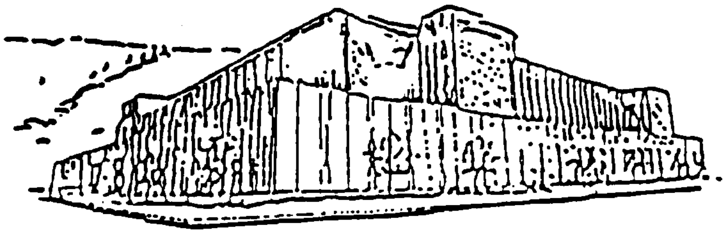
1999

Modeling the initiation and spread of crown fires

Miguel Gomes da Cruz
The University of Montana

Recommended Citation

Gomes da Cruz, Miguel, "Modeling the initiation and spread of crown fires" (1999). *Graduate Student Theses, Dissertations, & Professional Papers*. 2996.
https://scholarworks.umt.edu/etd/2996



MODELING THE INITIATION AND SPREAD OF CROWN FIRES

By

Miguel Gomes da Cruz

B.S. Forestry, Coimbra Polytechnic Institute, Portugal, 1994

Presented in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

UNIVERSITY OF MONTANA

1999

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

11-29-99

Date

Gomes da Cruz, Miguel, M.Sc., September 1999 Forestry

Modeling the Initiation and Spread of Crown Fires

Director: Ronald H. Wakimoto

The unknowns in fire phenomenology lead to a simplified empirical approach to build models designed to forecast crown fire initiation and spread. This information is needed to support decision making in a large array of fire management problems.The present study is based on a large fire behavior database from experimental fires in North American fuel complexes. These fires cover a wide spectrum of fire environment and behavior conditions.

Three types of models were develop in this study: A crown fire initiation model, a crown fire spread model, and models to predict canopy bulk density. Crown fire initiation was modeled through a logistic approach using as independent variables wind speed, fuel strata gap, a surface fuel consumption class and dead fine fuel moisture content. Spread rates for active and passive crown fires were modeled through multiple non-linear regression analysis following physical reasoning. Independent variables used in the crown fire spread models were wind speed, canopy bulk density and dead fine fuel moisture content. Models to predict canopy bulk density in some common fuel complexes in the U.S. were developed by linking foliar biomass equations with stand data from the Forest Inventory and Analysis. Canopy bulk density was modeled as a function of species, stand density and stand basal area.

The crown fire initiation model correctly predicted 85 % of the cases in the dataset used for its construction. The active crown fire spread model yield a R^2 of 0.61. Comparison of predictions from both fire behavior models against an independent dataset from wildfire crown fire runs revealed good model performance. The crown fire initiation model correctly predicted all the wildfires as crown fires. The active crown fire spread model yielded a mean absolute percent error of 34 % when compared against the independent dataset.

The wide variation in fuel complex structure and fire behavior in datasets used to build the crown fire initiation and spread models gives confidence that the models might work well in fuel complexes different from the original ones, given an adequate description of the physical characteristics of the fuel complex.

Keywords: Fire behavior modeling; Crown fire initiation; Crown fire spread; Canopy bulk density; Model evaluation.

ACKNOWLEDGEMENTS

This thesis was made possible by the assistance of many people. I am immeasurably indebted to Marty Alexander by his original ideas, guidance and support given throughout this study. I would like extending my sincere thanks to my advisor Ron Wakimoto for his support, guidance and patience. Thanks also to my other committee members, namely Richard Lane for providing assistance on the statistical portion of the analysis, and Don Potts and Bobbie Bartlette for their support. I want to also thank Kelsey Milner and Hans Zuring for their advise and assistance in the analysis of the canopy bulk density data. Thanks also to Brian Stocks for making available to me some of the unpublished data used in this study. Thanks also to the Canadian Forest Service for inviting me to participate in the 1999 Phase III of the International Crown Fire Modeling Experiment, Fort Providence, NWT.

I would like to recognize Domingos Xavier Viegas from the University of Coimbra, Portugal for his encouragement for me to seek an advanced educational degree, and the financial support given by ADAI – University of Coimbra. Financial support is also acknowledged from Fundação Luso-Americana para o Desenvolvimento, and Blackfoot Forest Protective Association.

Thanks to all my friends who made my stay in Missoula so enjoyable.

My sincere and heartfelt thanks to Isabel for her never-ending patience and constant support throughout the period of this study.

A todos o meu muito obrigado.

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF FIGURES

Figure

INTRODUCTION

It has been recognized by numerous authors, that disturbances, as fire, are an essential component of ecosystem dynamics (Christensen 1989; Arno 1996). Davis and Mutch (1994) in their classification of fire regimes pointed the importance of high intensity surface fires and crown fires in certain ecosystems with 25-to 300- years return interval. In ecosystems with such fire regimes, e.g., lodgepole pine and lodgepole pine-spruce-fir in western U.S. and southwestern Canada; jack pine and black spruce in northern Minnesota, Wisconsin and Michigan; and Douglas-fir from southern Oregon to southern British Columbia, ecologically significant fires need to burn significant areas. In the recent past, high intensity stand replacement fires have been applied in ecosystem management in various areas of the U.S. (Benedict et al. 1989; Kilgore and Heinselman 1990; Custer and Thorsen 1996). The increase in the state of knowledge concerning the role of fire in ecosystem dynamics, namely, the interaction between various fire regimes and intensities and the various components of the ecosystems demands a more holistic and complex management.

Recommendations in the Federal Wildland Fire Management Policy and Program Review (USDI/USDA 1995) include the use of fire based on sound scientific information as an essential process to improve and maintain wildland ecosystems. This situation requires that management decisions be made based on sound scientific principles using precise and reliable information concerning the prediction of fire effects on the ecosystem. The knowledge of fire behavior is of key importance in fire management decision making, as the spectrum of fire effects, at a local scale, depend primarily on the fire characteristics and the fire environment. This situation requires the use of reliable models to predict fire behavior and effects, in order to conduct prescribed fires to achieve established fire use objectives. The implementation of fire behavior and effects algorithms and equations in fire growth models constitutes an efficient tool for land managers to support decision making in prescribed fire programs, evaluating the effectiveness of different fuel treatment options, and predicting real-time fire behavior for strategic planning in wildfire situations.

