Petawawa Forest Experimental Station (PFES) in eastern Ontario, Canada (Van Wagner 1977) offer a complete description of the fuel complex and fire weather conditions, thereby meeting the various model input requirements. Red pine plantations offered an idealized fuelbed for conducting outdoor experimental fires because of the homogeneous nature. The published data on PFES experimental fire R1 (Van Wagner 1968, 1977) was selected for the model evaluation being

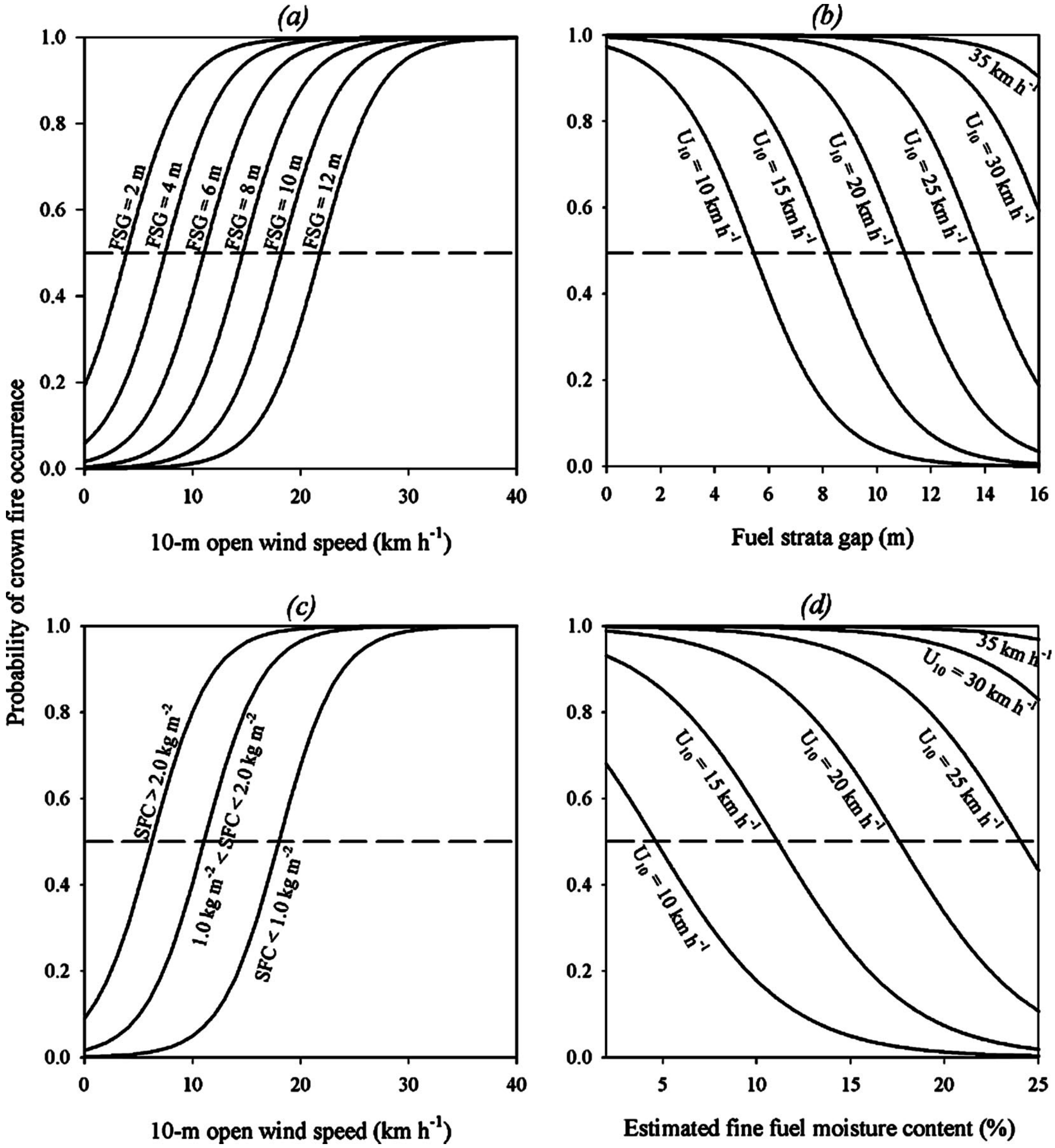

Figure 3. Graphical comparison of the effect of the input variables in the logistic crown fire occurrence model represented by Equation 4 (U_{10}, 10-m open wind; FSG, fuel strata gap; SFC, surface fuel consumption; and EFFM, estimated fine fuel moisture). (a) effect of U_{10} under variable FSG; (b) effect of FSG under various U_{10}; (c) effect of SFC under variable U_{10}; (d) effect of EFFM under variable U_{10}. Constant conditions are: FSG = 6 m; EFFM = 6%; 1.0 kg m^{-2} < SFC < 2.0 kg m^{-2}. The horizontal dashed line in each graph represents the approximate threshold value for the onset of crowning.

undertaken here. This is incidentally the same experimental fire that Van Wagner (1977) used to derive the proportionality constant for his crown fire initiation model.

For the simulation exercise carried out here, the fixed inputs for PFES experimental crown fire R1 were (Van Wagner 1968): in-stand wind speed, 5.5 km h^{-1}; FMC, 100%; EFFM, 10%; 10-h timelag (TL) fuel moisture content (per Rothermel 1983), 11%; SFC, 2.2 kg m^{-2}; and FSG, 6.0 m. The Fine Fuel Moisture Code and Buildup Index components of the Canadian Forest Fire Weather System (Van Wagner 1987) were 92 and 70, respectively (Alexander 1998)[3]. The in-stand wind measured at a height of 1.2 m aboveground is considered equivalent to the mid-flame wind (Rothermel 1972) as used in the BEHAVE system.

Intermodel comparison was restricted to the analysis of model output, given changes in the two input variables common to all models, namely U_{10} and FSG. These two variables can be considered the two main determinants in crown fire occurrence given their significance in the logistic model. Although U_{10} is not a direct input in the Van Wagner (1977) model per se, it is a significant variable determining fireline intensity (Byram 1959).

We compared the various models by examining the U_{10} threshold requirements for crowning given a variable FSG. The FSG was varied from 0.5 to 10.0 m. For the case study scenario described, critical fireline intensities for crowning using the Van Wagner (1977) and Alexander (1998) models varied between 106 and 60 kW m^{-1} for an FSG of 0.5 m, and 5,327 and 4,336 kW m^{-1} for an FSG of 10 m, respectively.

The critical fireline intensities for Alexander's (1998) model were based on a flame front residence time of 45 seconds as observed in R1 (Van Wagner 1968). For the variable proportionality constant, as required of his model, a value of 16 was selected as deemed applicable to needle litter-dominated surface fuelbeds (Alexander 1998).

