CFIS:
A software tool for simulating crown fire initiation and spread

M.E. Alexander
Forest Engineering Research Institute of Canada - Western Division, Wildland Fire Operations Research Group, 1176 Swizter Drive, Hinton, AB, Canada T7V 1V3
Present address: Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB, Canada T6H 3S5, malexand@nrcan.gc.ca

M.G. Cruz
Associação para o Desenvolvimento da Aerodinâmica Industrial, Apartado 10131, 3031-601 Coimbra, Portugal
Present address: Ensis Bushfire Research, Ensis – Forest Biosecurity and Protection, CSIRO, PO Box E4008, Kingston, ACT, Australia 2604 Miguel.Cruz@ensisjv.com

A.M.G. Lopes
Department of Mechanical Engineering, Faculty of Science and Technology, University of Coimbra, 3030-100 Coimbra, Portugal, antonio.gameiro@dem.uc.pt

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Abstract: CFIS – which stands for *Crown Fire Initiation and Spread* -- is a software tool or system incorporating several recently developed models designed to simulate crown fire behavior. The main outputs of CFIS are: (1) the likelihood of crown fire initiation or occurrence; (2) the type of crown fire (active vs. passive) and its rate of spread; and (3) the minimum spotting distance required to increase a fire's overall forward rate of spread. The onset of crowning can be predicted through two distinct approaches. One approach relies on the knowledge of canopy base height and certain components of the Canadian Forest Fire Weather Index System and/or the 10-m open wind speed. The other approach requires the 10-m open wind, the estimated fine fuel moisture, fuel strata gap (or canopy base height), and an estimate of surface fuel consumption as inputs. Required inputs to predict crown fire rate of spread are 10-m open wind speed, estimated fine fuel moisture, and canopy bulk density. The minimum spotting distance to affect overall crown fire rate of spread, which assumes a point ignition and subsequent fire acceleration to an equilibrium rate of spread, requires the predicted crown fire spread rate and an ignition delay as inputs. The primary models incorporated into CFIS have been evaluated against experimental and wild fire observations with good results. CFIS has applicability as a decision support aid in a wide variety of fire management activities ranging from near-real time prediction of fire behavior to analyzing the impacts of fuel treatments on potential crown fire behavior.

Keywords: Canadian Forest Fire Weather Index System, crown fire behavior, crown fire occurrence, crowning, fire behavior, fire behavior prediction, fire modelling, rate of fire spread, spotting.

1. Introduction

Kerr *et al.* (1971) considered that "In the foreseeable future there is little prospect of predicting the behavior of a fast spreading crown fire in timber over any extended period of time". Much progress has been made in past 35 years or so in developing mathematical models to predict the onset and propagation of crown fires in conifer forests beginning with Van Wagner's (1977) theories. Nevertheless, a complete understanding of the crown fire phenomena remains a continuing goal for the wildland fire research community.

Rothermel (1972) acknowledged that his model for predicting surface fire rate of spread was "not applicable to crown fires" because the "nature and mechanisms of heat transfer" were quite different between these two modes of fire spread.. However, as a result of the crown fire behavior observed during the 1988 Yellowstone fires, Rothermel (1991) developed a simple crown fire rate of spread model based on an empirical correlation derived between his surface fire model and a small set of wildfire observations (n = 8). Van Wagner's (1977, 1993) crown fire theories coupled with Rothermel's (1991) crown fire spread model are presently the basis for predicting crown fire behavior in all of the computerized fire behavior prediction systems presently used in the U.S.

The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992; Taylor *et al*., 1997) represents the culmination of nearly 30 years of experimental burning in major Canadian fuel types coupled with monitoring and documentation of numerous high-intensity wildfires. The FBP System output includes the identification of intermittent and continuous crowning in those fuel types subject to such phenomena as well as the spread rate and intensity. The FBP System does rely on Van Wagner's (1977) criteria for crown fire initiation.

Cruz *et al*. (2003b, 2004, 2005) have recently developed a suite of empirically-based models for predicting the onset and spread rate of crown fires (Figure 1). Cruz *et al.* (2006) has at this conference reported on the development and evaluation of a new semi-physical model for predicting the initiation of crown fires which shows promise for field application. One of the objectives of the International Crown Fire Modelling Experiment (ICFME) (Stocks, Alexander and Lanoville, 2005) was the testing of a physically-based model (Albini 1996) for predicting crown fire rate of spread developed by the late Dr. Frank A. Albini. While his model accurately predicted the relative response of fire spread rate to fuel and environment variables, it overpredicted the magnitude of the spread rates observed on the ICFME crown fires (Butler *et al.*, 2004). As a result, there still appears to be a need for empirically-based models to predict crown fire behavior.

In 2005, the Wildland Fire Operations Research Group of the Forest Engineering Research Institute of Canada (FERIC) in collaboration with the Centre for Forest Fire Studies of the Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI) in Coimbra, Portugal (ADAI is a private non-profit research organization linked to the Department of Mechanical Engineering at the University of Coimbra), developed a user-oriented crown fire modeling tool suitable for use in fire management operations/planning and in fire research studies. This software tool (programmed in visual basic by A.M.G. Lopes) or system is called *Crown Fire Initiation and Spread* or CFIS for short (Figure 2). A copy of the software is available by contacting the authors or by downloading from the ADAI website (http://www2.dem.uc.pt/antonio.gameiro/ficheiros/CFIS.exe). The purpose of this paper is to provide an overview of the models comprising the CFIS.

