Development and evaluation of a semi-physical crown fire initiation model

Miguel G. Cruz
Ensis Bushfire Research, Ensis - Forest Biosecurity and Protection, CSIRO, PO Box E4008, Kingston, ACT 2604, Australia, Miguel.Cruz@ensisjv.com
Bushfire Cooperative Research Centre, Melbourne, Victoria, Australia

Bret W. Butler
USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 US W Highway 10, Missoula, MT, USA 59808-9361, bwbutler@fs.fed.us

Martin E. Alexander
Canadian Forest Service, Northern Forestry Centre 5320-122 Street, Edmonton, AB, Canada T6H 3S5, malexand@nrcan.gc.ca

D.X. Viegas
Associação para o Desenvolvimento da Aerodinâmica Industrial, Apartado 10131, 3031 – 601 Coimbra, Portugal, Xavier.Viegas@dem.uc.pt

---

Abstract: A model was developed to predict the ignition of forest crown fuels above a surface fire based on heat transfer theory. The crown fuel ignition model (CFIM) integrates fluid dynamics and heat transfer principles with empirical formulations where our knowledge of the physical processes is still incomplete or unsatisfactory. The CFIM uses surface fire flame front properties to define the heat source, determines the buoyant plume dynamics and heat transfer (gain and losses) to the crown fuels. Fuel particle temperature increase is determined through an energy balance relating heat absorption to fuel particle temperature. The final CFIM output is the temperature of the crown fuel particles which upon reaching ignition temperature are assumed to ignite

The performance of the CFIM was evaluated through the analysis of its behaviour and comparison against other crown fire initiation models. Results indicate that the primary factors influencing crown fuel ignition are those determining the depth of the surface fire burning zone and the vertical distance between the ground/surface fuel strata and the lower boundary of the crown fuel layer. A comparative analysis of the relative role of surface fuelbed structure and wind and fuel moisture conditions on the likelihood of crowning did not identify any superior role of these variables over surface fuelbed structure, or vice-versa, with respect to inducing crowning. The results suggest that the relative role of these variables are not independent and that their effect varies with the fuel complex characteristics and burning conditions. The simulations indicate that some fuel types showed higher sensitivity to changes in burning conditions, implying a dominance of the role of climate/weather variables, while for other fuel types, changes in the severity of burning conditions on the likelihood of crowning were inconsequential. Comparison of CFIM predictions against predictions from empirical based models gave encouraging results relative to the validity of the model system.

Keywords: crown fire, crowning, fire behaviour, fire behaviour prediction, fire modelling, heat transfer.

1. Introduction

Within a given forest stand, the variation in weather conditions and fuel complex structure, and interaction between fire phenomena and local weather leads to a range of fire behaviour covering several orders of magnitude. The onset of crowning -- i.e., the transition from a surface fire into a fire involving all strata of the fuel complex -- can induce abrupt changes in fire behaviour (Burrows *et al.*, 1988; Taylor *et al.*, 2004). Once crowning has commenced, the resulting "wall of flame" is fully exposed to the prevailing wind field leading to increased radiation, turbulence and spotting activity which generally precludes any direct suppression action. Hardy and Franks (1963), for example, found over a nine-year period (1950-58) in Alaska that 47% of the Class E fires (i.e., greater than 300 acres or ~120 ha) were crowning at the time of initial attack. They noted that "Records indicate that if a fire is not controlled by the time it reaches 300 acres in size, it may not be controlled until it reaches several hundred or even several thousand acres". They go on to say that "If fires could be reached while still small and before they start to run, the total control effort would be considerably lessen … That goal can never be completely reached, as some fires may begin running and spotting almost immediately after they start …". As Douglas (1964) notes, "Action to attack the heads of crown fires can only be justified where it is possible to take advantage of a reduction in quantity or changes in the type of fuel. Otherwise, it is better to do nothing more than watch it from a safe distance and use all available equipment on the fire flanks".

Models describing the initiation of crown fires are an important component of fire behaviour prediction systems aimed at supporting fire management decision making (Cruz *et al.*, 2002, 2003). Furthermore, an understanding of the conditions and processes that determine the initiation of crown fires has direct applicability in devising fuel management prescriptions that preclude the propensity for crown fire development (Cruz *et al.*, 2005)

The objective of this paper is to describe the development (Cruz, Butler, Alexander, Forthofer and Wakimoto, 2006) and evaluation (Cruz, Butler and Alexander, 2006) of a model aimed at predicting the temperature and ignition of canopy fuels. The structure of the model is such that it should have application to a diverse array of fuel complexes and also allow for the understanding of the effect of surface fuelbed characteristics on the energy transfer processes determining the ignition of crown fuels. Finally, we describe the integration of the model within a model system aimed at the prediction of fire behaviour in forest stands over a wide range in burning conditions from gentle surface fires to fully developed, active crown fires. See Appendix 1 for a list of symbols and their meaning.

2. Previous Approaches to Modelling Crown Fire Initiation in Brief

The empirical and semi-empirical approaches to the modelling of the onset of crowning have resulted in a number of models suitable for operational implementation (e.g., Van Wagner, 1977; Alexander, 1998; Cruz *et al.*, 2004). Van Wagner (1977), through a combination of physical theory and empirical observation, defined certain quantitative criteria to predict the onset of crowning. His analysis was based on plume theory developed by Yih (1953) that linked an idealized linear heat source with the maximum temperature attained at a certain height in the buoyant plume:

[1] $$\Delta T \propto \frac{I^{2/3}}{z}$$

Or solving for I:

[2] $I = (\Delta T \cdot z)^{1.5}$

where ΔT is the temperature increase above ambient conditions, I is intensity of a line heat source, and z is the height above ground in this case. This relationship, based on dimensional analysis, was rearranged by Van Wagner (1977) to allow for the determination of a critical surface fireline intensity I_o as per Byram (1959) needed to induce crown combustion, as a function of the canopy base height z, the heat required for ignition (as determined by the foliar moisture content, *FMC*, of the available canopy fuel), and a proportionality constant C, "best regarded as an empirical constant of complex dimensions" (Van Wagner, 1977):

[3] $I_0 = (C \cdot z \cdot (460 + 26FMC))^{1.5}$

The value of C was estimated by Van Wagner (1977) to be 0.01 based on a single experimental fire conducted in a red pine (*Pinus resinosa*) plantation stand (Alexander, 1998). Van Wagner's (1977) model is presently used in whole or in part for assessing crown fire initiation in several North American fire behaviour prediction systems (e.g., Forestry Canada Fire Danger Group, 1992; Scott and Reinhart, 2001; Finney, 2004).

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 based on flame and convection column temperature measurements of wind tunnel fires; and (2) predict the time to ignition for foliage of three different conifer species (Xanthopoulos and Wakimoto, 1993). These equations were coupled with the Rothermel (1972) surface fire spread model to produce a crown ignition score. Xanthopoulos (1990) acknowledged that his "… model has a number of deficiencies … the major one being a lack of extensive testing in real crown fires" but perhaps the major limitation of Xanthopoulos' (1990) model involves the scale effects and realism associated with the wind tunnel environment.