Present state-of-the-art in fire behavior modeling has yet to produce a physical model that, by its fundamental approach, can answer a large array of fire phenomenology questions, ranging from combustion time in ground fires to rates of spread in crown fires. The present situation is characterized by a multitude of models, mainly empirically based, that answer specific fire behavior questions, as fire rate of spread, fire intensity, or fuel consumption.

In the last few years, fire behavior research, has focused on the development of new models that are designed to link fire behavior with fire effects. Major modeling efforts have been put into modeling smoldering ground fires (Frandsen 1991), large fuel burnout (Albini and Reinhard 1995), surface fire spread (Andrews 1996; Catchpole et al. 1998) and a physically based crown fire model (Albini 1996; Call and Albini 1997). These models are expected to support a conscientious use of fire in wildlands in the near future.

When considering the application of ecologically appropriate large scale, high intensity fires under predefined prescriptions a major concern is to know how well existing models can forecast extreme fire behavior, namely the onset and spread of crown fires. Presently available crown fire behavior models possess limitations that might hamper their application in certain conditions.

CHAPTER I

REVIEW OF THE STATE-OF-KNOWLEDGE AND MODEL EVALUATION

1.1. OBJECTIVES

A crown fire is by definition a fire that spreads through a fuel complex burning from the surface fuels to the treetops (Cheney 1989). In this study, the term "crown fire" will be restricted to "timber crown fires". Fires that burn in the canopies of certain fuel complexes with different vertical structure, as California chaparral, or Mediterranean high *macchia*, will be considered here as spreading in a surface fire regime, as there is not a marked stratification in the fuel complex between the surface and aerial fuels. Within this study, crown fire phenomena was divided into crown fire initiation and crown fire spread as their dynamics and sensitivity to fire environment variables are distinct.

The objectives of this chapter are to give a review of the state-of-knowledge on the prediction and understanding of crown fire initiation and spread phenomena, and to evaluate the performance of the crown fire spread model (Rothermel 1991a) used operationally in the U.S. (NWCG 1993; Finney 1998).

1.2. PREDICTION OF CROWN FIRE INITIATION

The knowledge of the combination of fire environment conditions that originate the transition from a surface fire to a crown fire is a critical need when predicting fire behavior for decision support in fire management. One of the earlier works on the quantitative analysis of crown fire phenomena was the one from Molchanov (1957). This author, through the analysis of heat balances on crown fires in pine stands, computed amounts of surface fire heat output required to ignite crown fuels at a certain height, and reasoned in the influence of the effect of the amount of fuel in the crown, foliar moisture content, and foliage chemical composition on the onset of crowning.

Fahnestock (1970) through its Crowning Key produced one of the first tools to allow fire managers to assess crown fire potential in forest stands He identified several fuel complex characteristics that lead to the onset of crowning, namely, canopy cover density, existence of ladder fuels, and foliage state, and ranked their possible combinations into a crown fire potential scale. Kilgore and Sando (1975) assess crown fire potential in Sequoia stands through the knowledge of crown base height and crown volume ratio as a measure of canopy density. This first quantitative description of the crown fuel strata was not accompanied at the time by quantitative fire behavior models that could give deterministic outputs to support fire management decisions.

Van Wagner (1977) through a combination of physical criteria and empirical observation defined quantitative criteria to predict the onset of crown combustion. Van Wagner based his analysis on a relationship developed by Thomas (1963) that linked fire intensity, I_B, as defined by Byram (1959), with the maximum temperature, ΔT, attained at a height, z, in the convection plume above the fire:

$$\Delta T \propto \frac{I^{2/3}}{z} \qquad [1.1]$$

This relationship, based on dimensional analysis, was independent of the thickness of the flame front, and valid on still air conditions only (Van Wagner 1973). It was rearranged by Van Wagner (1977) to allow the determination of a critical surface fire intensity, I_0, needed to induce crown combustion function of crown base height, CBH, heat of ignition, h, and a quantity C, "*best regarded as an empirical constant of complex dimensions*":

$$I_0 = (C \cdot h \cdot CBH)^{1.5} \qquad [1.2]$$

Being the heat of ignition calculated as (Van Wagner 1972):

$$h = mC_w(100° - T_0) + lm + C_f(T_{ig} - T_0) + C_d \qquad [1.3]$$

where, the first term represents the energy required to heat the water existent in the fuel to the boiling point, m being the moisture content of the fuel expressed as a fraction, C_w the specific heat of water, and T_0 the fuel temperature; the second term expresses the energy required to vaporize the water, being l the latent heat of vaporization; the third term represents the energy required to heat the dry fuel to ignition temperature, C_f is the specific heat of fuel, and T_{ig} the ignition temperature; the fourth term, C_d, represents the heat of desorption of water in the fuel. Assuming l as 2250 kJ/kg, C_f as 1.47 kJ/kg, and C_d as 50.23 kJ/kg, Equation [1.3] simplifies:

$$h = 2585m + 460 \qquad [1.4]$$

The quantity C was estimated from an experimental fire in a Jack pine (*Pinus banksiana*) stand (fire PNFI SC in Table A.2, Appendix) that spread as a passive crown fire. Its intensity at the onset of crowning was estimated as 2500 kW/m. For a CBH of 6 meters and foliar moisture content of 100 %, C was estimated to be 0.01.

This model is presently used for predicting crown fire initiation in the conifer fuel types (Van Wagner 1989, 1993) of the Canadian Fire Behavior Prediction System (Fire Danger Group 1992), in the fire growth simulator FARSITE (Finney 1998), and was used by Scott (1998) to assess crown fire hazard in ponderosa pine (*Pinus ponderosa*) stands.