2. Component Models

The CFIS is comprised of a group of mathematical models. These involve: (1) four separate logistic models for predicting the probability of crown fire initiation based largely on components of the Canadian Forest Fire Weather Index (FWI) System; (2) a single, more generalized logistic model for predicting the probability of crown fire occurrence; (3) separate models for predicting passive and active crown fire rate of spread; and (4) the formulation of a simple theoretical model to estimate the minimum spotting distance

required to increase a fire's overall forward rate of spread. The first three sets of models are based on outdoor experimental fires carried out principally in boreal forest fuel types as previously published on by the Canadian Forest Service fire research group (Stocks, Alexander and Lanoville, 2004; Stocks, Alexander, Wotton *et al.*, 2004). These experimental fires form part of the database used in the development of the FBP System.

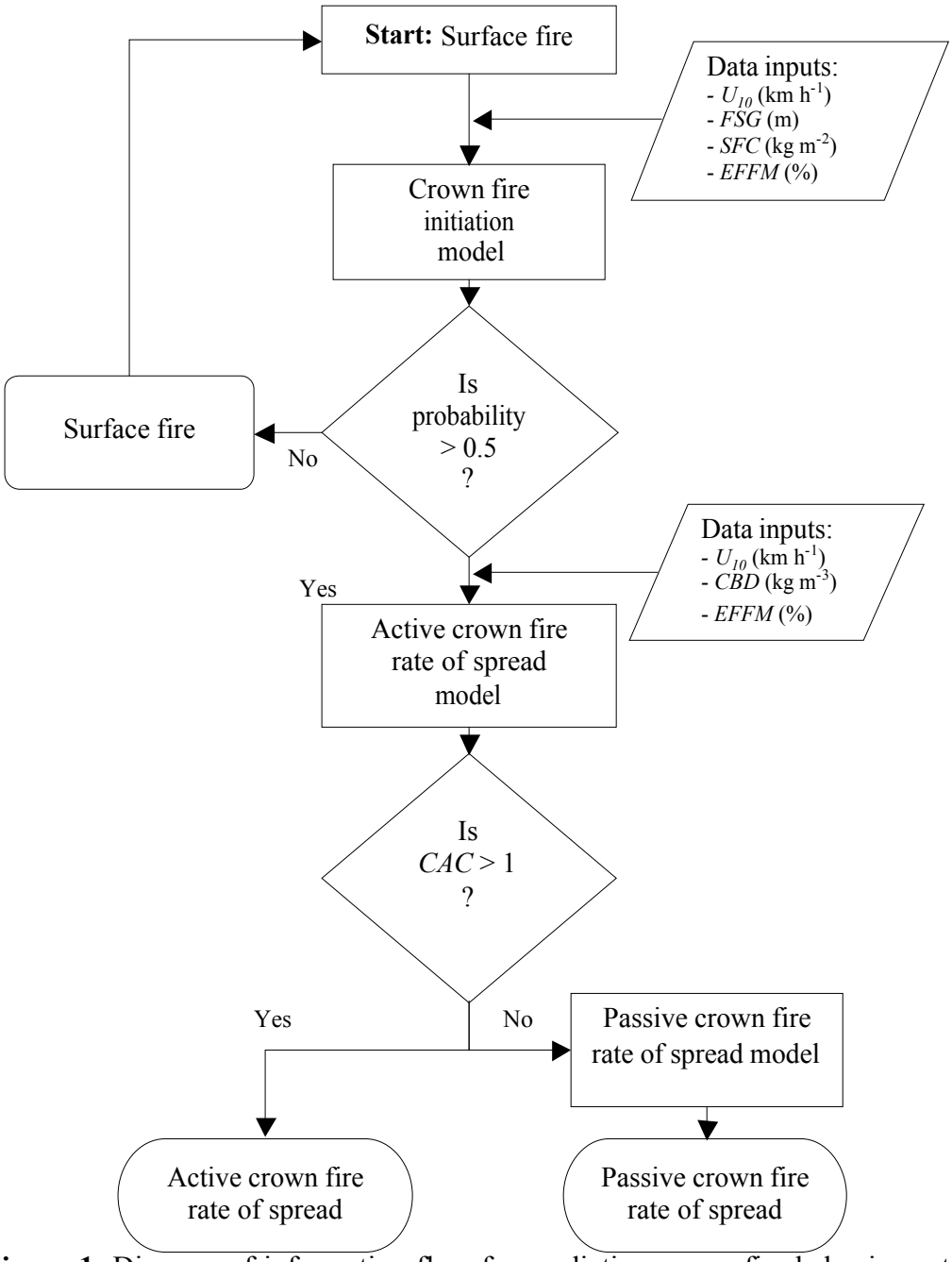

Figure 1. Diagram of information flow for predicting crown fire behavior potential based on the crown fire occurrence and crown fire rate of spread models developed by Cruz *et al.* (2004, 2005); *CAC* = criteria for active crowning. Model inputs: U_{10} – 10-m open wind speed; *CBH* – canopy base height; *SFC* – surface fuel consumption; *EFFM* – estimated fine fuel moisture; and *CBD* – canopy bulk density. Alternatively, the Cruz *et al.* (2003b) or Cruz *et al.* (2006) crown fire initiation models could be used for determining the onset of crowning. All of the inputs are readily amenable to measurement and/or estimation.