When using Van Wagner's (1977) and Alexander's (1998) models to predict the possibly of crown fire initiation, they need to be used within a model system where fireline intensity and flame front residence time, two major fire-behavior characteristics in themselves, can also be predicted. To better understand how different models for rate-of-fire spread and fireline intensity influence the model system outcome (e.g., critical U_{10} values necessary to achieve crowning given changes in the FSG), we evaluated the models through the use of two distinct rate-of-fire spread models and two different fireline intensity models (Figure 4).

Two distinct models were used to estimate fireline intensity (I_B): Byram's (1959) original formulation, Equation 6, and fireline intensity derived from reaction intensity (I_R), Equation 7, given as follows:

$$I_B = R \cdot w_a \cdot H_c \tag{6}$$

$$I_B = \frac{I_R}{R \cdot \tau_r} \tag{7}$$

where R is the fire rate of spread (m s^{-1}), w_a is the fuel consumed in the flame front (kg m^{-2}), H_c is the fuel particle heat content (kJ kg^{-1}), and τ_r is the flame front residence time (s). I_B is expressed in kW m^{-1}, and I_R in kW m^{-2}. Equation 6 was used by Van Wagner (1977) to determine a needed empirical proportionality constant in his crown fire initiation model. Model systems that incorporate Rothermel (1972) surface fire spread model, such as the FARSITE (Finney 1998) and NEXUS (Scott and Reinhardt 2001) fire-behavior model linkages, derive I_B from Equation 7. This method consistently yields lower I_B values than Equation 6, with the differences proportionally increasing with increasing fuelbed density (Catchpole et al. 1993). To track errors caused by the two different calculation methods, I_B was calculated through three different approaches: (1) as the direct output from the BEHAVE system using Equation 7 (i.e., CUSTIR and CALIR in Figures 4 and 5); (2) relying on Equation 6 and using $w_a = 0.6$ kg m^{-2} from the description of the fuel model (i.e., CUSTIB06 and CALIB06 in Figures 4 and 5); and (3) relying on Equation 6 and using the w_a consumed in PFES experimental fire R1, namely 2.2

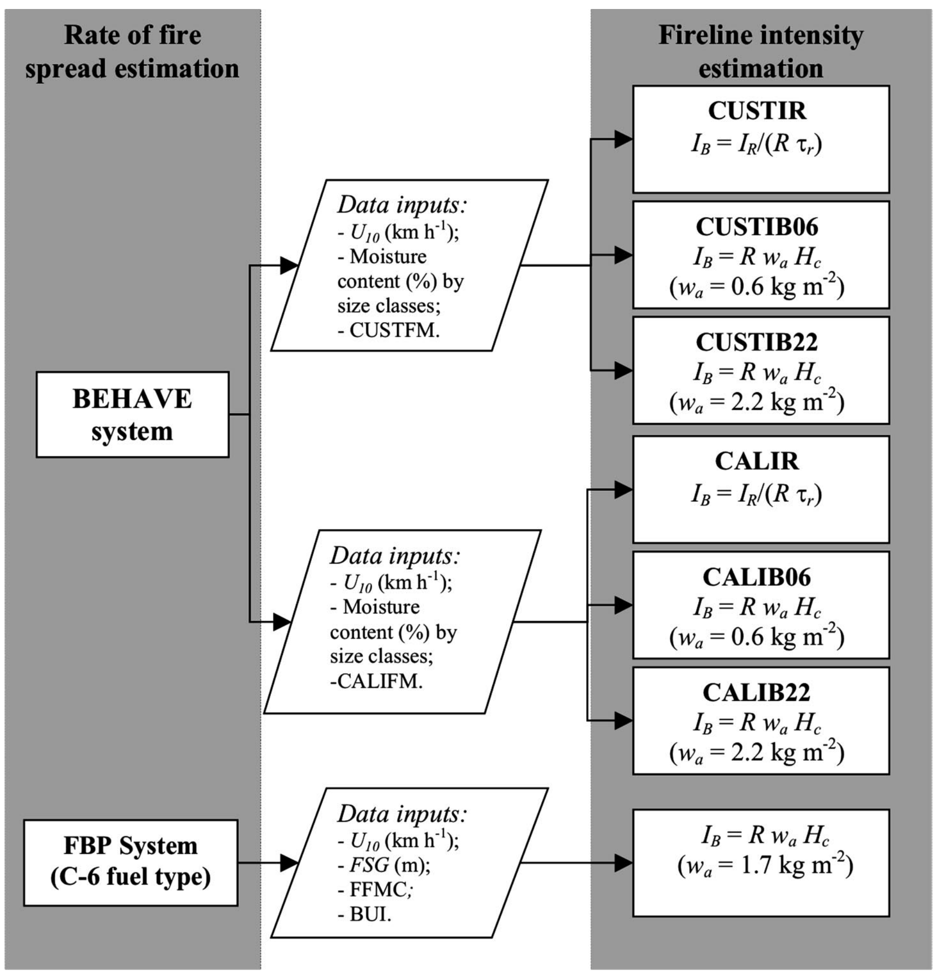

Figure 4. Flow diagram describing the methods used in estimating the critical fire line intensities to evaluate Van Wagner (1977) and Alexander (1998) crown fire initiation models in comparison to the logistic crown fire occurrence model developed in the present study.