Following Weber's (1990) advice, Alexander (1998) developed a simple algorithm to predict the onset of crowning in Australian exotic pine plantations from a combination of physical insights and mathematical modeling coupled with relevant field and laboratory experiments. His model 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), and a surface fire's flame front residence time. Alexander's (1998) formulation thus considered the duration of heating by a surface fire and variable ambient conditions, which was not accounted for in Van Wagner's (1977) model. A proportionality constant was also used to characterize specific fuel complexes. The model was tested against independent documentation obtained from experimental fires, operational prescribed fires, and a detailed wildfire case study, with quite encouraging results

Cruz *et al.* (2004) modelled the likelihood of crown fire occurrence based on logistic regression analysis (as suggested by Alexander, 1998) applied to an experimental fire behaviour dataset. In contrast to the models developed by Van Wagner (1977), Xanthopoulos (1990) and Alexander (1998) that attempt to characterize and quantify the main processes involved in crown fire initiation, this logistic model does not directly incorporate any physical reasoning relative to the heat transfer processes taking place during a forest fire. Nevertheless, the analysis from the experimental fire dataset and model results provided qualitative information on the effects of several fire environment variables presumed to influence the onset of crowning. For example, foliar moisture content was not found to be a statistically significant variable determining the occurrence of crown fires.

For more in-depth discussions on the subject of crown fire initiation, readers are encouraged to consult the reviews contained in Alexander (1998), Cruz (1999, 2004) and Plucinski (2003).

3. Model Description

The description of the process of crown fire initiation using first principles requires an understanding of the combustion characteristics of a surface fire, the dissipation of heat within the sub-canopy space, heat transfer to the crown fuel particles and the energy requirements for crown fuel ignition. The idealization of the crown fuel ignition model (hereafter referred to as the CFIM) developed in this study considers a surface fire, spreading at a steady state, and describes the upward radiative and convective heat energy released. The model then determines heat transfer to the fuels at the base of the crown and the change in the surface temperature of these fuels (Figure 1). The surface fire front is characterized by its rate of spread, *ROS*, reaction time, τ_r, flame depth, D_F, flame height, H_F, flame temperature-time profile above the fuelbed, and the average gas temperature and vertical velocity at the tip of the flame. These characteristics define the initial conditions to solve the radiative heat transfer and buoyant plume models.

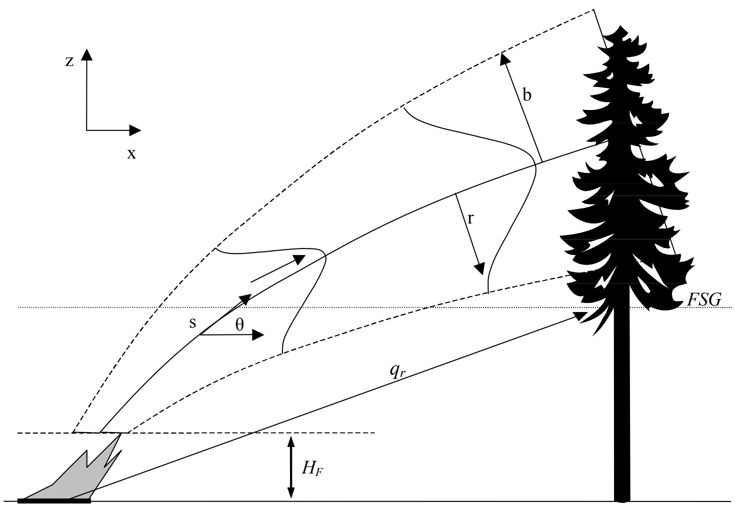

Figure 1. Schematic diagram of the buoyant plume and radiative heat source dimensions and location in the two-dimensional crown fuel ignition model developed by Cruz (2004).

The radiative energy transfer process considers the energy transfer between two flat surfaces: the surface fire idealized as a radiating plane and the base of the canopy fuel layer. The radiant heat flux leaving the radiating surface is given by integrating the radiative intensity, obtained from the Stefan-Boltzmann equation, over the flame surface. By taking into account the non-constant radiosity of the surface fire (Cruz Butler, Alexander, Forthofer and Wakimoto, 2006), the attenuation of the radiation within the sub-canopy space (Committee on Fire Research, 1961) and the view factor, the radiative transfer to the surface of the crown fuel particles can be computed:

[4] $$I_{12} = \int_{-\frac{L_p}{2}}^{\frac{L_p}{2}} \int_{D_x}^{D_x+D_F} \int_{-\frac{W_p}{2}}^{\frac{W_p}{2}} \int_{-\frac{W_F}{2}}^{\frac{W_F}{2}} \frac{\varepsilon \cdot \sigma_{SB} \cdot \left(T_F{}^4(x_F) - T_f{}^4\right) \cdot e^{-\alpha S} \cdot \left(\frac{z}{S}\right)^2}{\pi \cdot S^2} dy_F dy_p dx_F dx_p$$

with S defined as:

[5} $$S = \sqrt{\left(y_p - y_f\right)^2 + z^2 + \left(x_f - x_p\right)^2}$$

Davidson's (1986) model (see also Mercer and Weber, 1994) was used to describe the buoyant plume above the surface fire. This model is based on the integral approach in which a system of coupled ordinary differential equations were derived from the equations for the conservation of mass, momentum and energy. The equations for conservation of mass, s-momentum (along the plume centerline), r-momentum (normal to the plume centerline), temperature (by rearranging the mass and thermal energy equations) along the plume centerline and its trajectory in two dimensions form a system of six coupled ordinary differential equations that are solved simultaneously. The steady state solution does not consider the interaction of the fire generated buoyancy with the ambient cross flow. The required initial conditions are the initial plume half width, initial vertical velocity in the plume and initial plume temperature. The initial half width of the plume is assumed to equal half flame depth. The plume model only applies to the buoyant plume, and its base should correspond with the height where exothermic reactions due to oxidation of pyrolized fuels have ceased. This is assumed to coincide with what we perceive as the flame height, given by Albini's (1981) flame height model (see also Nelson and Adkins, 1986). The initial plume temperature is the flame tip temperature, assumed as 800 K (Draper point), the temperature at which red light first becomes visible.