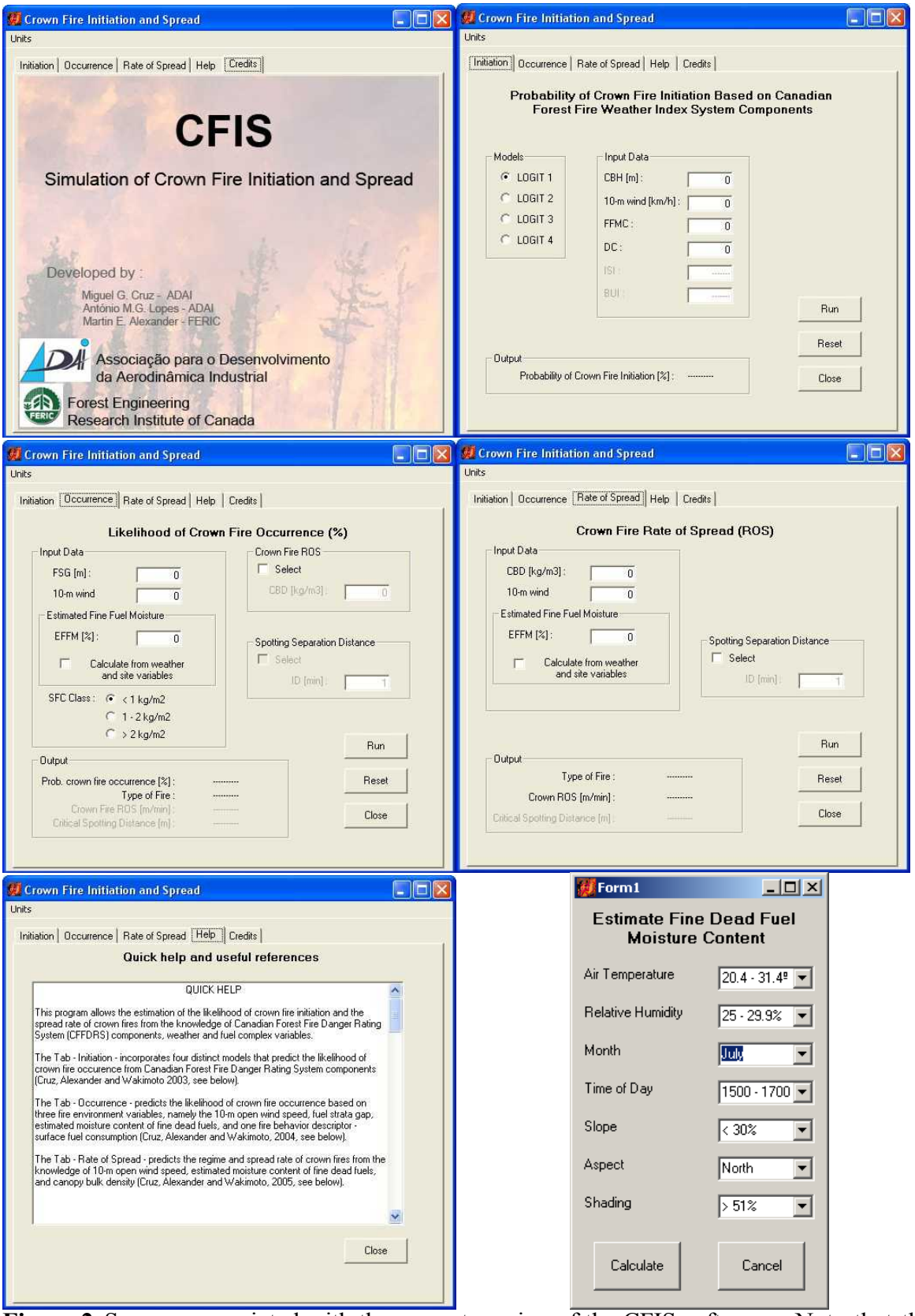

Figure 2. Screens associated with the current version of the CFIS software. Note that the option to operate in both English and SI units exist (select *Units*) and that a *Help* section is available.

2.1 *Initiation – Probability of Crown Fire Initiation Based on Canadian Forest Fire Weather Index System Components*

The initiation of crown fires in conifer forest stands was modeled through logistic regression analysis using canopy base height and selected components of the FWI System (Van Wagner, 1987) as independent variables. Four models were built with decreasing input needs (Table 1) and performance. Four of the six standard components of the FWI System were used in the logistic models along with canopy base height (*CBH*) and 10-m open wind speed (U_{10}). This included two fuel moisture codes – the Fine Fuel Moisture Code (FFMC) and Drought Code (DC) and two fire behavior indexes – the Initial Spread Index (ISI) and the Buildup Index (BUI) which are defined as follows:

- FFMC – a numerical rating of the moisture content of litter and other cured fine fuels.
- DC – a numerical rating of the average moisture content of deep, compacted organic layers.
- ISI – a numerical rating of the effect of wind and FFMC on rate of spread without the influence of variable quantities of fuel.
- BUI – is a numerical rating of the total amount of fuel available for combustion that combines the DC and the Duff Moisture Code (DMC) which is a numerical rating of the average moisture content of loosely compacted organic layers of moderate depth.

Table 1. Summary of inputs involved in the Cruz *et al.* (2003b) logistic crown fire initiation models.

Logistic			**Inputs**			
model	*CBH*	FFMC	DC	ISI	BUI	U_{10}
1	X	X	X			X
2	X		X	X		
3	X			X	X	
4			X	X		

The *CBH* represents the vertical distance between the ground surface and lower portion of the live canopy fuel layer (i.e., needle foliage in conifer forest stands). It is worth noting that the mean *CBH* associated with logistic model 4 is 3.9 m. U_{10} is the wind speed measured at a height of 10 m above open ground as per the World Meteorological Organization standard. Wind speeds measured at 6.1 m or 20 ft as is the practice in U.S. fire management (Finklin and Fischer, 1990) should be increased by 15% to approximate a U_{10} value (Turner and Lawson, 1978).