As main limitations of this model, it can be pointed that:

- Equation [1.1] is related to a maximum temperature, whereas when considering the ignition of fuels it would be more appropriate to consider a temperature profile and its relation with the desiccation and ignition of fuels.
- Equation [1.2] is applicable to still air conditions. Under wind, the tilt of the convection column and the increased entrainment of air in the convection plume are expected to lower the temperature within the plume (Mercer and Weber 1994).
- The heat of ignition equation assumes that all water must be evaporated from the fuels before ignition takes place. Several authors (e.g. Xanthopoulos 1990, Alexander 1998) pointed out that fuel ignition take place before all moisture is driven off, function of the time and intensity of pre-heating processes (Molchanov 1957).
- Equation [1.2] is independent of flame thickness, whereas it is expected that variation in flame geometry, as influenced by the amount and structural characteristics of the available fuel for combustion in the flaming phase of the surface fire, will influence the vertical buoyant velocity and temperature profiles at different height in the plume.
- Byram's (1959) fireline intensity might not be the best descriptor of the heat fluxes from a surface fire reaching the base of the crown. This aspect is addressed in Alexander (1998) and will be discussed in more detail in Section 2.2.

- It is expected that the quantity C encompass much of the effects of the limitations pointed above. Doing so, this quantity C would vary with the fuel complex, and with the amount of fuel available for combustion in the surface strata.

To overcome certain of these limitations, Xanthopoulos (1990) approached the crown initiation problem through the determination of the temperature reaching a certain height in the surface fire convection plume combined with a duration measurement. Through twos sets of different experiments, Xanthopoulos developed equations to predict time-temperature profiles at different heights in the convection plume and time to ignition equations of foliage of ponderosa pine, lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*). The time-temperature profile equations were generated from data on wind tunnel and are of the form (Xanthopoulos 1990):

$$D_x = \beta_0 + \beta_1\left(\frac{I_R}{z}\right) + \beta_2\left(\frac{W}{z}\right) + \beta_3 U_c + \beta_4 U^2 \qquad [1.5]$$

Where,

D_x is the temperature above a certain time period x;

I_R is the reaction intensity (kW/m^2) as defined by Rothermel (1972);

z is height (m) over the top of the fuel bed;

W is fuel loading (kg/m^2);

U_c is the wind coefficient, as calculated by Rothermel (1972);

U is wind speed (km/h).

The time-to-ignition equations developed were species dependent, function of temperature and foliar moisture content and of the form (Xanthopoulos 1990):

$$t_i = \beta_0 e^{(\beta_1 T + \beta_2 m)} \qquad [1.6]$$

where,

t_i is the time to ignition (sec);

T is the temperature in the convection plume (°C)

m is foliar moisture content (%).

The coupling of this two equations with the output from the surface fire spread model (Rothermel 1972; Albini 1976) embodied in the BEHAVE system (Andrews 1986; Andrews and Chase 1989) would overcome some of the limitations of the Van Wagner

(1977) model listed before. Alexander (1998) point out some of the limitations existent in Xanthopoulos (1990) model due to the laboratory setup used that would limit the performance of the model in "real world" situations. Fire behavior data from laboratory experiments can be biased to the low width of the fire front, no free convection, homogeneous fuels, low windspeeds and scale effects.

Combining and refining the Van Wagner (1977) and Xanthopoulos (1990) approaches, Alexander (1998) developed an algorithm to predict the onset of crowning. The computational procedure involve the following steps (after Alexander 1998):

1. estimation of the convective plume angle based on Taylor (1961) and Thomas (1964) relationship between plume angle and fireline intensity and windspeed:

$$\tan P_A \propto \left(\frac{bI}{U^3} \right)^{0.5} \qquad [1.7]$$

where,

P_A is the convective plume angle of a surface fire (angle between the plume and the surface;

b is a buoyancy term that can be assumed constant (Van Wagner 1973).

Equation [1.7] was parameterized from data of Fendel et al. (1990).

2. estimate the temperature increase above the ambient temperature (ΔT) at the base of the crown, z, through a refinement of Equation [1.1]:

$$\Delta T = \frac{kI^{2/3} \sin P_A}{z} \qquad [1.8]$$

where k is a proportionality constant determined from field observations.

3. The convection plume temperature (T_c) at the base of the crown is determined adding ΔT to the ambient temperature. If T_c is higher than the defined ignition temperature (assumed as 400 °C), flame residence time and time to ignition of the foliage (from Equation [1.6]) are calculated. If the flame residence time is larger than the time to ignition, it is assumed that crown fire initiation is possible.

Although Alexander (1998) refinements improved the Van Wagner (1977) approach, several limitations arise, namely:

- The already referred to use of Byram's fireline intensity;
- The inadequacy of present models (e.g. Anderson 1969) to predict flame residence time based on structural properties of the fuel bed and fuel availability for flaming combustion.

Apart from the crown fire initiation models described, other models have been developed (e.g. Grishin and Perminov 1990; and Grishin 1997), but have no immediate applicability due to the computational requirements needed to solve these intrinsically complex, physically based models.

Little work as been devoted to evaluate under field conditions the three (Van Wagner 1977; Xanthopoulos 1990; Alexander 1998) deterministic crown fire initiation models under field conditions. A major difficulty in gathering data for evaluating these crown fire initiation models is that the window of fire environment conditions to be able to monitor fire behavior in the transition phase is narrow. An objective evaluation would require the initiation of an experimental fire under conditions below the threshold conditions that induce crowning, followed by a steady increase in fire intensity, or wind in the case of Xanthopoulos model, and precise monitoring of the transition moment.

A further difficulty for the operational application of Van Wagner (1977) and Alexander (1998) models in U.S. fuel complexes is the need to determine or validate respectively the C and k constant for fuel complexes with different structural characteristics.