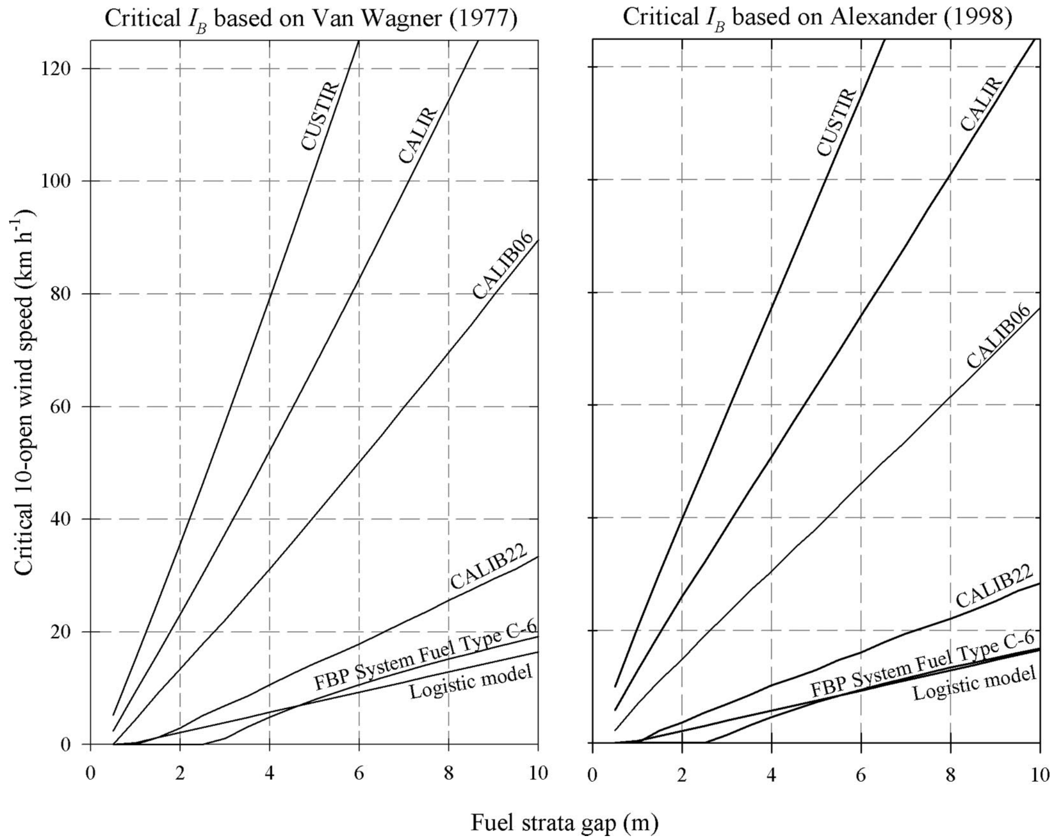

Figure 5. Critical 10-m open wind speeds for crown fire initiation as a function of the fuel strata gap for the models under analysis in comparison to the logistic crown fire occurrence model developed in the present study. The baseline conditions for the simulation are taken from experimental crown fire R1 as described by Van Wagner (1968).

kg m^{-2} (i.e., CUSTIB22 and CALIB22 in Figures 4 and 5). This last method is consistent with the method used by Van Wagner (1977) to determine the needed proportionality constant in his model.

The R component of Equations 6 and 7 was estimated from the two FBP systems used in North America, the US BEHAVE FBP system (Andrews et al. 2003) and the Canadian FBP System (Forestry Canada Fire Danger Group 1992). To minimize the effect of any error introduced by the estimation of rate of spread, two distinct custom fuel models (Burgan and Rothermel 1984) were used for the BEHAVE system predictions. One custom fuel model, CUSTFM, was developed from the physical description of the surface fuel layer given in Van Wagner (1968). This replicates a common practice in wildland fire research, where fuel models are developed directly from fuel inventory data (e.g., Bessie and Johnson 1995, van Wagtendonk 1996, Kalabokidis and Omi 1998, Scott 1998b, Stephens 1998, Fulé et al. 2001b, Brose and Wade 2002, Fulé et al. 2002, Hummel and Agee 2003). The other custom fuel model, CALIFM, was based on the fuel inventory data and subject to calibration. The calibration relied on the experimental surface fires in red pine plantations ($n = 6$) reported by Van Wagner (1968). The calibration process consisted of modifying the fuel model heat content and fuelbed depth (Burgan and Rothermel 1984, Burgan 1987b) of CUSTFM fuel model to minimize the root mean square error (RMSE) of the observed versus predicted surface fire rate of spread. The calibrated fuel models yielded an root mean square error of 0.01 m s^{-1}. The fuel model descriptions for CUSTFM and CALIFM were: 1-h TL fuel load, 0.3 kg m^{-2} for both; 10-h TL fuel load[4], 0.3 kg m^{-2} for both; surface area-to-volume ratio, 5500 m^{-1} for both; fuelbed depth, 0.18 and 0.25 m, respectively; moisture of extinction, 55% for both; and H_c,18,600 and 22,000 kJ k^{-1}, respectively. For the FBP system, the fuel complex was described using the conifer plantation fuel type (C-6).

For the case study scenario considered here, the logistic model represented by Equation 4 and the FBP System C-6 fuel type model produced the lowest U_{10} requirements for crown fire initiation (Figure 5), with both of these models giving similar results for FSG above 5.0 m. The Van Wagner's (1977) model is less conservative than Alexander's (1998) model for low FSG values, and more conservative for larger FSG values. In the current scenario, Van Wagner's (1977) model yielded higher critical fireline intensity requirements for FSG values greater than 4.0 m, with the differences increasing linearly with FSG.

The results derived from the use of the BEHAVE system show that this modeling approach produced the highest wind speed requirements for crowning. The results vary broadly with the rate of spread/fireline estimation method used. Though CALIB22, relying on the calibrated fuel model for the prediction of rate-of-fire spread and using

Equation 6 with a w_a of 2.2 kg m^{-2} is the modeling approach that follows more closely the results of the FBP System C-6 fuel type model and the logistic model represented by Equation 4. This was expected because the errors introduced by the rate-of-fire spread model are minimized and the estimation of fire line intensity is thereby consistent with the Van Wagner's (1977) model.

The difference in the critical U_{10} for crowning obtained by the BEHAVE system, through the use of a custom fuel model, and the FBP System fuel type C-6 model is larger than one order of magnitude. This demonstrates the error propagation problem inherent in the former model system, where the outputs from a subsystem are used as inputs to other components of the system. The errors propagated as a result of indirect prediction can bias the final results. The larger differences between these two modeling approaches are due to differences originating from the output of the rate of fire spread and fireline intensity models.

Figure 5 allows us to visualize the effects of the Van Wagner (1977) and Alexander (1998) crown fire initiation models separately and in relation to the logistic model represented by Equation 4. For example, the differences in U_{10} levels required for crowning to occur between CUSTIR and CALIR is 50 km h^{-1} for an FSG of 7.0 m. This difference is due to the distinct rate of fire spread predictions for the custom and the calibrated fuel models alone. The differences between the predictions for CALIR and CALIB06 are due to the fireline estimation calculation method. The U_{10} requirement for crowning for CALIR was larger than the one for CALIB06 by a factor of 1.7. The difference between the predictions for CALIB06 (w_a = 0.6 kg m^{-2}) and CALIB22 (w_a = 2.2 kg m^{-2}) can be described as an error resulting from the application of the model without concern for the underlying assumptions in the model, namely how the empirical proportionality constants were determined. Wind requirements for crowning in CALIB06 were 2.6–4.5 times greater than for CALIB22. The results for CUST06 and CUST22 are not shown in Figure 5 because the results from the CUSTIR fuel models are similar to the ones obtained for the calibrated fuel model.

It is worth noting that the results of the present model comparison are restricted to a sole situation. Given the distinct model forms and sensitivities to input parameters, the model results could possibly turn out quite differently for some other combinations of burning conditions. For example, the variation in FMC that affects both the Van Wagner (1977) and Alexander (1998) crown fire initiation models is not considered in the logistic model developed here.

Tests against Independent Experimental Data

The results of the application of the logistic model to the two independent experimental fire data sets are summarized in Table 5. All 19 of the experimental fires were correctly classified as crown fires. Of the eight Porter Lake Project fires, five were considered as intermittent crown fires and the other three as fully developed, active crown fires (Alexander et al. 1991). The logistic model failed to discriminate these differences, and all fires were predicted to have a probability of crown fire occurrence of 1.0. The probability of crown fire occurrence predictions for the ICFME fires varied between 0.5 and 1, with two predictions of the 11 crown fire observations having a value of less than 0.7. It is not possible at this time to suggest that the type of crown fire—i.e., passive/intermittent or active (Van Wagner 1977) can be related to a certain probability level. However, a companion model developed by the authors (Cruz et al. 2002) can distinguish the type of crown fire based on the predicted crown fire rate of spread as determined by the canopy bulk density (Cruz et al. 2003a), EFFM, and U_{10}.