Graphical representations of logistic models 2 to 4 are presented in Figures 3-4. The complexity of model 1 (i.e., four inputs) unfortunately does not easily lend itself to the possibility of this same sort of presentation. Model output is expressed as the probability of initiating a crown fire between 0 and 100% for the stated environmental conditions as defined by the inputs. The probabilities are estimates of likelihood that allow uncertainty to be quantified. A threshold probability of 50% is presently assumed to separate a surface fire (<50%) from a crown fire (≥50%). The horizontal dashed line in Figures 3-4 represents this threshold value for the onset of crowning. Experience with the CFIS may eventually suggest otherwise. Polack (2003) has suggested the following general interpretative guidelines with respect to probabilities:

- <1% - extremely unlikely
- 1-10% - little chance or very unlikely
- 10-33% - some chance or unlikely
- 33-66% - medium likelihood
- 66-90% - likely or probable
- 90-99% - very likely or very probably
- >99% - virtual certainty.

The results of a limited evaluation involving two independent experimental fire data sets for distinctly different fuel complexes were encouraging (see Cruz *et al.*, 2003b, p. 981). This involved the Porter Lake experimental burning project (Alexander *et al.*, 1991) and the ICFME crown fires (Stocks, Alexander, Wotton *et al.*, 2004).

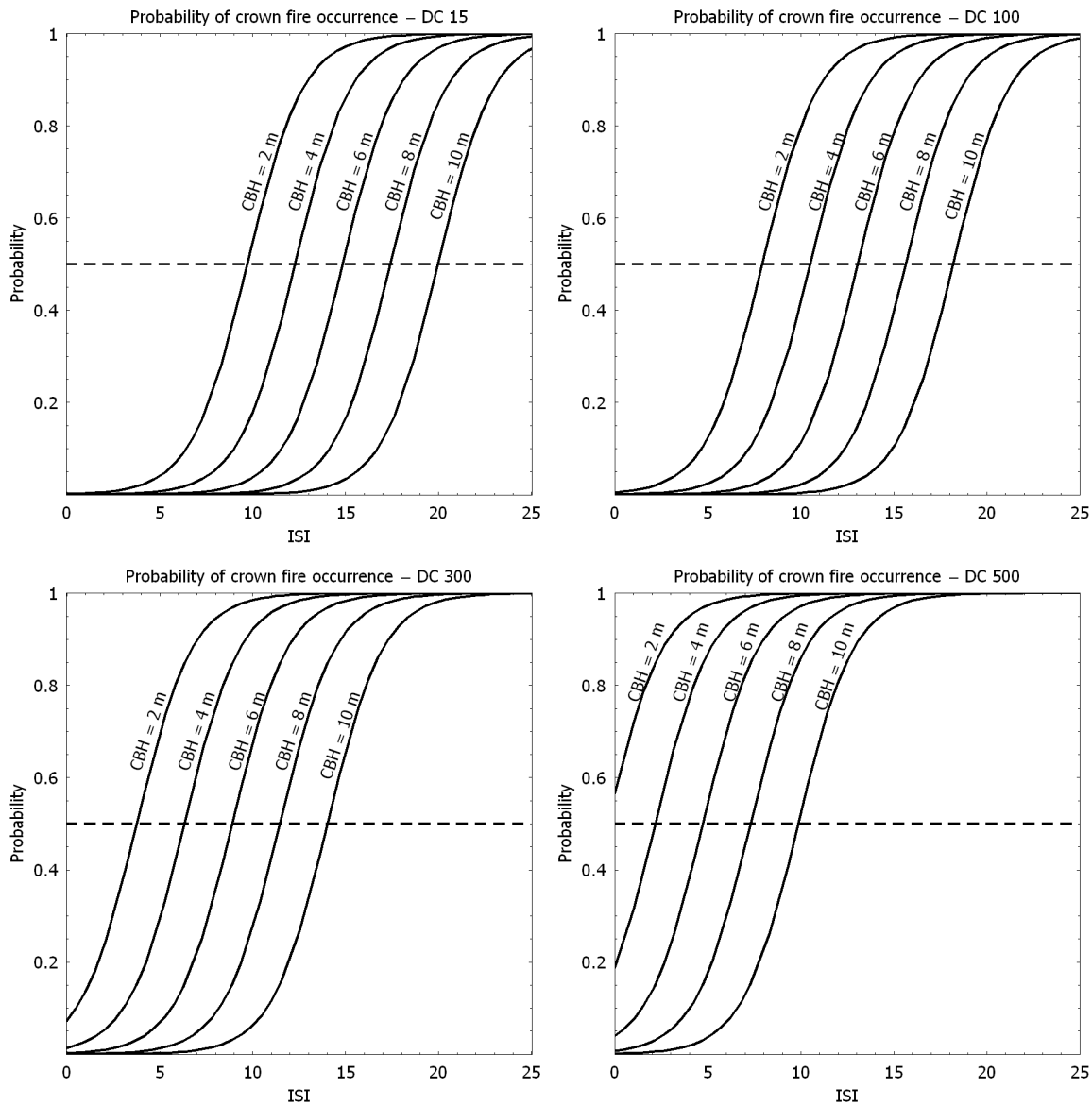

Figure 3. Graphical representation of the Cruz *et al.* (2003b) logistic model 2 for predicting the probability of crown fire initiation on the basis of the canopy base height (*CBH*), Drought Code (DC), and Initial Spread Index (ISI).