1.3. PREDICTION OF CROWN FIRE SPREAD

Crown fires have been classified differently by several authors, considering various aspects of fire behavior. Van Wagner (1977) divided crown fires into three classes, according to the dependence of the crown phase on the surface phase, based on a heat balance equation (Thomas et al. 1964) and some theoretical reasoning. Crown fire spread was characterized as passive, active and independent crown fires based on three limiting criteria: (i) the rate of flame spread (ii) the mass flow rate of fuel, and (iii) the horizontal heat flux.

Passive or intermittent crown fire – In this type of fire, the fire spread rate is less than the critical fire spread rate (criteria that must be achieved to make crown spread possible) and the critical mass flow rate cannot be obtained just from the crown phase. Consequently, the presence of the surface phase is required to supply some of the fuel. The crown phase will depend on the surface phase, which spread rate will condition the flame front displacement.

Active crown fire – In an active crown fire the spread rate have exceed the critical spread rate, having developed a solid flame sheet from the ground to the canopy. This will enhance the heat output to the surface phase, inducing an increase of the spread rate above the previous equilibrium. The crown phase is independent from the surface phase in terms of mass flow, i.e. it supplies its own fuel, but still requires the surface phase for a part of the ignition energy, as the required horizontal heat flux is not attained alone by the crown phase.

Independent crown fire – The concept of independent crown fire is dubious as a stable phenomenon. Following Van Wagner (1977), in this type of fire, the horizontal heat flux would be supplied by the crown phase alone, allowing the crown phase to run ahead and independently of the surface phase. Molchanov (1957) through the computation of heat balances in crown fires concluded that the burning process in the canopy requires additional flow of heat from the surface fire. Van Wagner (1993) considered the independent crown fire concept as a short-lived non-stable phenomenon occurring in steep terrain under extreme conditions, and improbable of occurring in level terrain.

Van Wagner (1977) defined criteria to classify fires within these three classes: Assuming that the critical fire intensity, Equation [1.2], criteria is satisfied, a crown fire spread criteria is calculated based on the ratio between a critical mass flow rate, S_0, empirically derived from observations in experimental fires (fire R1 in Table A.2, Appendix) and canopy bulk density. For rate of spread expressed in m/min, and canopy bulk density in kg/m^3 the critical mass flow rate is 3 kg/m^2 – min. If the estimated critical fire spread rate is not satisfied, a fire is spreading as a passive crown fire. If the observed spread rate is above the estimated critical value, the fire should spread as an active crown fire. There is no practical guideline to estimate if a fire would be spreading as an independent crown fire.

These three types of crown fire spread are normally recognized by various authors, although sometimes not with the same denomination. Grishin (1997) classified crown fires in simple crown fire, general crown fire and top fire, which corresponds to the classification of passive, active and independent crown fires respectively.

Rothermel (1991a) considered two fire behavior patterns in crown fire phenomenology, wind driven fires and plume dominated fires, based on the interaction of the fire convection column and the surrounding wind field. He used Byram (1959) energy criterion, which is a very simplified comparison between the rate of energy flow in the wind field with the rate at which thermal energy is converted into kinetic energy in the convection column over the fire. This computation allows the determination of whether the fire is a thermal phenomenon dominated by its own buoyant energy, or a forced convection phenomena dominated by the energy of the wind field.

From the various types of forest fire propagation, i.e., ground, surface, and crown, the crown fire regime is the type of fire propagation which behavior seems most difficult to model. This is due to the lack of understanding and knowledge of:

(1) various chemical processes occurring during combustion and the resulting flame and ignition interface characteristics, e.g., ignition temperature, flame geometry and flame radiometric temperature;

(2) the contribution of each heat transfer (i.e. radiation and convection) mechanism to the overall energy transferred to the unburned fuels ahead of the fire depending on the fire environment and behavior characteristics;

(3) the interaction between the combustion of two separate and independent layers of fuel (surface and crown);

(4) the violent turbulent interaction in crown fires between the fire buoyant plume and the wind field due to the release of great amounts of energy, which is extremely difficult to simulate at different scales;

(5) unknowns in combustion processes in live fuels.

Of the five considered points above, the two former and the last one can be also considered as common to surface forest fire modeling, and (3) and (4) specific to crown fire phenomenology, although at a different scale they are also present in surface fire behavior.

These limitations in forest fire science have conditioned the modeling philosophies of the most important crown fire behavior descriptors, namely spread rate and fire intensity. The various approaches used to model crown fire behavior, physical, empirical and combination of both (other authors expand these classification to heuristic, mathematical, and theoretical), have reflected the basic background of the modelers, with the physical and semi-physical approach being carried by mathematicians, physicists, and mechanical engineers; and the empirical approach being followed mainly by foresters.

Empirical fire spread models are those models that are based on fire behavior data from fire behavior experiments and wildfires and make no attempt to incorporate physical processes. These models normally perform quite accurately under the conditions for which they where built, but their use outside of the range (fuels, weather, fire behavior) of the original data can give erroneous results.

Physical fire spread models are mechanistic models that incorporate combustion processes and heat transfer into a heat balance equation solved for a fuel volume element. These models would include all the important variables and, due to their fundamental nature, would be able to predict most of forest fire behavior phenomena and their interaction with local meteorological conditions (Packam 1989). Due to the limitations in knowledge related to the chemical and physical processes occurring during combustion, and the difficulty to solve them mathematically (Catchpole and de Mestre 1986), most of the so-called "physical models" are just heat transfer models, as they assume or use empirical relationships to derive combustion processes outputs, e.g. as flame radiometric temperature and flame geometry, which will be used in the heat transfer computations. Such models are considered by certain authors to be "semi-physical" or semi-empirical models (Konev 1993; Grishin 1997). These mechanistic models base their calculations in the heat transfer processes through a heat balance equation applied to a unit volume containing fuel and air, and isolating and using one or more heat transfer processes in one or two (in more sophisticated models, e.g., Albini 1985b; Albini and Stocks 1986) dimensions.