The canopy fuel layer is assumed as a homogeneous layer of a certain depth composed of randomly distributed thermally thin cylindrical particles characterized by their surface area to volume ratio (σ), density (ρ_f), specific heat (c_f) and *FMC*. Fuel heating assumes that the net energy gained or lost by the fuel particle equates to its internal energy, and consequently its temperature. The two fuel variables of the crown fuels determining the increase in temperature are σ and *FMC*. The quantity σ determines the surface area available for heat transfer between the gaseous and the solid phase per fuel particle unit volume. The moisture content increases the energy required to increase fuel temperature due to the high specific heat and latent heat of vaporization of water. By integrating the three step heating model of Albini (1985) that includes the latent heat of the water present in the fuel and the specific heats of water and fuel as the fuel particle is taken from ambient temperature to ignition temperature, an average specific heat value (c*) can be calculated (Catchpole *et al.*, 2002):

[6] $$c^* \cdot \left(T_{ig} - T_a\right) = \left(c_f + MC \cdot c_w\right) \cdot \left(373 - T_a\right) + \left(MC \cdot La\right) + \left(c_f\right) \cdot \left(T_{ig} - 373\right)$$

This model assumes that moisture is continually being evaporated from ambient to ignition temperature and that all moisture must be driven out before ignition takes place. Based on a simplified heat balance equation the governing equation for heat transfer to a single fuel particle is defined as follows:

[7] $$\rho_f \cdot V \cdot c_f * \frac{dT_f}{dt} = h_c \cdot A_f \cdot \left(T_g - T_f\right) + I_{12} \cdot \frac{A_f}{2} - F_{23} \cdot A_f \cdot \sigma_{SB} \cdot \left(T_f^4 - T_a^4\right)$$

The convective heat transfer coefficient (h_c) was determined from the dimensionless Nusselt number, given by (Mendes-Lopes *et al*., 2002):

[8] $$N_u = 0.1417 \cdot R_e^{0.6053}$$

The differential equation for the temperature of a fuel particle can be integrated as the fire front approaches and passes the fuel particle location. By integrating Equation 7 over *dt* we obtain:

[9] $$\rho_f \cdot V \cdot c_f * \cdot T_f = \int_{x_0}^{\infty} h_c \cdot A_f \cdot \left(T_g - T_f\right) dt + \int_{x_0}^{\infty} I_{12} \cdot \frac{A_f}{2} dt - \int_{x_0}^{\infty} F_{23} \cdot A_f \cdot \sigma_{SB} \cdot \left(T_f^4 - T_a^4\right) dt$$

The model is implemented in a Cartesian coordinate system with origin (x = 0, y = 0) coinciding with the crown fuel particle location. The model represented by Equation 9 is iterated until ignition temperature (600 K) is attained or the back of the flaming front passes the fuel particle location.

The temperature of the fuel particle being subject to the impinging convective and radiative heat fluxes is the final model output. At ignition temperature it is presumed that piloted ignition of the fuel volatiles being released by the fuel particles occur, and fire propagates vertically into the crown. The sources of pilot ignition can be embers and firebrands carried in the buoyant plume, occasional flame flashes extending above the flame envelope, torching of understory vegetation (small trees and tall shrubs) and flame attachment and vertical spread on the lee side of tree boles (Alexander, 1998). In its present form the model does not consider the effect of lower ladder fuels and short range spotting in changing the geometry of the heat source and its power output.

Table 1 provides a summary of the models (and their sources) integrating the CFIM system. Current CFIM implementation relies on the estimation of the surface fire rate of spread given by Rothermel (1972) model, although other models can be used to describe the movement of surface fire front (e.g., Noble *et al*., 1980; Forestry Canada Fire Danger Group, 1992; Beck, 1995; Catchpole *et al*., 2002).

4. Model Evaluation

4.1 *Effect of Input Variables*

In order to understand the effect of individual input variables on model behaviour we analysed how variables determining the heat source, heat transfer and heat sink affect the final model output, crown fuel particle temperature. The variables influencing the heat source tested were 10-open wind speed (U_{10}), surface fuel available for flaming combustion (w_a) and moisture content of dead surface fuels (*MC*). The variables influencing the heat transfer were fuel strata gap (*FSG*) and σ. *FMC*, a variable determining the heat required for ignition was also tested. The variables were varied within a range expected to be found on both prescribed and wild fires.

Figure 2 displays the response of crown fuel particle temperature profile to changes in input variables. The 0 in the x-location indicates that the surface fire ignition interface (i.e., the leading edge of the flame front) is directly beneath the crown fuel particle being heated. The model simulation stops when the fuel particles reach ignition temperature (600 K), hence the truncated profiles. Of the various input variables under analysis, U_{10} (Figure 2a) and w_a (Figure 2c), showed the most effect on canopy fuel temperature. Wind speed affects the energy transfer processes by determining surface fire rate of spread, fireline intensity, depth of the combustion zone, and flame height. The combustion zone defines the depth of the buoyant plume base, which largely determines its strength, and the size of the radiating surface as seen by crown fuels. Increases in w_a results in corresponding increases in fireline intensity, flame height and reaction time which lead to proportional increases in radiative and convective energy fluxes to the canopy fuels.

FSG and *MC* also showed a strong effect on the model output, albeit lower than U_{10} and w_a (Figures 2b and 2d). *FSG* affects the incident radiative heat flux due to the reduction in the view factor with increased *FSG* and convective energy flux due to air entrainment and consequent cooling of the plume with height.

Table 1. List of intermediate models, their input variables and their use in the CFIM system.

Model	Output	Use to estimate
Vertical wind profile (Cionco, 1965; Albini, 1983)	Wind velocity vertical profile	$ROS, H_F, \tau_r, T_{Fmax}, T_p, U_p, b_p$
Rate of forward fire spread (Rothermel, 1972; Albini, 1976)	Rate of movement of the fire front	I_B, F_{12}, x_F
Fireline intensity (Byram, 1959)	Integrated rate of energy released per unit time per unit length of the fire front	$F_h, U_{pi},$
Flame height (Nelson and Adkins, 1986)	Height of the surface fire flame	T_p, U_p, b_p
Reaction time (Nelson, 2003*b*)	Duration of flaming combustion at a fixed point in the fuelbed	I_{12}, b_i
Maximum gas temperature (surface fire)	Maximum temperature attained in the surface fire flame	I_{12}
Initial buoyant velocity (Nelson, 2003*a*)	Initial buoyant velocity above the flame	U_p
Plume dynamics model (Mercer and Weber, 1994)	Fluid temperature, fluid velocity and half-width of the buoyant plume	h_c
Flame temperature–time distribution	Temperature–time history of the surface fire flame	I_{12}
Radiative heat source	Radiative energy leaving heat source	q_r
Radiative heat flux	Radiative heat flux to crown fuel particle	T_f
Convective heat flux	Convective heat flux to crown fuel particle	T_f