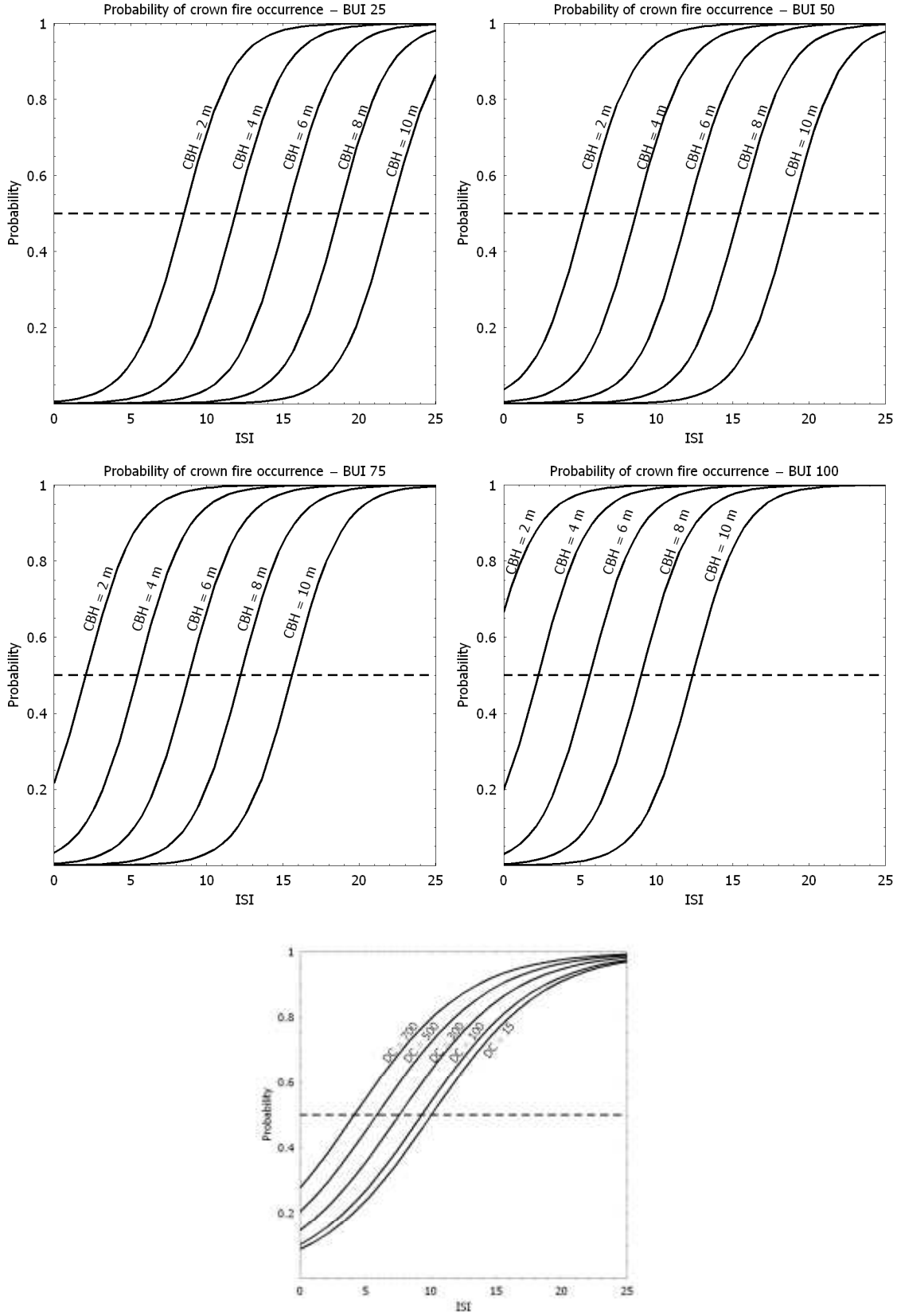

Figure 4. Graphical representation of the Cruz *et al.* (2003b) logistic models 3 and 4 for predicting the probability of crown fire initiation on the basis of the canopy base height (*CBH*), Initial Spread Index (ISI), Buildup Index (BUI) and Drought Code (DC)

2.2 *Occurrence – Likelihood of Crown Fire Occurrence*

The model for predicting the likelihood of a crown fire occurrence in a conifer forest stand (Cruz *et al.*, 2004) is also a logistic regression equation. The crown fire occurrence model requires three fire environment inputs (Figure 1) -- U_{10}, fuel strata gap (*FSG*), and the estimated fine fuel moisture (*EFFM*), plus one fire behavior descriptor – namely an estimate of the likely surface fuel consumption (*SFC*). A graphical representation of the Cruz *et al.* (2004) crown fire occurrence model is presented in Figure 5.