Much of the complexity in physical modeling of the spread of a line fire is the isolation and the determination of the physical process governing heat transfer, although it is assumed through experiments and computations that forest crown fires are spread mainly by thermal radiation (Telitsin 1968, Albini 1996), and the assumptions that have to be made concerning combustion outputs. A fire-spread model that assumes a single predominant heat transfer mechanism would be not applicable to situations where that heat transfer process is not the predominant one anymore. In the same context, the assumption of certain flame properties, such as emissivity and radiometric temperature, preclude the use of the model in the wide spectrum of fire behavior situations existing at a single moment along a wildfire perimeter. Apart from the large number of assumptions and approximations used to derive certain unknown fire characteristics, the physical models are also limited by the difficulty in modeling certain extreme fire phenomena. Extreme fire behavior phenomena, such as prolific spotting ahead of the fire front and the effect of massive fire whirls due to turbulence (Van Wagner 1971), common to crown fires in certain fuel complexes, are believed to play a significant role in fire spread but are not accounted in crown fire spread modeling.

Several mechanistic models developed to predict crown fire spread have been published in the literature (Kurbatskiy and Telitsin 1977; Fleeter et al. 1984; Albini 1985a, 1985b; Telitsin 1992; Grishin 1997). As a common characteristic, the various models considered radiation as the dominant heat transfer mechanism, since near the fire front the movement of air is towards the fire rather than away from it (Albini 1996). Main differences between them are relative to how the volùme element is positioned in the fuel bed, how the fuel medium is considered, conditioning the way radiation propagates and scatter in the fuelbed, and simplifying assumptions. Kurbatskiy and Telitsin (1977) published a radiation driven fire spread model which considered external (flame) and internal (combustion zone) radiative heat transfer. The incorporation of the combustion zone radiation component makes the model applicable to thick fuel beds such as the crown fuel stratum. These authors considered the fuelbed depth of the volume element as one equal to the effective length of free radiation, and composed by isothermally fine fuels. Their model considers heat losses as negligible and an energy balance equation is used to give rate of spread. Fleeter et al. (1984) approached the modeling of crown fire spread from an approach distinctly different from the usual heat transfer problem. They concentrated on the dynamics of the convective-plume interaction with a cross-flow, to predict quasi-steady one-dimensional fire spread in an open atmosphere, by passing fuel loading as an important variable, and considering the strength of the buoyant plume as dependent on the fireline intensity computed from the consumption of fine fuels. This computation of the buoyant energy in the convection column come in disagreement with other authors, such as Rothermel (1983), who considered the convection pulse as the result of the consumption of larger fuels, with 10- and 100-hr time lag. Grishin's (1997) deterministic approach considered conservation of energy, mass and momentum for modeling several phenomena of crown fire behavior. This model, considered as "encyclopedic" by Albini (1996) and as a "refined scheme of physical and chemical processes occurring in the fire zone" by its author, apart from the inclusion of fluid mechanics processes referred above, describes the kinetics of pyrolysis and assumes that the transfer of energy by radiation is affected by the radiation, absorption, reflection and scattering by fuel components and byproducts formed during the combustion of forest fuels.

Albini's (1985a,b) radiation driven fire spread model has been considered by the fire behavior research community as a promising model for prediction of crown fire spread. The model attempts to predict the velocity of displacement and shape of the ignition interface within the fuelbed from a local energy balance using an iterative process. The model requires a description of the fuel complex, with fuels assumed to be blackbody particles. Also assumed are knowledge of the effective radiometric temperature in the burning zone and in the free flame, flame height and tilt angle (Albini 1996). Two parameters, effective radiometric temperature of the burning zone and the radiation intensity from free flame relative to that from burning zone, remain to be determined and were empirically estimated. Albini and Stocks (1986) compare the model outputs with a set of fire behavior data from high-intensity experimental fires in immature jack pine (Stocks 1987) The model produced good results in predicting active crown fire spread rates and ignition interface shape after scaling flame geometry from one of the fires, assuming reasonable values for the two unknown parameters referred to above, and modeling the process as with two layers and, considering a new vertical radiation source extending from the base of the canopy to the ground. The model was not considered closed, as flame height, tilt angle and radiometric temperature were estimated and not predicted. Albini (1996) extended the model, by (1) including more than one fuel stratum (in the previous version of the model, other fuel stratum were considered as thermally inert); (2) homogenizing each fuel bed into an equivalent uniform size class; and (3) implementing the Albini (1981) wind-blow flame model for prediction of flame height and tilt angle from fireline intensity. The model is closed through an iterative process, in which rate of spread and flame geometry parameters are related, through the relation between rate of spread – intensity – flame characteristics – rate of spread, until a stable solution is achieved.

These physically based models, apart from their heavy computation requirements, have not been subject to output evaluation (apart from Albini and stocks 1986), which raises questions relatively to their use as management tools. The author sees their utility more as a method to better understanding fire phenomena, and from which simpler empirical modeling approaches can be based.

From the two crown fire modeling approaches referred here, the empirically based is the one that have produced operational fire management tools. In the U.S. the Rothermel (1991a) crown fire spread model is used operationally in various fire management aspects. The Canadian Fire Behavior Prediction System (Fire Danger Group 1992), the Mk 5 Forest Fire Danger Meter for eucalyptus forests in Australia (McArthur 1967; 1973), and the "Red Book", for eucalyptus stands and pine plantations in western Australia (Sneeuwjagt and Peet 1985), are examples of the utility of this approach in producing operational fire management tools. A brief review of these models will be follow, with special emphasis on Rothermel (1991a) model as it is the model adopted to predict crown fire spread in U.S. fuel complexes.