Conclusions

The present study approached the problem of modeling the onset of crowning quite differently from previous studies. Previous modeling approaches (e.g., Van Wagner 1977, Alexander 1998) were based on the combination of surface fireline intensity and ignition requirements at the base of the tree crowns. The empirical-based linkage between fireline intensity and convective heat transfer theory admittedly gives these models the potential for wide applicability. Nevertheless, the application of these models in a system where endogenous variables are determined from within the system has the potential to compound the errors in the final result.

The logistic model developed in this study is designed to predict the likelihood of crown fire occurrence. This simple model can be readily used to support fire management decisionmaking, namely assessing the effectiveness of fuel management treatments in reducing crown fire potential, in planning and executing prescribed fires, in near-real time prediction of wildfire behavior, and in simulating fire impacts and effects. The four straightforward model inputs allow fire practitioners to use it as a stand-alone guide (Figure 3) or use it in conjunction with models to predict crown fire rate of spread (Rothermel 1991, Cruz et al. 2002). Conversely, the model can also be incorporated into more complex, computerized FBP systems like BEHAVE (Andrews et al. 2003) and FARSITE (Finney 1998).

One distinct advantage of the logistic model over existing crown fire initiation models is the form of the output—i.e., a probabilistic basis. The need for such a model was recognized some time ago (USDA Forest Service 1980). Both the Van Wagner (1977) and Alexander (1998) models provide a simple dichotomous (i.e., crowning or no crowning) or deterministic (i.e., yes or no) answer. The probabilistic outcome of the logistic model allows users to interpret the result by taking into account fuel types and perhaps terrain conditions as well. Threshold scores or values for the decision criteria defining the occurrence of crowning could possibly be locally identified, based on user experience with the model.

An obvious limitation of the logistic model is that the effect of slope steepness in determining crown fire occurrence is not incorporated (i.e., the model applicability is restricted to level terrain). Model predictions are considered valid for conifer-dominated forest stands that are not unduly affected by insect- or disease-exhibiting canopy-bulk densities sufficient to support vertical fire spread beyond the FSG. Furthermore, the predictions are not considered applicable to point-source fires (McAlpine and Wakimoto 1991), including prescribed fire ignition patterns (Sackett 1968, Johansen 1984) that do not approximate free-burning wildfires[5].

In contrast to other models that attempt to characterize and quantify the main processes involved in crown fire initiation, the logistic model does not directly incorporate any physical reasoning relative to the heat transfer processes taking place during a forest fire. Our analysis of an experimental fire data set provided qualitative information on the effects of several fire environment variables presumed to influence the onset of crowning.

The model is a reflection of the data set used in its development, and so, it may be biased to some extent by the distribution of the original variables. One shortcoming of the data set used in the model development is that the distribution of the FSG data is concentrated in the lower part of its spectrum of variability (i.e., 60% of the situations are for $<$3.0 m). In addition, SFC was included in the model as a surrogate for the heat energy released by the surface fire, specifically the upward heat flux component. This variable is not easily estimated a priori and was thus included in the model as a categorical variable, with three broad classes that should allow coherent decisions based on the available fuel in the surface fuelbed based on fuelbed structure and its moisture status. The use of fuel-consumption models to support a more deterministic basis for the choice of the SFC class should be considered, thereby limiting the uncertainty this variable might induce in the logistic crown fire-occurrence model represented by Equation 4.

Model evaluation in this study consists of a sensitivity analysis and comparison of model behavior with two crown fire initiation models. These tests give some insight into the strengths and limitations of the model. A limited evaluation of the logistic crown fire-occurrence model against two independent data sets produces some encouraging results.

Research into high-intensity fire behavior is conditioned by budget and operational and social constraints. The present study emphasized both the potential and the constraints of using published data in the understanding of crown fire initiation processes. The study has also highlighted the need for outdoor experimental fire studies to assemble and report physical data that comprehensively describe fuel-complex structure, fire weather, and the associated fire-behavior characteristics. Data that, at some point in time, may be seen as marginally important can later be of critical importance in providing insight into certain fire phenomena (Alexander 1998). As others before us have stated (e.g., Van Loon and Love 1973, Zeide 2002), we hope that this article will stimulate those involved in conducting experimental fires to quantitatively describe and document the fire environment and the corresponding fire-behavior phenomena, and to share such data with the wildland fire research community at large.

Endnotes

[1] Crown base height as defined by Van Wagner (1977). In the present study the term “crown” is applied to describe aerial fuels at the tree level and “canopy” at the stand level.

[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 a contributor to the database used in the development of the FBP System and thus had access to the database.

[3] The Fine Fuel Moisture Code and Buildup Index components of the Canadian Forest Fire Weather System are relative numerical ratings of the moisture content of litter (and other cured fine fuels) and the total amount of fuel available for combustion, respectively.

[4] The 0.3 kg m^{-2} fuel load assigned to 10-h size class was originated from the contribution of the duff component to the heat released by the surface fire reaction zone (Rothermel 1994). The fuel modeling approach in the BEHAVE system does not consider the duff layer as participating in the heat release in the flame front, and consequently this fuel layer is not a component of the fuel model. Nevertheless, when considering the integrated heat release in the flame front, some duff consumption is expected to occur in the reaction zone. The 0.3 kg m^{-2} corresponds to an available duff depth of 8 mm. The exclusion of this fuel layer from the fuel model would result in marginal fire propagation under the simulated burning conditions.

[5] The Bor Island Fire Experiment (FIRESCAN 1994, 1996) that took place in a Scots pine (*Pinus sylvestris*) stand in the Krasnoyarsk Region of the central Russian Federation on the afternoon of July 6, 1993 represents a case in point. A perimeter ignition pattern contributed to strong convective activity that resulted in the development of an active crowning on this experimental prescribed fire. The fuel and weather conditions at the time were: dry-bulb temperature, 30.2° C; relative humidity, 36%; EFFM, 9%; U_{10}, 7 km h^{-1}; SFC, 2.441 kg m^{-2}; and FSG, 11 m. The probability of crown fire occurrence predicted by Equation 4 was 0.03.

Literature Cited

AGEE, J.K., C.S. WRIGHT, N. WILLIAMSON, AND M.H. HUFF. 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. For. Ecol. Manage. 167:57–66.

ALBINI, F.A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30. 92 p.

ALBINI, F.A. 1981. A model for wind-blown flame from a line fire. Combust. Flame 43:155–174.

ALBINI, F.A. 1985. A model for fire spread in wildland fuels by radiation. Combust. Sci. Tech. 42:229–258.

ALBINI, F.A., AND E.D. REINHARDT. 1995. Modeling ignition and burning rate of large woody natural fuels. Int. J. Wild. Fire 5:81–91.

ALBINI, F.A., AND B.J. STOCKS. 1986. Predicted and observed rates of spread of crown fires in immature jack pine. Combust. Sci. Tech. 48:65–76.

ALEXANDER, M.E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60:349–357.