The *FSG* represents the vertical distance between the top of the surface fuelbed and the lower limit of the aerial or crown fuel layer constituted by ladder and canopy fuels capable of sustaining vertical fire propagation. In some conifer forest stands, the *FSG* could be equivalent to the mean live canopy base height or *CBH*. The *EFFM*, representing the moisture content of fine, dead surface fuels, must be computed on the basis of the air temperature, relative humidity, time of year (i.e., month) and day, and degree of shading (based on cloud cover and canopy coverage) as per the table look-up procedure in Rothermel (1983). Software is now available for making computations (Andrews *et al.*, 2005). A similar program has been included in the CFIS (Figure 2) which is formatted for the Northern Hemisphere. To use this part of the program in the Southern Hemisphere, adjust the months accordingly (e.g., June = December, July = January, August = February, etc.). The *SFC* represents the amount of forest floor material, dead-down woody debris and understory vegetation consumed by the surface fire. Users are only required to select one of three *SFC* classes: <1.0, 1.0-2.0 or >2.0 kg/m^2.

Like the Cruz *et al.* (2003b) crown fire initiation models, the output of the Cruz *et al.* (2004) crown fire occurrence model is also expressed on a probabilistic basis and a 50% probability is also assumed to represent the threshold for crowning. A comparison test against the Porter Lake and ICFME experimental fires also produced some encouraging results (see Cruz et al., 2004, p. 648).

2.3 *Rate of Spread – Passive and Active Crown Fire Rate of Spread*

Passive and active crown fire rate of spread are modeled separately. Passive crown fire rate of spread was modeled through a correction factor based on a criterion for active crowning (*CAC*) related to the canopy bulk density (*CBD*) as suggested by Van Wagner (1977):

[1] $$CAC = \frac{CROS_A}{3/CBD}$$

where $CROS_A$ is the predicted active crown fire rate of spread (m/min). The *CBD* represents the available fuel weight per unit volume (kg/m^3) in the canopy fuel layer. In practical terms the *CBD* is a function of the mass of needle foliage and small branchwood divided by the depth of the crown fuel layer which is in turn the difference between the stand height and the *CBH* (Cruz *et al.*, 2003a).

The model for predicting active crown fire rate of spread in conifer forest stands is represented by a non-linear regression equation requiring three fire environment inputs – U_{10}, *EFFM* and *CBD*. A graphical representation of both the passive and active crown fire rate of spread models is presented in Figure 6. 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). It is worth noting that these models 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 crown bulk density (Figure 7). The notion of a critical *CBD* threshold value of ~0.1 kg/m^3 for active crowning (Agee, 1996) is quite evident in this illustration.

The active crown fire rate of spread model has been evaluated against the Porter Lake and ICFME experimental fires, again with good results (see Cruz et al. 2005, pp. 1634-1635). Alexander and Cruz (2006) have also tested the active crown fire rate of spread model against 57 wildfire observations gleaned from Canadian (n = 43) and U.S. (n = 14) case studies (Figure 8).