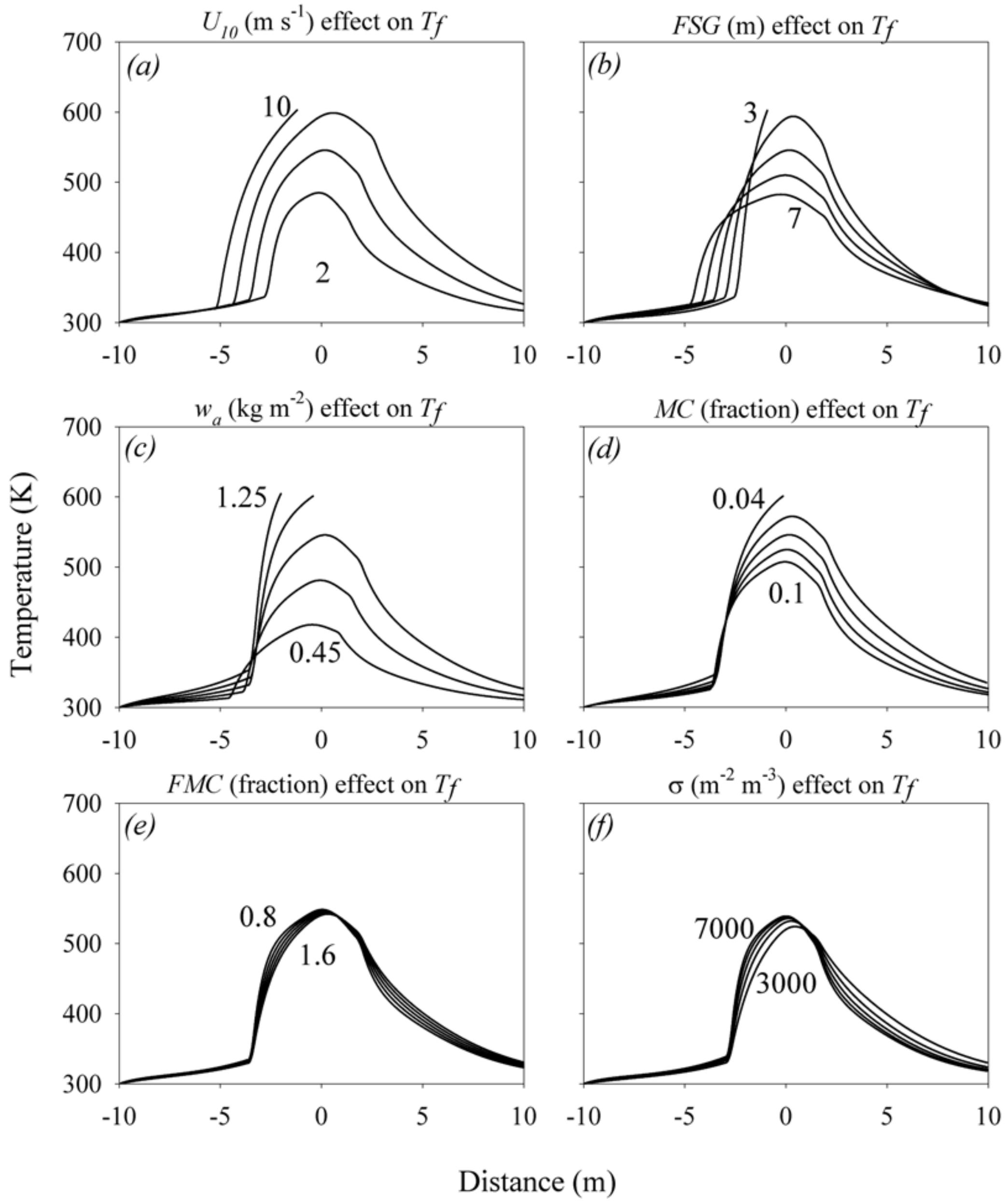

Figure 2. Predicted temperature of lower canopy fuel particles above a spreading surface fire as a function of various input parameters: (a) wind speed (m s^{-1}); (b) fuel strata gap (m); (c) surface fuel available for flaming combustion (kg m^{-2}); (d) surface dead fuel moisture content (fraction); (e) foliar moisture content (fraction); and (f) crown fuel particles surface area to volume ratio (m^{-2} m^{-3}). Plots can be interpreted as a snapshot in time while surface fire ignition interface is at x = 0. Baseline values (and variation in parenthesis) for simulations are: U_{10} = 6 (2, 4, 8 and 10) m s^{-1}; *FSG* = 5 (3, 4, 6 and 7) m; w_a = 0.85 (0.45, 0.65, 1.05 and 1.25) kg m^{-2}; *MC* = 0.07 (0.04, 0.055, 0.085 and 0.1) fraction of oven-dry weight; *FMC* = 1.2 (0.8, 1.0, 1.2 and 1.6) fraction of oven-dry weight; and σ = 5000 (3000, 4000, 6000 and 7000) m^{-2} m^{-3}. Curves are truncated when T_f reaches 600 K.

The two crown fuel variables defining the energy required for ignition, *FMC* and σ, showed the least effect on the predicted crown fuel particle temperature profile (Figures 2e and 2f). *FMC* influences the energy required to ignite the fuel particle by increasing the average specific heat of the crown fuels (Albini, 1985; de Mestre *et al*., 1989). Crown fuel particles are subjected to continuous and prolonged heating while the surface fire approaches and pass under their location (Alexander, 1998). The change in energy required to ignite the fuel particle due to increases in *FMC* is comparatively small when compared to the cumulative energy flux absorbed by the fuel particles. This theoretical result corroborates the analysis of Cruz *et al.* (2004), which failed to find a statistically significant effect of *FMC* on the likelihood of crown fire occurrence based on field experiments. For the range of values tested, σ exhibited a negligible effect on crown fuel temperature and time to ignition.

4.2 *Comparison Against Other Models*

The comparison between models describing the same event provides insight into differences between models, their deficiencies and limits of applicability. CFIM was compared with predictions from Van Wagner (1977), Alexander (1998) and Cruz *et al.* (2004) models. Model comparison was based on the determination of the U_{10} - *FSG* conducive to the attainment of: (1) a critical fireline intensity in the Van Wagner (1977) and Alexander (1998) models; (2) a probability of crown fire occurrence of 0.5 in the Cruz *et al.* (2004) model; and (3) a crown fuel particle temperature of 600 K in CFIM. The current implementation of CFIM relies on Rothermel's (1972) surface fire rate of spread model (with modifications by Albini, 1976) to estimate the movement of the flaming front based on the Northern Forest Fire Laboratory (NFFL) or fire behaviour fuel models (Albini, 1976; Anderson, 1982). NFFL fuel model 2 (open forest stand with grass and understory as main surface fuels) and NFFL fuel model 10 (closed forest stand with compacted litter, down woody fuels and understory) plus a custom fuel model describing a red pine plantation (RPP) (Van Wagner, 1968, Cruz *et al.,* 2004) were used for the comparison.