ALEXANDER, M.E. 1988. Help with making crown fire hazard assessments. P. 147–156 *in* Proc. Symp. and Workshop on Protecting people and homes from wildfire in the Interior West, Fischer, W.C., and S.F. Arno (comps.). USDA For. Serv. Gen. Tech. Rep. INT-251.

ALEXANDER, M.E. 1998. Crown fire thresholds in exotic pine plantations of Australasia. Ph.D. thesis, Austral. Natl. Univ., Canberra, ACT, Australia. 228 p.

ALEXANDER, M.E. 2000. Fire behaviour as a factor in forest and rural fire suppression. For. Res., Rotorua in association with

N.Z. Fire Serv. Comm. and Natl. Rural Fire Authority, Wellington, NZ. For. Res. Bull. No. 197, For. Rural Fire Sci. Technol. Ser. Rep. No. 5. 28 p.

ALEXANDER, M.E., AND R.A. LANOVILLE. 1989. Predicting fire behavior in the black spruce–lichen woodland fuel type of western and northern Canada. For. Can., North. For. Cent., Edmonton, AB and Govt. Northwest Territories, Dep. Renewable Resour., Territ. For. Fire Cent., Fort Smith, NT. Poster with text.

ALEXANDER, M.E., AND D. QUINTILIO. 1990. Perspectives on experimental fires in Canadian forestry research. Math. Comput. Modell. 13(12):17–26.

ALEXANDER, M.E., C.N. STEFNER, J.A. MASON, B.J. STOCKS, G.R. HARTLEY, M.E. MAFFEY, B.M. WOTTON, S.W. TAYLOR, N. LAVOIE, AND G.N. DALRYMPLE. 2004. Characterizing the jack pine–black spruce fuel complex of the International Crown Fire Modelling Experiment (ICFME). Can. For. Serv. Inf. Rep. NOR-X-393. 49 p.

ALEXANDER, M.E., B.J. STOCKS, AND B.D. LAWSON. 1991. Fire behavior in black spruce–lichen woodland: The Porter Lake Project. For. Can. Inf. Rep. NOR-X-310. 44 p.

ANDERSON, H.E. 1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69. 20 p.

ANDREWS, P.L. 1980. Testing the fire behavior model. P. 70–77 *in* Proc. of sixth conf. on Fire and forest meteorology, Martin, R.E., R.L. Edmonds, D.A. Faulkner, J.B. Harrington, D.M. Fuquay, B.J. Stocks, and S. Barr (eds.). Soc. of Am. For., Washington, DC.

ANDREWS, P.L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system—BURN subsystem, part 1. USDA For. Serv. Res. Pap. INT-260. 130 p.

ANDREWS, P.L., C.D. BEVINS, AND R.C. SELI. 2003. BehavePlus fire modeling system, version 2.0: User's guide. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-106WWW. 132 p.

ANDREWS, P.L., AND C.H CHASE. 1989. BEHAVE: Fire behavior prediction and fuel modeling system—BURN subsystem, part 2. USDA For. Serv. Res. Pap. INT-194. 93 p.

BARTLINK, H.H. 1998. A model of dry matter partitioning in trees. Tree Physiol. 18:91–101.

BESSIE, W.C., AND E.A. JOHNSON. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76:747–762.

BROSE, P., AND D. WADE. 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. For. Ecol. Manage. 163:71–84.

BUCKLEY, A. 1992. Fire behavior and fuel reduction burning: Bemm River wildfire, October 1988. Aust. For. 55:135–147.

BUNTING, S.C., H.A. WRIGHT, AND W.H. WALLACE. 1983. Seasonal variation in the ignition time of redberry juniper. J. Range Manage. 36:169–171.

BURGAN, R.E. 1987a. A comparison of procedures to estimate fine dead fuel moisture for fire behavior predictions. South Afr. For. J. 142:34–40.

BURGAN, R.E. 1987b. Concepts and interpreted examples in advanced fuel modeling. USDA For. Serv. Res. Pap. INT-238. 40 p.

BURGAN, R.E., AND R.C. ROTHERMEL. 1984. BEHAVE: Fire behavior prediction and fuel modeling system—FUEL subsystem. USDA For. Serv. Res. Pap. INT-167. 126 p.

BURROWS, N.D., B. WARD, AND A. ROBINSON. 1988. Aspects of fire behaviour and fire suppression in a *Pinus radiata* plantation. West. Aust. Dep. Conserv. Land Manage., Perth, WA, Australia. Landnote 2/88. 4 p.

BYRAM, G.M. 1959. Combustion of forest fuels. P. 61–89, 554–555 *in* Forest fire: Control and use. Davis, K.P. (ed.). McGraw-Hill, New York.

CALL, P.T., AND F.A. ALBINI. 1997. Aerial and surface fuel consumption in crown fires. Int. J. Wild. Fire 7:259–264.

CARRIER, G.F., F.E. FENDELL, AND M.F. WOLFF. 1991. Wind-aided firespread across arrays of discrete fuel elements. I. Theory. Combust. Sci. Tech. 75:31–51.

CATCHPOLE, E.A., W.R. CATCHPOLE, AND R.C. ROTHERMEL. 1993. Fire behavior experiments in mixed fuel experiments. Int. J. Wild. Fire 3:45–57.

CATCHPOLE, T., AND N. DE MESTRE. 1986. Physical models for a spreading line fire. Aust. For. 49:101–111.

CHENEY, N.P., J.S. GOULD, AND W.R. CATCHPOLE. 1993. The influence of fuel, weather and fire shape variables on the fire-spread in grasslands. Int. J. Wild. Fire 3:31–44.

CHROSCIEWICZ, Z. 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. Can. J. For. Res. 16:157–162.

COHEN, W.B., P.N. OMI, AND M.R. KAUFMANN.1990. Heating-related water transport to intact lodgepole pine branches. For. Sci. 36:246–254.

CRUZ, M.G. 1999. Modeling the initiation and spread of crown fires. M.Sc. thesis, Univ. Montana, Missoula, MT. 162 p.

CRUZ, M.G., M.E. ALEXANDER, AND R.H. WAKIMOTO. 2002. Predicting crown fire behavior to support forest fire management decision-making. *In* Proc. of fourth int. conf. on Forest fire research/2002 wildland fire safety summit. Viegas, D.X. (ed.). Millpress Scientific Publ., Rotterdam, The Netherlands. 11 p.

CRUZ, M.G., M.E. ALEXANDER, AND R.H. WAKIMOTO. 2003a. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wild. Fire 12:39–50.

CRUZ, M.G., M.E. ALEXANDER, AND R.H. WAKIMOTO. 2003b. Definition of a fire behavior model evaluation protocol: A case study application to crown fire behavior. P. 49–67 *in* conf. proc. on Fire, fuel treatment an ecological restoration, Omi, P.N., and L.A. Joyce (eds.). USDA For. Serv. Proc. Symp. RMRS-P-29.

CRUZ, M.G., M.E. ALEXANDER, AND R.H. WAKIMOTO. 2003c. Assessing the probability of crown fire initiation based on fire danger indices. For. Chron. 79:976–983.