The Forest Fire Danger Meter Mark 5

The MacArthur (1967) Forest Fire Danger Meter (FFDM) appeared as an upgrade of the fire danger rating tables (MacArthur 1958) with the function of enable the forecasting of fire danger and the prediction of probable site specific fire behavior for fire control operations and prescribed fire application in eucalyptus forests. This meter is based on fire behavior information of 800 data points from experimental fire behavior studies and wildfire analysis over a wide range of environments in the Australian region, combining the effect of fuel dryness, wind speed, fuel quantity and slope. The meter was constructed without pre-conceived notions of the functional relationships between the variables (Noble et al. 1980). The fact that the fire danger meter was bound to a maximum value of 100, reflecting "worst possible" fire weather conditions, allows that under extremely severe fire weather, the meter tend to underestimate fire spread rate (Cheney 1988; Buckley 1992; McCaw et al 1992; Catchpole and de Mestre 1986).

Forest Fire Behaviour Tables for Western Australia

The Sneeuwjagt and Peet (1985) Forest Fire Behaviour Tables for Western Australia (FFBT) provide predictions of fuel (available fuel quantity and fuel moisture profiles) and fire behavior characteristics for various fuel complexes[1], along with daily variation of temperature, relative humidity and indices to support prescribed fire planning and fire suppression. The actual tables are the result of the evolution of the original ones (Peet 1965) by the acquisition of fuel moisture and fire behavior data along the years for the fuel complexes considered (Hatch 1969; Beggs 1976; Sneeuwjagt and Peet 1979). The tables were derived empirically from fire environment and behavior data from experimental fires and supplemented with wildfire data, using eye fitting and least squares procedures (Beck 1995). The FFBT consider as main inputs to predict fire behavior: (1) fuel moisture content; (2) available fuel quantity; (3) windspeed at 1-2 meters within the forest stand; and (4) slope. These four parameters are used to estimate a fire danger index (FDI), that with a fuel quantity correction factor and slope, is used to

---

[1] *Eucalyptus marginata*; *E. calophylla*; *E diversicolor*; *E wandoo*; *Pinus radiata*; *P. pinaster*.

estimate the spread rate of the fuel complexes with different fuel structural characteristics from the standard fuel (5 year old karri – *Eucalyptus diversicolor*).

As for the FFDM, the FFBT has been given reliable fire spread rate predictions for low intensity fires, but for extreme fire weather conditions, the outputs tend to underestimate the rate of spread of wildfires (Burrows and Sneeuwjagt 1988). This can be explained by several reasons. High intensity fire behavior studies can not replicate the full scale of fire phenomena existent in wildfires (e.g. massive short-range spotting, large-scale convection column interaction with the wind field). Data from well-documented wildfires are subject to a large number of uncertainties (e.g., fuels structural properties, weather data assumptions, fireline location and personal opinions in interviews).

Canadian Fire Behavior Prediction (FBP) System[2]

The Canadian Fire Behavior Prediction System (Fire Danger Group 1992) provides quantitative estimates of crown fire spread rates in various Canadian fuel complexes. The rate of spread is given by a S shaped asymptotic function (Van Wagner 1989) based on the relationship of the Initial Spread Index (ISI)[3] and fire spread data from a large database of experimental and wildfire data,. The predicted rate of spread is adjusted for the effect of drought in the availability of fuels through the use of the Buildup Index (BUI)[4]. From the various empirical models discuss here, the FBP is the one with a sounder scientific basis. The modeling approach was based not only on mathematical models and correlation techniques, but also in moisture physics, heat transfer theory, and physical theories of fire behavior (Van Wagner 1998). For the various conifers fuel types (C-1 to C-5, and C-7) the rate of spread follow a sigmoid curve, encompassing the effects of crowning and spotting, reaching an asymptote at higher ISI values. The lower section of the spread rate S-shaped curve represents surface fires, the steeper segment a transition zone between surface and crown fires and the

---

[2] The author participated and successfully completed the *Advanced Wildland Fire Behavior Course* and *Wildland Fire Behavior Specialist Course* of the Canadian Interagency Forest Fire Center.

[3] The Initial Spread Index is an intermediate index of the Fire Weather Index of the Canadian Forest Fire Danger Rating System (Van Wagner 1987).

[4] The Build up index is an intermediate index of the Fire Weather Index of the Canadian Forest Fire Danger Rating System (Van Wagner 1987).

flattened sector crown fire spread. The leveling off at higher ISI was chosen due to the lack of knowledge of fire spread characteristics at the extreme end of the ISI spectrum.

For the C-6 fuel type, conifer plantation, a dual equation model, with the same sigmoid shape, is applied to estimate rate of spread (Van Wagner 1993), as the more structured fuel complex allow an objective modeling with a separation of surface and crown fire (Fire Danger Group 1992). The lower curve is related to surface fire spread, and the upper to crown fire spread, with the space between the two curves associated with the transition between the surface and crown phase. Abrupt change exists in spread rate when surface fire intensity exceeds the critical surface fire intensity for combustion of the crowns, which is a function of the height of live crown base and foliar moisture content.

Foliar moisture content is used in the C-6 fire spread model for the estimation of the critical surface intensity and the crown fire spread. Although the effect of fuel moisture content on the heat of fuel ignition can be estimated assuming equation [1.4], the estimation of water content effect on crown ignition and crown spread is not easily made. Further discussion of the effect of foliar moisture content on crown fire initiation and crown fire spread are in Section 2.2 and 3.2 respectively.

Rothermel (1991a) crown fire spread model

Rothermel (1991a) developed an empirically based crown fire spread model based on the correlation between predicted surface fire spread rate for NFFL fuel model 10 (Albini 1976) and observed average crown fire rates of spread from 8 wildfires with sustained crown fire runs. A ratio between observed and predicted spread rates yields an average value of 3.34, with a standard deviation of 0.59. The model simply states that crown fire spread rate will be 3.34 times faster than the predicted rate of spread for fuel model 10. Several major assumptions were made in the process of preparing the data for analysis. It was considered that the surface fire spread rate to be used would be the one predicted with fuel model 10, considering windspeed measured in the open at 6 meters and using a fixed wind reduction factor of 0.4.