The results obtained for the CFIM presented in Figure 3 qualitatively follow the behaviour of the empirically-based models and are consistent over a broad range of burning conditions. CFIM predictions fell between the Van Wagner (1977) and Alexander (1998) models for the RPP custom fuel model and lower than the Van Wagner (1977) and Alexander (1998) models for NFFL fuel model 2. The CFIM required the highest wind speeds for crowning for the surface fuelbed characteristics associated with NFFL fuel model 10. The large differences in CFIM predictions between NFFL fuel models 2 and 10 are the result of the low spread potential of the latter fuel model. In fuel types characterized by low rates of surface fire spread, the development of a deep flaming front necessary to yield high convective and radiative energy fluxes to the crown fuels depends on the occurrence of strong wind speeds (Alexander, 1998). Conversely, these high wind speeds reduce convective heat transfer to the crown fuels due to plume tilting and cool air mixing with the plume (Alexander, 1998). An important question is the relative role of surface fuelbed structure and burning conditions (i.e., fuel moisture and wind) on the likelihood of crowning. Based on CFIM output, no definitive trend suggesting a dominance of fuel moisture and wind over surface fuelbed structure, or vice-versa, with respect to inducing crowning could be identified. The RPP custom fuel model showed the largest variation in U_{10} required for crowning over the two standardized fuel moisture

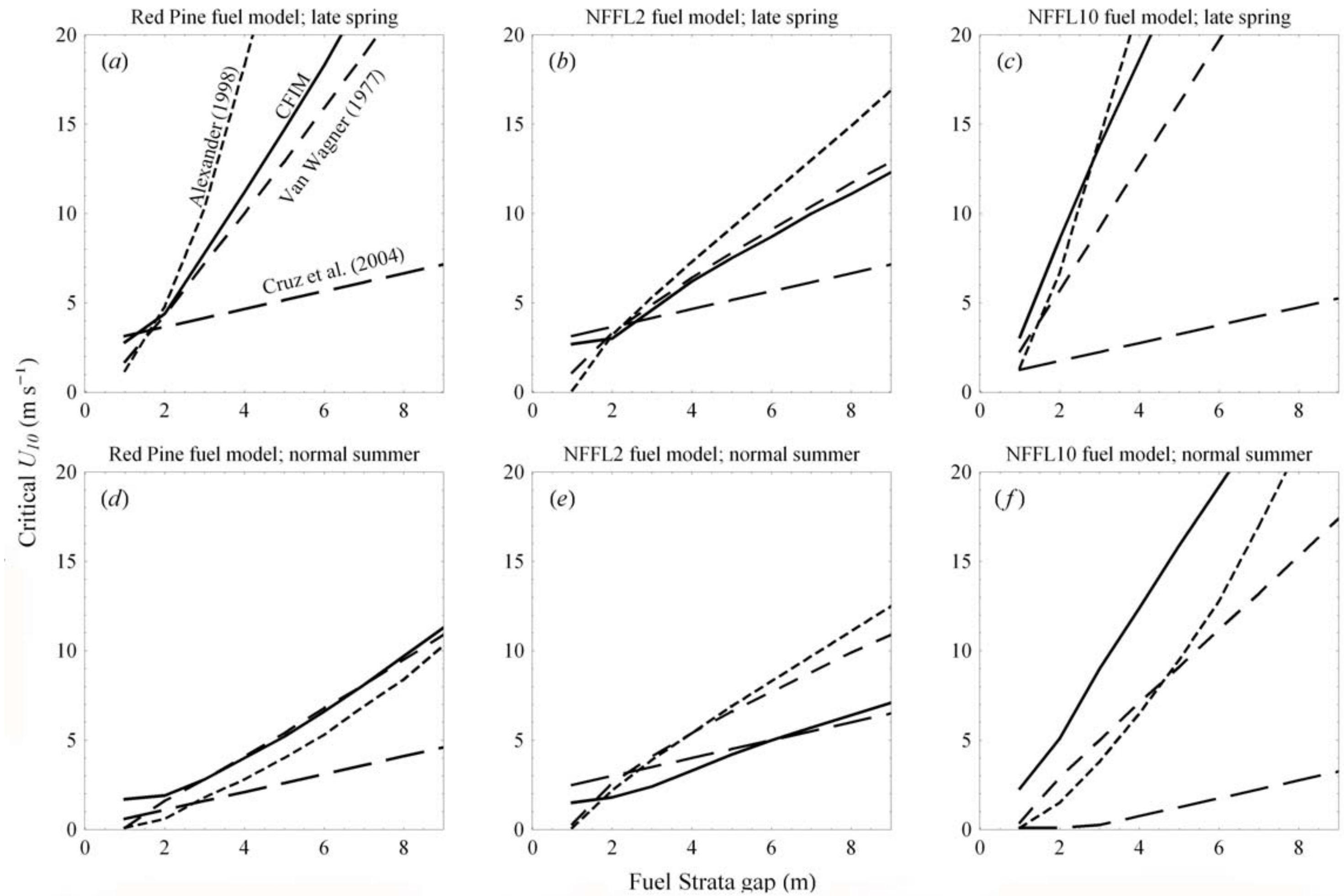

Figure 3. Critical 10-m open wind speed for crown fire initiation as a function of fuel strata gap for the models of Van Wagner (1977), Alexander (1998) and Cruz *et al.* (2004) in relation to the CFIM. Fuel moisture content (fraction of oven-dry weight) characteristic of spring and normal summer conditions are as follows (after Rothermel 1991): 1-hr = 0.09 and 0.06, 10-hr = 0.11 and 0.08, 100-hr = 0.13 and 0.1; and live herbaceous = 1.95 and 1.17.

conditions tested (Figures 3a and 3d). Conversely, model simulations based on NFFL fuel model 10 resulted in moderate differences between fuel moisture conditions (Figures 3c and 3f). Comparative analysis between the RPP custom fuel model and NFFL fuel model 10 shows small differences for the late spring conditions but large differences for the late summer conditions. This is believed to be the result of how surface fuelbed properties that affect the rate of spread and fuel consumption predictions, change throughout the burning season.

For the surface fuels tested, model predictions showed the greatest variability under marginal burning conditions (e.g., late spring). The high wind speed requirements for crown fire initiation needed by the Alexander (1998) model and the CFIM for the RPP custom fuel model and NFFL fuel model 10 fuel for the "late spring" conditions are believed to be the result of the effect of wind speed on plume behaviour and fire intensity. Strong winds tend to dissipate the thermal plume but also result in increased rates of spread leading to increased fireline intensities (a critical value for Alexander's model) and deep flaming zones in the CFIM.

5. Management Implications

The integration of CFIM with Cruz *et al.* (2005) models for crown fire rate of spread (Figure 4) allows for the prediction of the full range of fire behaviour over a variety of fuel complex structures and environmental conditions. The fundamental models within the system have been subject to evaluation with acceptable results (Hough and Albini, 1978; Cruz, 2004; Alexander and Cruz, 2006; Cruz, Butler and Alexander, 2006). Within the model system, the surface fire rate of spread is the quantity showing the widest variation (3 orders of magnitude) and where we believe the highest errors can arise. Essential input requirements are wind, weather variables driving dead fuel moisture content, surface fuelbed structure, fuel strata gap and canopy bulk density. Knowledge of stand structure, in order to compute stand specific wind profiles and radiation interception by tree boles, could possibly improve model performance. The final system output is the type of fire (i.e., surface fire, passive crown fire or active crown fire) and its forward rate of spread. Additional models for predicting fire intensity and flame length (Byram, 1959) and firefighter safety zone sizes (Butler and Cohen, 1998), for example, could be accommodated within the system to answer specific management questions.