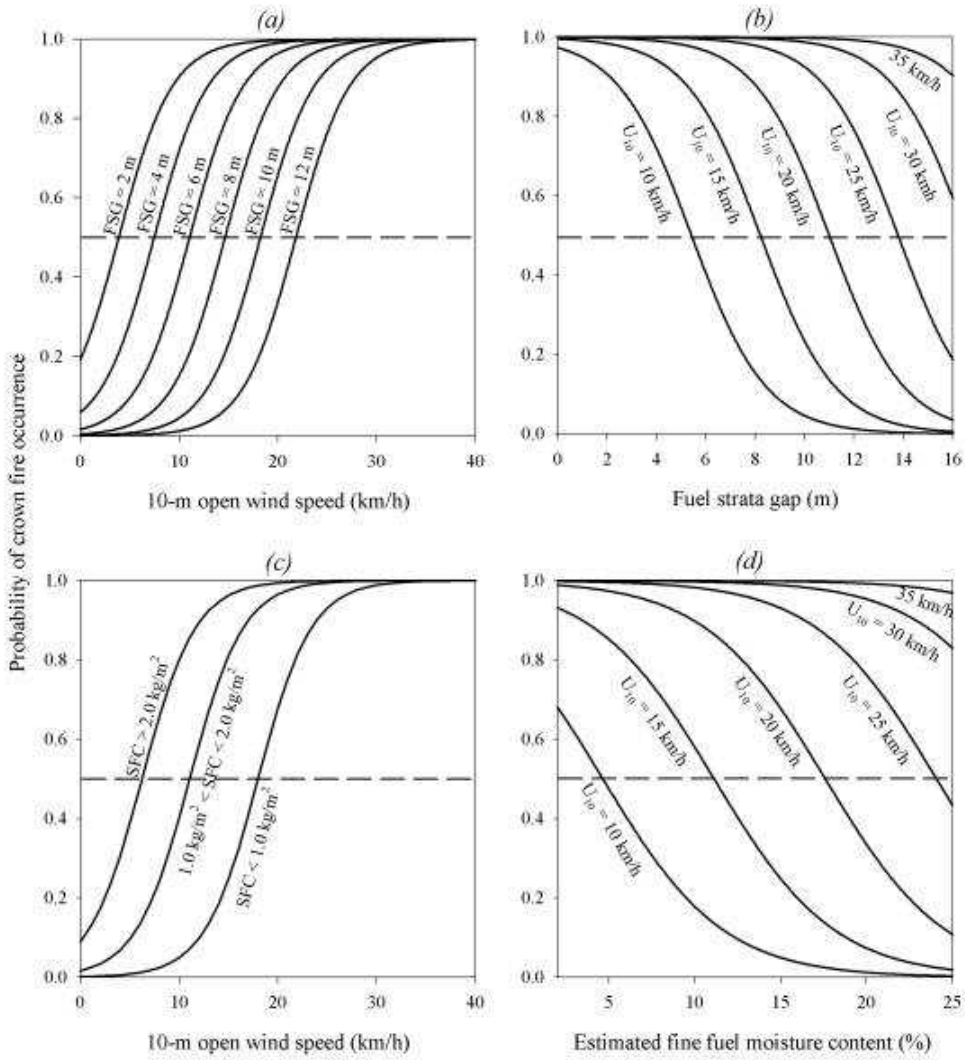

Figure 5. Graphical comparison of the effect of the various input variables in the Cruz *et al.* (2004) crown fire occurrence model (U_{10} = 10-m open wind speed; *FSG* = fuel strata gap; *SFC* = surface fuel consumption; and *EFFM* = estimated fine fuel moisture): (a) effect of U_{10} under variable *FSG;* (b) effect of *FSG* under variable $U_{10;}$ (c) effect of *SFC* under variable $U_{10;}$ and (d) effect of *EFFM* under variable $U_{10.}$ Constant conditions in the above graphs are: *FSG* = 6 m; 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.

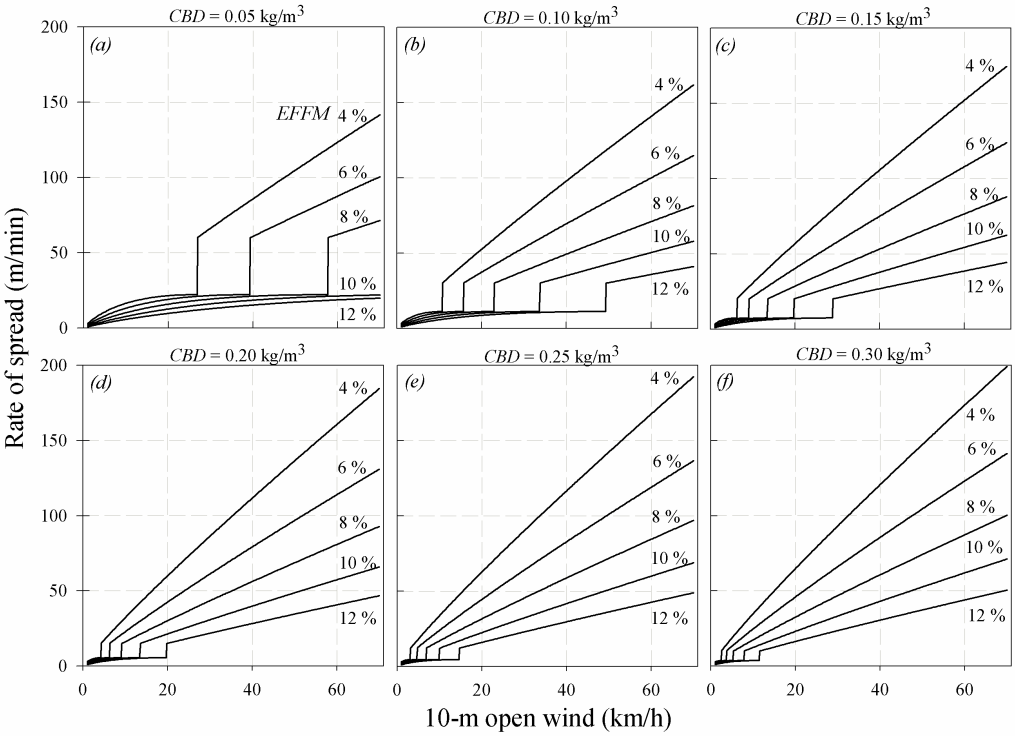

Figure 6. Crown fire rate of spread as a function of wind speed and estimated fine fuel moisture (*EFFM*) for various levels of canopy bulk density (*CBD*) based the *Cruz et al.* (2005) passive and active crown fire rate of spread models.

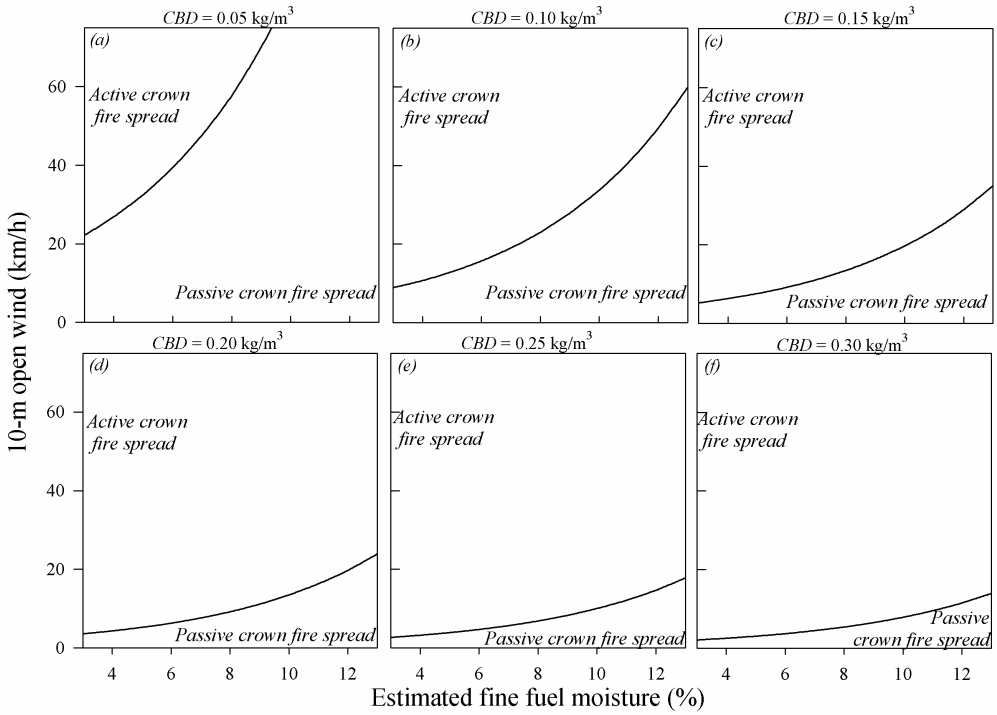

Figure 7. Graphical representation of the threshold conditions for passive versus active crown fire spread in terms of fuel moisture and wind speed for various levels of canopy bulk density (*CBD*) according to the Cruz *et al.* (2005) active crown fire rate of spread model and Van Wagner's (1977) criterion for active crowning.