With the objective of providing an operational fire management tool, Rothermel produced a series of nomograms designed to provide an estimate of crown fire behavior in wind driven fires. These nomograms also help identify the possibility of the occurrence of plume dominated crown fires. The nomograms estimate (1) the rate of spread by the above referred processes, (2) fireline intensity by Byram (1959) formula, (3) flame length by Thomas (1963) model, and (4) the power of the fire and the power of the wind field by the Byram (1959) energy criterion equations. The results are then used to identify the onset of a convection column dominated fire.

Besides the assumptions already referred to and those embodied in the other above mentioned models, other major assumptions and limitations of the crown fire spread model is that the model should be restricted to the Northern Rocky Mountains conifers fuel complexes. The model also assumes level ground for estimating average fire behavior, and the effect of short range spotting on the overall spread rate of the fire is accounted for (Rothermel 1991a).

Although Rothermel explicitly listed the assumptions and limitations of the crown spread model, the model has being pushed outside its bounds without previous evaluation of its applicability. The Rothermel (1991a) nomograms are used for calculation of crown fire spread rates in the national level National Wildfire Coordination Group S-490 Advanced Wildland Fire Behavior Calculations Course (NWCG 1993). Finney (1998) FARSITE fire growth model uses the 3.34 factor to estimate the maximum crown fire spread rate. This constant is used in the computation of the active crown fire spread rate through the use of Van Wagner (1993) theory for determination of this parameter in C-6 fuel type of the Canadian Fire Behavior Prediction System. Also FARSITE is taught as a regional level course (S-493) by the National Wildfire Coordination Group, which will increase the use of the Rothermel crown fire spread model to fuel complexes different from the originals. Van Wagtendonk (1996) used FARSITE to analyze how specific fuel and stand treatments in mixed conifer-pine typical of the Sierra Nevada affect fire behavior, extending the use of the model outside the fuel type for which it was designed.

1.4. MODEL EVALUATION

Testing and evaluation of models is an important and fundamental component of the scientific method (Fleming and Shoemaker 1992), leading to model understanding and the increase of their credibility (e.g. Albini and Stocks 1986). Model evaluation, namely their validation, has been seen in different ways by several authors, from the concept that model validation is impossible (following the hypothesis testing concept that theories can only be proven wrong), to considering that models can be validated (e.g. McCarl 1984, and Law and Kelton 1991 in Rykiel 1996).

An important aspect when considering model evaluation is the definition of the criteria that should be followed. The definition of evaluation criteria depends on the type of model being evaluated and the potential application of the model. Theoretical models developed to understand certain physical and chemical phenomena (e.g. Grishin 1997) should be evaluated in a different form than operational models build to support decision making (Rothermel 1972; Albini 1976; Fire Danger Group 1992; Alexander 1998). Although theoretical and operational models should both be evaluated through their conceptual validity to prove that the model is scientifically valid, the later should be subject to a through evaluation, encompassing sensitivity analysis, comparing results with other models, testing under extreme condition, and predictive and statistical validation.

In the following section Rothermel (1991a) crown fire spread model is evaluated on its conceptual validity and operational validation.

1.4.1. Conceptual validity

As described in Section 1.3, Rothermel (1991a) crown fire spread model consists in an empirically based adjustment of the surface fire spread rate predicted by the Rothermel (1972) semi-empirical model, with modifications from Albini (1976), for fuel model 10 (Albini 1976). This fact makes that the behavior of the crown fire spread model directly follows the output of the surface model, although it is know that fire environment variables do not affect the behavior of fires burning as a surface or crown fires in the same way.

The Rothermel (1972) surface fire spread model consists in an ingenious blend of heat transfer principles and laboratory experimental fire data. The laboratory nature of the model may introduce a scale error when extrapolating the use of the model to phenomena as crown fires. The ranges in wind and fuels used in the laboratory experiments, and the fire behavior exhibited in these experiments, have different magnitudes relatively to the situations encountered during crown fire spread. Crown fires exhibit intensities up to four orders of magnitude higher than the laboratory experiments. Wilson (1990) points out that the empirically derived functions "might not be universally applicable to other fuel particle configurations". Empirically derived parameters as the propagating flux, the fraction of the reaction intensity that drives the fire, might not hold consistent for combustion zones characteristic of crown fires.

The fact that the Rothermel crown fire model is function of the NFFL fuel model 10, which has a low sensitivity to wind due to its packed fuel bed and moderately small fuel particle surface to volume ratio, makes the crown model exhibit some insensitivity to wind speed variation. This aspect is illustrated in Figure 1.1.a, where the wind factor (Rothermel 1972) is computed for three structurally different surface fuelbeds. Fuel model 1 represents short grass, fuel model 5 shrubland, and fuel model 10 timber litter and understory. Fuelbed bulk density and surface area to volume ratio increases from fuel model 1 to 10. This aspect will be further explored in Section 1.4.2.2.