CRUZ, M.G., AND D.X. VIEGAS. 1998. Fire behavior in some common Central Portugal fuel complexes: Evaluation of fire behavior models performance. P. 829–875 *in* Proc. of third int.

conf. on Forest fire research/14th conference on fire and forest meteorology, Vol. I, Viegas, D.X. (ed.). Univ. Coimbra, Coimbra, Portugal.

DAVIS, K.M., AND R.W. MUTCH. 2001. Wildland fires: Dangers and survival. P. 318–341 *in* Wilderness medicine: Management of wilderness and environment emergencies, 4th Ed., Auerbach, P.S. (ed.). Mosby-Year Book Inc., St. Louis, MO.

DE MESTRE, N.J., E.A. CATCHPOLE, D.H. ANDERSON, AND R.C. ROTHERMEL. 1989. Uniform propagation of a planar fire front without wind. Combust. Sci. Tech. 65:231–244.

DICKINSON, M.B., AND E.A. JOHNSON. 2001. Fire effects on trees. P. 447–525 *in* Forest fires: Behavior and ecological effects, Johnson, E.A., and K. Miyanishi. (eds.) Academy Press, San Diego, CA.

DIETERICH, J.H. 1979. Recovery potential of fire-damaged Southwestern ponderosa pine. USDA For. Serv. Res. Note RM-379. 8 p.

FINNEY, M.A. 1998. FARSITE: Fire area simulator—Model development and evaluation. USDA For. Serv. Res. Pap. RMRS-RP-4. 47 p.

FIRESCAN SCIENCE TEAM. 1994. Fire in boreal ecosystems of Eurasia: First results of the Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). World Resour. Rev. 6:499–523.

FIRESCAN SCIENCE TEAM. 1996. Fire in ecosystems of boreal Eurasia: The Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). P. 848–873 *in* Biomass burning and global change, Vol. 2: Biomass burning in South America, Southeast Asia, and temperate and boreal ecosystems, and the oil fires of Kuwait, Levine, J.S. (ed.). MIT Press, Cambridge, MA.

FORESTRY CANADA FIRE DANGER GROUP. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep. ST-X-3. 65 p.

FOSBERG, M.A., AND J.E. DEEMING. 1971. Derivation of the 1-hr and 10-hr timelag fuel moisture calculations for fire danger rating. USDA For. Serv. Res. Note RM-207. 8 p.

FUGLEM, P.L. 1979. Foliar moisture content of central Alberta conifers and its implications in crown fire occurrence. M.Sc. thesis, Univ. Alberta, Edmonton, AB, Canada. 148 p.

FUGLEM, P.L., AND P.J. MURPHY. 1979. Flammability of jack pine crown foliage during spring. Univ. Alberta. Dep. For. Sci., Edmonton, AB, Canada. 30 p.

FULÉ, P.Z., A.E.M. WALTZ, W.W. COVINGTON, AND T.A. HEINLEIN. 2001a. Measuring forest restoration effectiveness in reducing hazardous fuels. J. For. 99(11):24–29.

FULÉ, P.Z., C. MCHUGH, T.A. HEINLEIN, AND W.W. COVINGTON. 2001b. Potential fire behavior is reduced following forest restoration treatments. P. 28–35 *in* Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship, Vance, R.K., C.B. Edminster, W.W. Covington, and J.A. Blake (comps.). USDA For. Serv. Proc. RMRS-P-22.

FULÉ, P.Z., W.W. CONVIGTON, H.B. SMITH, J.D. SPRINGER, T.A. HEINLEIN, K.D. HUISINGA, AND M.M. MOORE. 2002. Comparing ecological restoration alternatives: Grand Canyon, Arizona. For. Ecol. Manage. 170:19–41.

GILL, A.M., AND P.H.R. MOORE. 1990. Fire intensities in eucalyptus forests of southeastern Australia. P. B24:1–12 *in* Proc. of int. conf. on Forest fire research. Univ. Coimbra, Coimbra, Portugal.

GRAHAM, R.T., A.E. HARVEY, T.B. JAIN, AND J.R. TONN. 1999. The effects of thinning and similar stand treatments on fire behavior in Western forests. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-463. 27 p.

GRISHIN, A.M. 1997. Mathematical modeling of forest fires and new methods of fighting them, Czuma, M., L. Chikina, and L. Smokotina (transl.). Albini, F. (ed.). Tomsk State University, Tomsk, Russia. 390 p.

HANLEY, J.A., AND B.J. MCNEIL. 1982. The meaning and use of the area under the receiver operating characteristic (ROC) curve. Radiology 143:29–36.

HARTFORD, R.A., AND R.C. ROTHERMEL. 1991. Fuel moisture as measured and predicted during the 1988 Yellowstone fires. USDA For. Ser., Res. Note INT-396. 7 p.

HELMS, J.A. (Ed.). 1998. The dictionary of forestry. Soc. Am. For., Bethesda, MD. 210 p.

HOSMER, D.W., AND S. LEMESHOW. 2000. Applied logistic regression. 2nd Ed. John Wiley & Sons, Inc., New York. 375 p.

HOUGH, W.A. 1973. Fuel and weather influences wildfires in sand pine forests. USDA For Serv. Res. Pap. SE-106. 11 p.

HUMMEL, S., AND J.K. AGEE. 2003. Western spruce budworm defoliation effects on forest structure and potential fire behavior. Northwest Sci. 77:159–169.

IZBICKI, S., AND R. KEANE. 1989. An attempt at developing a crown fire ignition model. USDA For. Serv., Intermountain Fire Sci. Lab., Missoula, MT. Coop. Agreement INT-88352-COA Final Report. 26 p.

JOHANSEN, R.W. 1984. Prescribed burning with spot fires in the Georgia Coastal Plain. Ga. For. Res. Pap. 49. 7 p.

JOHNSON, V.J. 1966. Seasonal fluctuation in moisture content of pine foliage. USDA For. Serv. Res. Note NC-11. 4 p.

KALABOKIDIS, K.D., AND P.N. OMI. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. Int. J. Wild. Fire 8:29–35.

KEYES, C.R., AND K.L. O'HARA. 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. 17:101–109.

KIIL, A.D. 1975. Fire spread in a black spruce stand. Can. For. Serv. Bi-mon. Res. Notes. 31:2–3.

KILGORE, B.M., AND R.W. SANDO. 1975. Crown-fire potential in a sequoia forest after prescribed burning. For. Sci. 21:83–87.

LAWSON, B.D. 1972. Fire spread in lodgepole stands. M.Sc. thesis, Univ. Montana, Missoula, MT. 119 p.

LINN, R.R. 1997. A transport model for prediction of wildfire behavior. Ph.D. dissertation. NM State Univ., Las Cruces, NM. 195 p.

LUKE, R.H., AND A.G. MCARTHUR. 1978. Bushfires in Australia. Aust. Govt. Publ. Serv., Canberra, Australia. 359 p.

MAGUIRE, D.A., AND D.W. HANN. 1990. A sampling strategy for estimating past crown recession on temporary growth plots. For. Sci. 36:549–563.