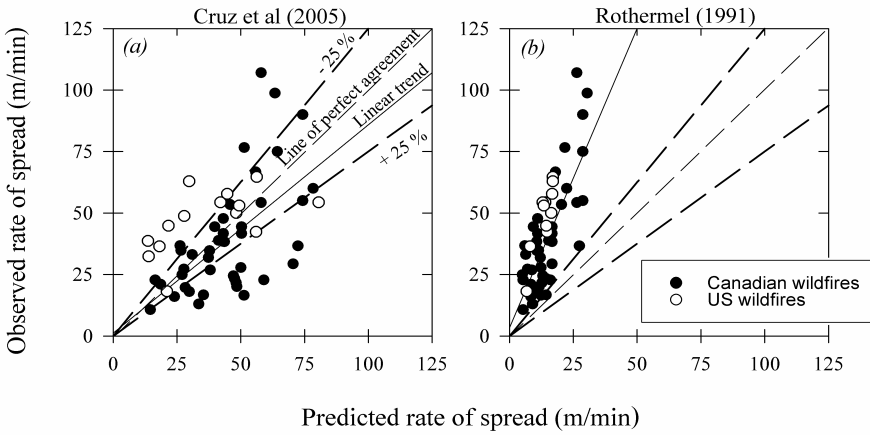

Figure 8. Observed rates of spread of Canadian and American wildfires versus active crown fire rate of spread predictions based on the Cruz *et al.* (2005) and Rothermel (1991) models (adapted from Alexander and Cruz, 2006).

2.4 *Spotting Separation Distance*

In most high-intensity wildfires that involve crowning, spot fires originating out ahead of the main advancing flame front are typically overrun and thus incorporated into the larger fire perimeter before they are able to develop and spread independently, or otherwise be influenced by the main fire (e.g., in-draft winds). The spotting separation distance in the CFIS represents the critical distance required for a newly developed spot fire to avoid being overtaken by the main flame front of a spreading fire as a function of the fire's forward rate of spread and an "ignition delay" (i.e., the elapsed time between a firebrand alighting downwind of the main fire front, the subsequent ignition followed by the onset of fire spread). This simplistic calculation described in Alexander and Cruz (2006) assumes an acceleration period or buildup time following a point source ignition and no in-draft winds. A graphical representation of the model is presented in Figure 9.

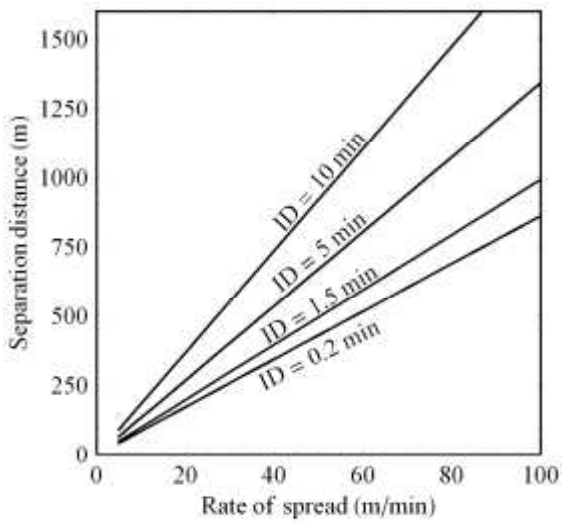

Figure 9. Graphical representation of minimum separation distance required for a newly ignited spot fire to avoid being overrun by the main advancing fire front under variable forward rate of spread and ignition delay (ID) according to Alexander and Cruz (2006).

3.0 Concluding Remarks

The CFIS is deemed suitable for assessing crowning potential of wildfires on an operational basis (Alexander and Thomas, 2004) and in fire research studies. At this point in time though, we do not know if the CFIS is superior to the FBP System in predicting the initiation and spread of crown fires. However, the CFIS does allow one to evaluate the impacts of proposed fuel treatments on potential crown fire behavior based on the ability to manipulate three characteristics of a fuel complex (i.e., available surface fuel load, *CBH* and *CBD*) by silvicultural and other vegetation management techniques. The FBP System with its rigid fuel types didn't readily allow for this degree of flexibility. Case study knowledge (Alexander and Thomas, 2003a, 2003b, 2006), coupled with experienced judgment and the kind of fire behavior modeling offered by the CFIS is considered to be the most effective way of appraising fire potential with respect to devising fuel management strategies (Brown, 1978).

In closing, it bears repeating that the models comprising CFIS are considered most valid for free-burning fires that have reached a pseudo steady-state, burning in live, boreal or boreal-like conifer forests (i.e., not applicable to insect-killed stands). Level terrain is assumed as the CFIS does not presently consider the mechanical effects of slope steepness on crown fire behavior.

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