The detail with which the model system treats surface fire behaviour along with convective and radiative heat transfer to the canopy fuels allows one to quantify fire hazard with stand aging for particular silvicultural prescriptions and determining through "what-if" scenarios and analyses the optimal level and timing of fuel treatments associated with a pre-defined allowable wildfire risk. Williams (1978) analysed the effect of four different thinning regimes on the fuel complex structure of a 12-year-old radiata pine plantation. The author measured the pre- and post-treatment fuel complex structure, namely surface fuel load by size classes, fuel strata gap, and canopy fuel load, but was unable to quantify the fire hazard associated with each thinning regime. His main doubts were related to how the rearrangement of the fuel complex, namely a reduction in crown fuel quantity, increase in fuel strata gap, an increase in surface fuel load, and changes in the stand microclimate would affect the overall fire spread and intensity potential.

The prediction of rate of spread in relation to fuel and weather conditions for the plantation stands sampled by Williams (1978) allows one to identify the impact of the thinning treatment on fire potential. The results presented in Figure 5 show that although the changes introduced by the treatment alter fire potential, no definite reduction/increase in fire potential were identified. The thinning resulted in an increase in the potential rate of fire spread for low and high wind speeds, while the unthinned stand showed the highest fire potential within the range 5 to 9 m sec^{-1}.

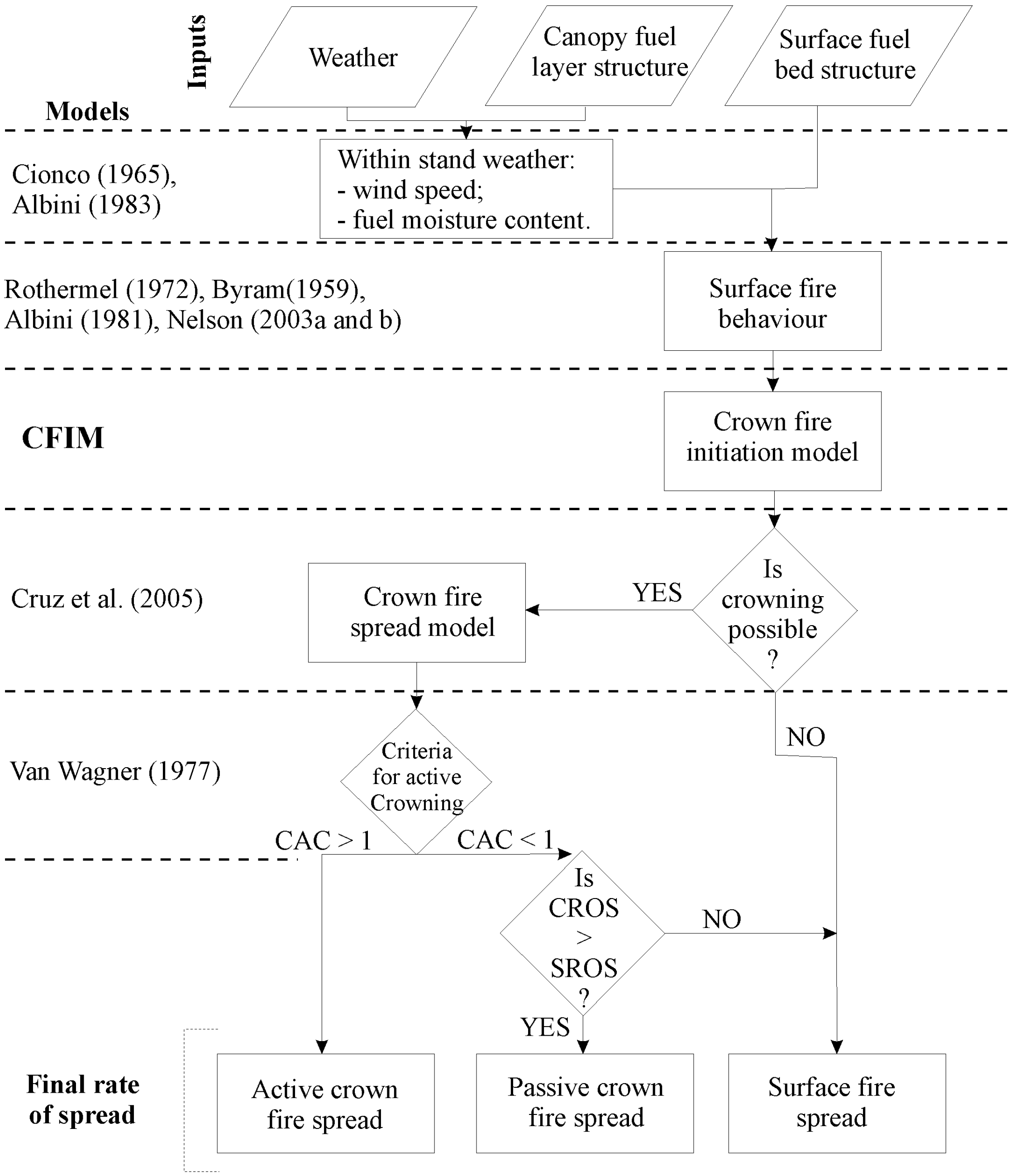

Figure 4. Flow diagram of a fire behaviour prediction system integrating the CFIM with models for predicting surface and crown fire spread.

The model system was able to identify the effect that the changes in different fuel complex properties had in the overall fire potential. For the lower wind speed condition (i.e., $U_{10} < 5$ m sec^{-1}) the increase in w_a and reduction in *MC* due to the thinning induced crowning earlier although the reduction in canopy bulk density limited the spread regime to passive crowning. The unthinned stand reached the threshold for active crowning at $U_{10} \sim 5$ m sec^{-1} and within the interval of $5 < U_{10} < 9$ m sec^{-1} this fuel complex had the highest fire potential. For $U_{10} > 9$ m sec^{-1} the conditions for active crown fire propagation were met for the thinned stand and its drier *MC* condition resulted in higher rates of spread.

From the standpoint of using silvicultural treatments as a means of reducing fire hazard, the simulation presented in Figure 5 indicates that the treatment (i.e., thinning from below with 50 % reduction in basal area) performed by Williams (1978) did not attain its intended purpose. The combination of the treatment with other operations (e.g., high pruning and/or surface fuel reduction), would be necessary to achieve a definitive reduction in fire potential.