MCALPINE, R.S., AND M.W. HOBBS. 1994. Predicting the height to live crown base in plantations of four boreal forest species. Int. J. Wild. Fire 4:103–106.

MCALPINE, R.S., AND R.H. WAKIMOTO. 1991. The acceleration of fire from point source to equilibrium spread. For. Sci. 37:1314–1337.

MERCER, G.N., AND R.O. WEBER. 1994. Plumes above line fires in a cross wind. Int. J. Wild. Fire 4:201–207.

MERCER, G.N., AND R.O. WEBER. 2001. Fire plumes. P. 225–255 *in* Forest fires: Behavior and ecological effects, Johnson, E.A., and K. Miyanishi (eds.). Academy Press, San Diego, CA.

NAGELKERKE, N.J.D. 1991. A note on a general definition of the coefficient of determination. Biometrika 78:691–692.

NATIONAL FIRE PROTECTION ASSOCIATION. 1992. Firestorm '91 case study. Natl. Fire Prot. Assoc., Quincy, MA. 31 p.

NELSON, R.M. JR., AND C.W. ADKINS. 1986. Flame characteristics of wind driven surface fires. Can. J. For. Res. 16:1293–1300.

NEWSTEAD, R.G., AND M.E. ALEXANDER. 1983. Short-term fire retardant effectiveness in a lowland black spruce fuel complex. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, AB, Canada. For. Rep. 28:3–4.

NICHOLLS, J.W.P., AND N.P. CHENEY. 1974. Effect of experimental and wild fires in pine plantations on wood characteristics. Aust. For. 36:164–177.

NORUŠIS, M.J. 1997. SPSS professional statistics Ed. 7.5. SPSS Inc., Chicago, IL. 276 p.

OTTMAR, R.D., R.E. VIHNANEK, AND C.S. WRIGHT. 1998. Stereo photo series for quantifying natural fuels. Vol. I: Mixed-conifer with mortality, Western Juniper, Sagebrush, and Grassland types in the Interior Pacific Northwest. Natl. Wildfire Coord. Group, Natl. Interagency Fire Cent., Natl. Fire Equip. Syst. [NFES], Boise, ID. Publ. NFES 2581. 65 p.

OTTMAR, R.D., R.E. VIHNANEK, AND C.S. WRIGHT. 2000. Stereo photo series for quantifying natural fuels. Vol. III: Lodgepole pine, quaking aspen, and gambel oak types in the Rocky Mountains. Natl. Wildfire Coord. Group, Natl. Interagency Fire Cent., Natl. Fire Equip. Syst. [NFES], Boise, ID. Publ. NFES 2629. 85 p.

OTTMAR, R.D., R.E. VIHNANEK, AND C.S. WRIGHT. 2002. Stereo photo series for quantifying natural fuels. Vol. Va: Jack pine in the Lakes States. Natl. Wildfire Coord. Group, Natl. Interagency Fire Cent., Natl. Fire Equip. Syst. [NFES], Boise, ID. Publ. NFES 2669. 49 p.

PEARCE, J., AND S. FERRIER. 2000. Evaluating the predictive performance of habitat models developed using logistic regression. Ecol. Model. 133:225–245.

PHILPOT, C.W. 1963. The moisture content of ponderosa pine and whiteleaf manzanita foliage in the central Sierra Nevada. USDA For. Serv. Res. Note PSW-39. 7 p.

PHILPOT, C.W., AND R.W. MUTCH. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa and Douglas-fir needles. USDA For. Serv. Res. Pap. INT-102. 21 p.

POOK, E.W., AND A.M. GILL. 1993. Variation of live and dead fine fuel moisture in *Pinus radiata* plantations of the Australian Capital Territory. Int. J. Wild. Fire 3:155–168.

QUINTILIO, D. 1977. Lodgepole pine flammability. Can. For. Serv., North. For. Res. Cent., Edmonton, AB, Canada For. Rep. 5(2):7.

QUINTILIO, D., G.R. FAHNESTOCK, AND D.E. DUBE. 1977. Fire behavior in upland jack pine: The Darwin Lake Project. Can. For. Serv. Inf. Rep. NOR-X-174. 49 p.

REINHARDT, E.D., J.K. BROWN, W.C. FISCHER, AND R.T. GRAHAM. 1991. Woody fuel and duff consumption by prescribed fire in northern Idaho mixed conifer logging slash. USDA For. Serv. Res. Pap. INT-443. 22 p.

REINHARDT, E.D., R.E. KEANE, AND J.K. BROWN. 1997. *F*irst *O*rder *F*ire *E*ffects *M*odel: FOFEM 4.0, user's guide. USDA For. Serv. Gen. Tech. Rep. INT-344. 65 p.

ROTHERMEL, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115. 40 p.

ROTHERMEL, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143. 161 p.

ROTHERMEL, R.C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA For. Ser. Res. Pap. INT-438. 46 p.

ROTHERMEL, R.C. 1994. Some fire behavior modeling concepts for fire management systems. P. 164–171 *in* Proc. of the 12th conference on Fire and forest meteorology. Soc. Am. For., Bethesda, MD. SAF Publ. 94–02.

ROTHERMEL, R.C., R.A. WILSON JR., G.A. MORRIS, AND S.S. SACKETT. 1986. Modeling moisture content of fine dead fuels: Input to the BEHAVE fire prediction system. USDA For. Serv. Res. Pap. INT-359. 61 p.

RYKIEL, E.J. 1996. Testing ecological models: The meaning of validation. Ecol. Model 90:229–244.

SACKETT, S.S. 1968. A field trial for regulating prescribed fire intensities. Fire Contr. Notes 29(3):5–6.

SANDO, R.W., AND C.H. WICK. 1972. A method for evaluating crown fuels in forest stands. USDA For. Serv. Res. Pap. NC-84. 26 p.

SARGENT, R.G. 1984. A tutorial on verification and validation of simulation models. P. 115–121 *in* Proc. of the 1984 Winter simulation conference, Sheppard, S., U. Pooch, and D. Pegden (eds.). Inst. Electrical and Electronics Engineers, New York. IEEE 84CH2098-2.

SAVELAND, J.M., AND L.F. NEUENSCHWANDER. 1990. A signal detection framework to evaluate models of tree mortality following fire damage. For. Sci. 36:66–76.

SCOTT, J.H. 1998a. Sensitivity analysis of a method for assessing crown fire hazard in the Northern Rocky Mountains, USA. P.

2517–2531 *in* Proc. of 3rd int. conf. on Forest fire research/14th Conference on fire and forest meteorology, Vol. I, Viegas, D.X. (ed.). Univ. Coimbra, Coimbra, Portugal.

SCOTT, J.H. 1998b. Fuel reduction in residential and scenic forests: A comparison of three treatments in a western Montana ponderosa pine stand. USDA For. Serv. Res. Pap. RMRS-RP-5. 19 p.

SCOTT, J.H., AND E.D. REINHARDT. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA For. Serv. Res. Pap. RMRS-RP-29. 59 p.