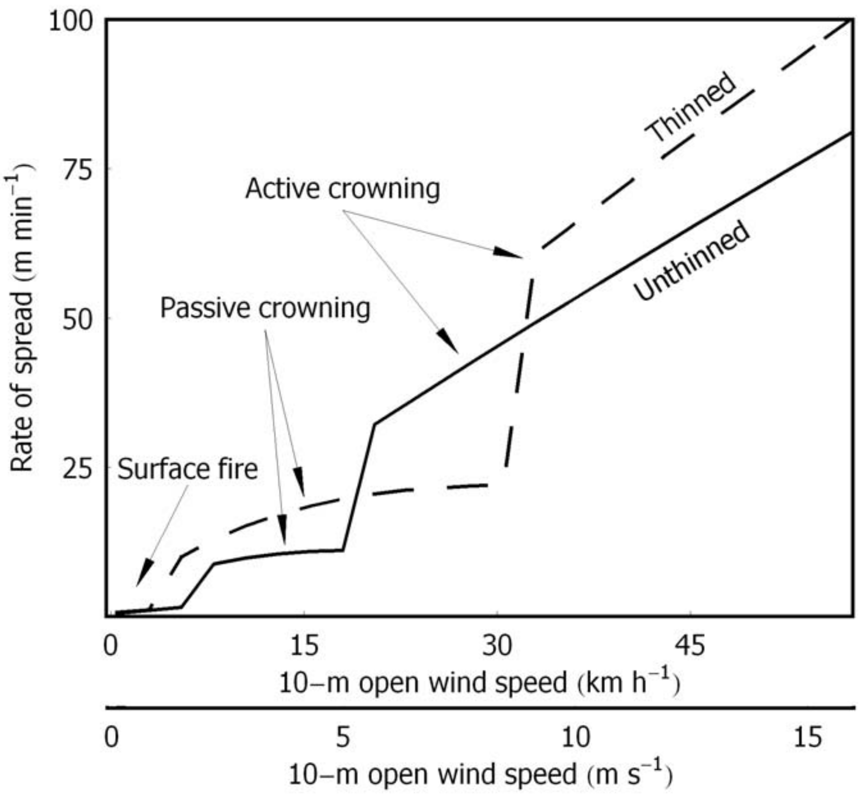

Figure. 5. Fire spread rate as a function of open wind speed for 12-year-old unthinned and thinned (i.e., 50% reduction in basal area treatment) radiata pine plantation stands as per Williams (1978). The burning conditions and fuel complex characteristics for the unthinned and thinned stands are, respectively, as follows: w_a - 0.5 and 1.1 kg m^{-2}; *FSG* - 0.6 and 1.7 m; canopy bulk density - 0.1 and 0.05 kg m^{-3}; and *MC* - 0.07 and 0.05 (fraction of oven-dry weight). *MC* values were based on Pook and Gill's (1993) models for thinned and unthinned radiata pine plantation stands using a air temperature of 40°C and relative humidity of 20%.

6. Conclusions

We described and evaluated a model intended to predict the temperature and ignition of crown fuel particles located above a spreading surface fire. The model combines heat transfer and fluid dynamics principles with empirically-based sub-models to describe the main phenomena determining the ignition of crown fuels. Simulation exercises suggest that the main variables determining crown fuel ignition are those controlling surface fire characteristics, namely wind speed, fuel available for flaming combustion and fine fuel moisture content. Foliar moisture content was found to have a limited effect on the onset of crowning. A comparative analysis with empirically-based models showed the CFIM results to be within the range of predictions produced by these models. The structure of the CFIM allows it to address "what-if" scenarios related to the implications of silvicultural operations and other fuel treatments on fire behaviour potential.

References

Albini, F.A., 1976. Estimating wildfire behavior and effects. USDA For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT, Gen. Tech. Rep. INT-30.

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

Albini, F.A., 1983. Wind flow into a model forest re-examined. In: Preprint Volume, Seventh Conference on Fire and Forest Meterology. Am. Meteor. Soc., Boston MA, pp. 115-122.

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

Alexander, M.E., 1998. Crown fire thresholds in exotic pine plantations of Australasia. Aust. Nat. Univ., Canberra, ACT, PhD Thesis.

Alexander, M.E., Cruz, M.G., 2006. Evaluating a model for predicting active crown fire spread using wildfire observations. Can. J. For. Res. 36, in press.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv., Intermt. For. Range Exp. Stn., Ogden UT, Gen. Tech. Rep. INT-122.

Beck, J.A., 1995. Equations for the forest fire behaviour tables for Western Australia. CALM Sci. 1, 325-348.

Burrows, N.D., Ward, B., Robinson, A., 1988. Aspects of fire behaviour and fire suppression in a *Pinus pinaster* plantation. Dep. Conserv. Land Manage., Perth, WA, Landnote 2/88.

Butler, B.W., Cohen, J.D., 1998. Firefighter safety zones: A theoretical model based on radiative heating. Int. J. Wildland Fire 8, 73-77.

Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P. (Ed.), Forest Fire: Control and Use. McGraw-Hill, New York, NY, pp. 61-89, 554-555.

Catchpole, W.R., Catchpole, E.A., Tate, A.G., Butler, B.W., Rothermel, R.C., 2002. A model for the steady spread of fire through a homogeneous fuel bed. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety, Proceedings of the IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit. Millpress Sci. Publ., Rotherdam, Netherlands, CD-ROM.

Cionco, R.M., 1965. A mathematical model for air flow in a vegetative canopy. J. Appl. Meteor. 4, 517-522.

Committee on Fire Research, 1961. A study of fire problems. U.S. Natl Acad. Sci., Natl. Res. Counc., Washington, DC, Publ. 949.

Cruz, M.G., 1999. Modeling the initiation and spread of crown fires. Univ. Mont., Missoula, MT, MSc Thesis.

Cruz, M.G., 2004. Ignition of crown fuels above a spreading surface fire. Univ.. Mont., Missoula, MT, PhD Thesis..

Cruz, M.G., Alexander, M.E., Wakimoto, R.H. 2002. Predicting crown fire behavior to support forest fire management decision-making. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety, Proceedings of the IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit. Millpress Sci. Publ., Rotherdam, Netherlands, CD-ROM.

Cruz, M.G., Alexander, M.E., Wakimoto, R.H. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wildland Fire 12, 39-50.

Cruz, M.G., Alexander, M.E., Wakimoto, R.H., 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. For. Sci. 50, 640-658.

Cruz, M.G., Alexander, M.E., Wakimoto, R.H., 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Can. J. For. Res. 35, 1626-1639.

Cruz, M.G., Butler, B.W., Alexander, M.E., Forthofer, J.M., Wakimoto, R.H., 2006. Predicting the ignition of crown fuels above a spreading surface. fire I: Model idealization. Int. J. Wildland Fire 15, 47-60.

Cruz, M.G., Butler, B.W., Alexander, M.E., 2006. Predicting the ignition of crown fuels above a spreading surface fire. Part II: Model behavior and evaluation. Int. J. Wildland Fire 15, 61-72.

Davidson, G.A., 1986. A discussion of Schatzmann's integral plume model from a control volume viewpoint. J. Climate Appl. Meteor. 25,858- 867.

de Mestre, N.J., Catchpole, E.A., Anderson, D.H., Rothermel, R.C., 1989. Uniform propagation of a planar fire front without wind. Combust. Sci. Tech 65, 231-244.

Douglas, D.R., 1964. Some characteristics of major fires in coniferous plantations. Aust. For. 28, 119-124.

Finney, M.A., 2004. FARSITE: Fire area simulator—model development and evaluation. USDA For Serv., Rocky Mt. Res. Stn., Fort Collins, CO, Res. Pap. RMRS-RP-4 Revised.

Forestry Canada Fire Danger Group, 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can., Ottawa, ON, Inf. Rep. ST-X-3.

Hardy, C.E., Franks, J.W., 1963. Forest fires in Alaska. USDA For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT, Res. Pap. INT-5.

Hough, W. A., Albini, F. A., 1978. Predicting fire behavior in palmetto-gallberry fuel complexes. USDA For. Serv., Southeast. For. Exp. Stn., Asheville, NC, Res. Pap. SE-174.

Mendes-Lopes, J.M.C., Ventura, J.M.P., Rodrigues, J.A.M., 2002. Determination of heat transfer coefficient through a matrix of *Pinus pinaster* needles. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety, Proceedings of the IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit. Millpress Sci. Publ., Rotherdam, Netherlands, CD-ROM.

Mercer, G.N., Weber, R.O., 1994. Plumes above line fires in a cross wind. Int. J. Wildland Fire 4, 201-207.

Nelson, R.M. Jr., Adkins, C.W., 1986. Flame characteristics of wind driven surface fires. Can. J. For. Res. 16, 1293-1300.

Nelson, R.M. Jr., 2003a. Power of the fire – a thermodynamic analysis. Int. J. Wildland Fire 12, 51-65.

Nelson, R.M. Jr., 2003b. Reaction times and burning rates for wind tunnel headfires. Int. J. Wildland Fire 12, 195-211.

Noble, I.R., Bary, G.A.V., Gill, A.M., 1980. McArthur's fire-danger meters expressed as equations. Aust. J. Ecol. 5, 201-203.

Plucinski, M.P., 2003. The investigation of factors governing ignition and development of fires in heathland vegetation. Univ. New South Wales, Aust. Def. Force Acad., Canberra, ACT, PhD Thesis.

Pook, E.W., Gill, A.M., 1993. Variation of live and dead fine fuel moisture in *Pinus radiata* plantations of the Australian Capital Territory. Int. J. Wildland Fire 3, 155-168.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT, Res. Pap. INT-115.

Rothermel, R. C., 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA For. Serv., Intermt. Res. Stn., Ogden, UT, Res. Pap. INT-438.

Scott, J. H., Reinhardt, E.D., 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA For. Serv., Rocky Mt. Res. Stn., Fort Collins, CO, Res. Pap. RMRS-RP-29.

Taylor, S.W., Wotton, B.M., Alexander, M.E., Dalrymple, G.N., 2004. Variation in wind and crown fire behaviour in a northern jack pine – black spruce forest. Can. J. For. Res. 34, 1561-1576.

Van Wagner, C.E., 1968. Fire behaviour mechanisms in a red pine plantation: Field and laboratory evidence. Can. Dep. For. Rural Develop., For. Branch, Ottawa, ON. Publ. 1229.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7, 23-34.

Weber, R.O., 1990. Where can physical fire models lead? In: Proceedings of the Third Australian Fire Weather Conference. Commonw. Aust., Bureau Meteor., Melbourne, VIC, pp. 26-34.

Williams, D.F., 1978. Fuel properties before and after thinning in young radiate pine plantations. For. Comm. Vic., Melbourne, VIC, Fire Res. Branch Rep. No. 3.

Xanthopoulos, G., 1990. Development of a wildland crown fire initiation model. Univ. Mont., Missoula, MT, PhD Thesis.

Xanthopoulos, G., Wakimoto, R.H., 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. In: Long, R.R. (Ed.), Fluid Models in Geophysics, Proceedings of the First Symposium on the Use of Models in Geophysics. U.S. Govt. Print. Off., Washington DC, pp.117-133.

Appendix 1. List of symbols, quantities and units used in equations and text.

A_f	Fuel particle area (m^2)
b	Plume half-width (m); b_i (initial)
$c*$	Average specific heat of fuel (kJ kg^{-1} K^{-1})
c_f	Specific heat of fuel particles (kJ kg^{-1} K^{-1})
c_p	Specific heat of air (kJ kg^{-1} K^{-1})
c_w	Specific heat of water (kJ kg^{-1} K^{-1})
D_F	Flame depth (m)
F_{23}	Geometrical view factor between fuel particle and surroundings
FMC	Foliar moisture content (fraction of oven-dry weight)
FSG	Fuel strata gap (m)
h_c	Fuel particle convective heat transfer coefficient (kJ m^{-2} s^{-1} K^{-1})
H_c	Fuel low heat of combustion (kJ kg^{-1})
H_F	Flame height (m)
I_{12}	Radiative transfer to the surface of the canopy fuel particles (kW m^{-2})
I_B	Fireline intensity (kW m^{-1})
L_p	Fuel particle length (m)
L_a	Latent heat of vaporization of water (kJ kg^{-1} K^{-1})
MC	Moisture content of fine dead fuel particles (fraction of oven-dry weight)
N_u	Nusselt number
ROS	Surface fire rate of spread (m s^{-1})
R_e	Reynolds number
T	Temperature (K)
t	Time (s)
T_a	Ambient temperature (K)
T_F	Flame temperature (K)
T_g	Gas temperature (K)
T_{ig}	Ignition temperature (600 K)
T_{Fmax}	Flame maximum temperature (K)
T_f	Fuel particle surface temperature (K)
T_p	Plume temperature (K) ; T_{pi} (initial)
U_F	Free flame velocity (m s^{-1})
U_{10}	10-m open wind speed (m s^{-1})
U_z	Wind speed at height z (m s^{-1})
U_s	Within-stand wind speed (m s^{-1})
U_p	Plume velocity (m s^{-1}); U_{pi} (initial)
V	Fuel particle volume (m^{-3})
v_e	Entrainment speed (m s^{-1})
W_p	Fuel particle width (m)
W_F	Flame front width (m)
w_a	Surface fuel available for flaming combustion (kg m^{-2})
x	Horizontal distance (m)
z	Vertical distance (m)
α	Radiation absorption coefficient (m^{-1})
α_U	Wind attenuation coefficient
σ	Fuel particle surface area-to-volume ratio (m^{-1})
σ_{SB}	Stefan–Boltzmann constant, $5.67 \cdot 10^{-8}$ W m^{-2} K^{-4}
ε	Flame emissivity
ρ_a	Ambient air mass density (kg m^{-3})
ρ_f	Fuel mass density (kg m^{-3})
τ_r	Reaction time (s)