SIMARD, A.J. 1968. The moisture content of forest fuels—1. A review of the basic concepts. Can. Dep. For. Rural Develop. Inf. Rep. FF-X-14. 47 p.

STEPHENS, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed conifer forests. For. Ecol. Manage. 105:21–35.

STOCKS, B.J. 1987. Fire behavior in immature jack pine. Can. J. For. Res. 17:80–86.

STOCKS, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res. 19:783–790.

STOCKS, B.J., M.E. ALEXANDER, B.M. WOTTON, C.N. STEFNER, M.D. FLANNIGAN, S.W. TAYLOR, N. LAVOIE, J.A. MASON, G.R. HARTLEY, M.E. MAFFEY, G.N. DALRYMPLE, T.W. BLAKE, M.G. CRUZ, AND R.A. LANOVILLE. 2004. Crown fire behavior in a northern jack-pine/black spruce forests. Can. J. For. Res. 34:1548–1560.

STOCKS, B.J., AND G.R. HARTLEY. 1995. Fire behavior in three jack pine fuel complexes. Can. For. Serv., Great Lakes For. Cent., Sault Ste. Marie, ON. Poster with text.

SULLIVAN, A.L., AND I.K. KNIGHT. 2001. Estimating error in wind speed measurements for experimental fires. Can. J. For. Res. 31:401–409.

THOMAS, P.H. 1964. The effect of wind on plumes from a line heat source. Dep. Sci. Indust. Res. and Fire Off. Comm., Joint Fire Res. Organ., Fire Res. Stn., Borehamwood, England. Fire Res. Note No. 572. 36 p.

TURNER, J.A., AND B.D. LAWSON. 1978. Weather in the Canadian Forest Fire Danger Rating System: A user guide to national standards and practices. Can. For. Serv. Inf. Rep. BC-X-177. 40 p.

USDA FOREST SERVICE. 1980. Report on the national fire behavior research conference, March 18–20, 1980, Boise, ID. USDA For. Serv., For. Fire Atmos. Sci. Res., Washington, DC. 75 p.

VAN LOON, A.P., AND L.A. LOVE. 1973. A prescribed burning experiment in young slash pine. For. Comm. N. S. W. Res. Note 25. 53 p.

VAN WAGNER, C.E. 1964. History of a small crown fire. For. Chron. 40:202–205; 208–209.

VAN WAGNER, C.E. 1967a. Flammability of Christmas trees. Rev. Ed. Can. Dep. For. Rural Develop. Publ. 1034. 27 p.

VAN WAGNER, C.E. 1967b. Seasonal variation in moisture content of eastern Canadian tree foliage and possible effect on crown fires. Can. Dep. For. Rural Devleop. Publ. 1204. 15 p.

VAN WAGNER, C.E. 1968. Fire behaviour mechanisms in a red pine plantation: Field and laboratory evidence. Can. Dep. For. Rural Develop. Publ. 1229. 30 p.

VAN WAGNER, C.E. 1971. Two solitudes in forest fire research. Can. For. Serv. Inf. Rep. PS-X-29. 7 p.

VAN WAGNER, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. 2:34–39.

VAN WAGNER, C.E. 1975. Convection temperatures above low intensity forest fires. Can. For. Serv. Bi-mon. Res. Notes 31:21–26.

VAN WAGNER, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23–34.

VAN WAGNER, C.E. 1985. Fire behavior modeling—How to blend art and science. P. 3–5 *in* Proc. of the eighth conference on Fire and forest meteorology, Donoghue, L.R., and R.E. Martin (eds.). Soc. Am. For., Bethesda, MD. SAF Publ. 85-04.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35. 37 p.

VAN WAGNER, C.E. 1989. Prediction of crown fire behavior in conifer stands. P. 207–212 *in* Proc. of the 10th conference on Fire and forest meteorology. MacIver, D.C., H. Auld, and R. Whitewood (eds.). For. Can. and Environ. Can., Ottawa, ON, Canada.

VAN WAGNER, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Can. J. For. Res. 23:442–449.

VAN WAGTENDONK, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. P. 1155–1165 *in* Sierra Nevada ecosystem project: Final report to congress, Vol. II: Assessments and scientific basis for management options. Univ. California, Cent. Water Wild. Resour., Davis, CA. Rep. No. 37.

VANCLAY, J.K., AND J.P. SKOVSGAARD. 1997. Evaluating forest growth models. Ecol. Model. 98:1–12.

VIEGAS, D.X., M.T. VIEGAS, AND A. FERREIRA. 1992. Moisture content of fine forest fuels and fire occurrence in central Portugal. Int. J. Wild. Fire 2:69–86.

WALKER, J.D., AND B.J. STOCKS. 1975. The fuel complex of mature and immature jack pine stands in Ontario. Can. For. Serv. Inf. Rep. O-X-229. 19 p.

WALKER, S.H., AND D.B. DUNCAN. 1967. Estimation of the probability of an event as a function of several independent variables. Biometrika 54:167–179.

WEBER, M.G., M. HUMMEL, AND C.E. VAN WAGNER. 1987. Selected parameters of fire behavior and *Pinus banksiana* Lamb. regeneration in eastern Ontario. For. Chron. 63:340–346.

WEISE, D.R., R.A. HARTFORD, AND L. MAHAFFEY. 1998. Assessing live fuel moisture for fire management applications. P. 49–55 *in* Tall Timbers Fire Ecol. Conf. Proc. 20. Fire in ecosystem management: Shifting the paradigm from suppression to prescription, Pruden, T.L., and L.A. Brennan (eds.). Tall Timbers Res. Stn., Tallahassee, FL.

WILLIAMSON, N.M., AND J.K. AGEE. 2002. Heat content variation of interior Pacific Northwest conifer foliage. Int. J. Wild. Fire 11:91–94.

Wilson, R.A. Jr. 1982. A reexamination of fire spread in free-burning porous fuel beds. USDA For. Ser. Res. Pap. INT-289. 28 p.

Wilson, R.A. Jr. 1987. A theoretical basis for modeling probability distributions of fire behavior. USDA For. Serv. Res. Pap. INT-382. 11 p.

Wilson, R.A. Jr. 1990. Reexamination of Rothermel's fire spread equations in no-wind and no-slope conditions. USDA For. Ser. Res. Pap. INT-434. 13 p.

Xanthopoulos, G. 1990. Development of a wildland crown fire initiation model. Ph.D. dissertation, Univ. Montana, Missoula, MT. 152 p.

Xanthopoulos, G., and R.H. Wakimoto. 1993. A time to ignition—Temperature–moisture relationship for branches of three western conifers. Can. J. For. Res. 23:253–258.

Yih, C.S. 1953. Free convection due to boundary sources. P. 117 –133 *in* Proc. of the first symposium on the use of Models in geophysics, Fluid models in geophysics. Long, R.R. (ed.). US Govt. Print. Off., Washington, DC.

Yih, C.S. 1969. Fluid mechanics: A concise introduction to the theory. McGraw-Hill, New York. 622 p.

Zeide, B. 2002. Sharing data. For. Chron. 78:152–153.