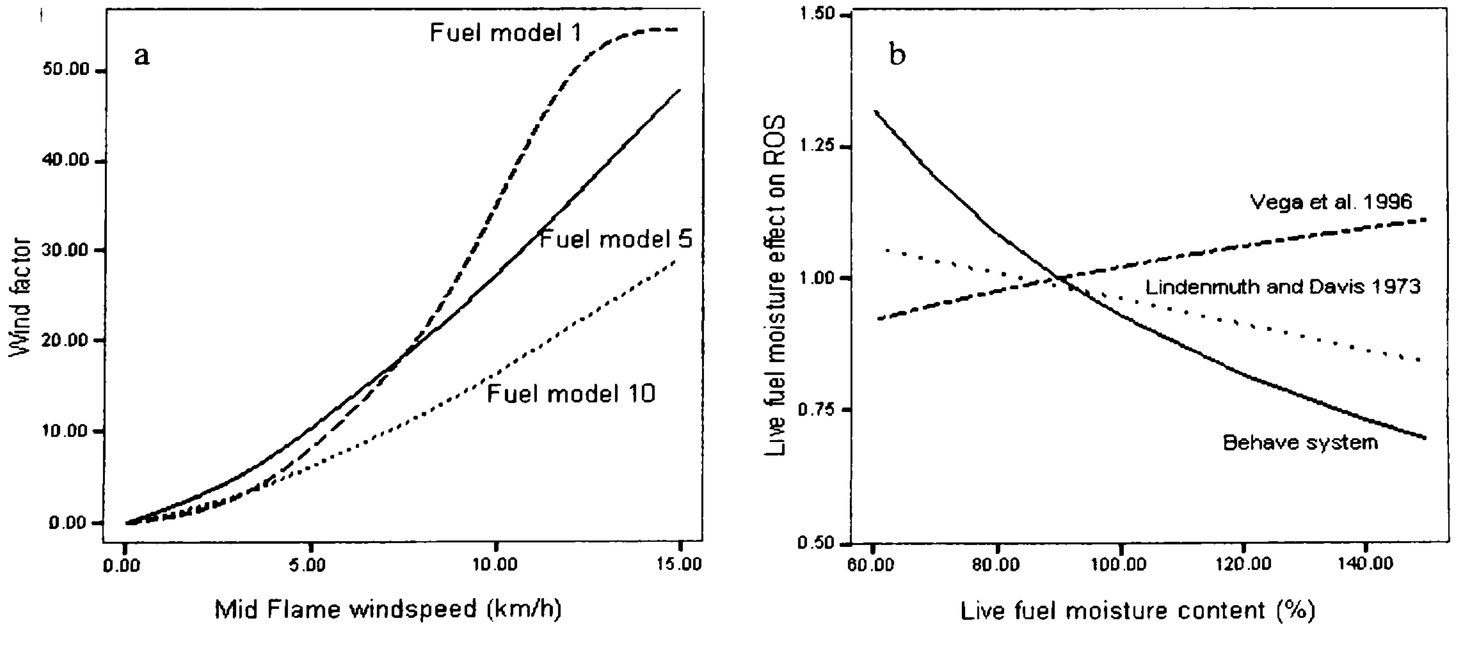


Figure 1.1. Plots of (a) wind factor effect on Rothermel (1972) model and (b) comparison between live fuel moisture effect on fire rate of spread on BEHAVE system and published empirical fire spread models.

The live fuel moisture content effect on the surface fire spread rate model is other aspect that might not hold applicable to crown fire phenomenology. The surface fire spread model considers the damping effect of the moisture existent in shrub live foliage and fine woody fuels in the same manner of dead fuels, but does not include foliar moisture content as a variable. Theoretically live fuels would not burn without the heat energy provided by dead fuels, but certain fuel complexes sustain combustion through the live fuels with minimal contribution from dead fuels. It has been noted in several fuel complexes, e.g. shrublands, where there is a major live fuel component burning in the flame front, that the damping effect of live fuel moisture is not statistically significant (Marsden-Smeley and Catchpole 1995; Fernandes 1998).

Figure 1.b illustrates live fuel moisture effect[5] on two shrub fuel complexes derived from empirical models and for fuel model 4 (Albini 1976) using the BEHAVE system. The BEHAVE system is the model where live fuel moisture have a stronger effect on fire spread. The effect of live fuel moisture in Vega et al. (1996) model is the opposite of what would be expected. This reinforces the idea that in certain fuel complexes dominated by shrubs live fuel moisture has no meaningful effect on rate of spread. Further considerations on the effect of moisture content of live fuels in crown fire behavior are in Sections 2.2 and 3.2.

Rothermel crown fire model does not consider crown structure as a variable influencing fire behavior. This disagrees with the theoretical considerations of Van Wagner (1977) who considered canopy bulk density as a key variable in the discrimination between passive and active crown fire spread. Further considerations on the effect of canopy bulk density in crown fire behavior are in Section 3.2.

1.4.2. Operational validation

Operational validation of fire behavior models has been recognized as an important step in model acceptance, and has been performed to some of the fire behavior models used operationally in North America. Surface fire spread outputs from the

Rothermel (1972) surface fire spread model, adjusted by Albini (1976), has been evaluated for several fuel types, as logging slash (Brown 1972; Bevins and Martin (1978), grasslands (Sneeuwjagt and Frandsen 1977; Gould 1988; van Wilgen and Wills 1988) and shrublands (van Wilgen et al. 1985; Marsden-Smeley and Catchpole 1995; Cuinas et al. 1996), based on data originated from experimental fires, prescribed fires and wildfires. Canadian FBP fire spread models have been evaluated mainly from wildfire data from case studies (e.g. De Groot and Alexander 1986; Stocks and Flannigan 1987; De Groot and Schisler 1988; Hirsch 1989) through comparisons between predicted and observed spread rates. Rothermel (1991b) compared predicted (by his crown fire model) and observed spread rates for some well know wildfire crown fire runs in the United States. Van Wagner (1977) qualitatively analyzed his crown initiation and spread theory with data from experimental fires and wildfires.

The analysis of these evaluation studies reveals the use of subjective and qualitative measures of model performance in some of the situations, and the above-mentioned nonexistence of validation standards, namely the type of statistical tests and acceptable levels of model performance. From the analysis of the fire behavior model evaluation studies and other validation studies of ecological models (Mayer and Butler 1993; Oderwald and Hans 1993; Bacsi and Zemankovics 1995), an operational validation protocol based on Rykiel (1996) approach was defined to evaluate Rothermel crown fire spread model. The defined protocol for fire behavior model evaluation include the following analysis:

Data validation – Data validation concerns with the definition and selection of real world data that represents the phenomena of interest and will be used in statistical validation of the model. This aspect assumes particular importance when analyzing crown fire data due to the relative inaccuracy and bias that may exist in data originated from wildfire case studies.

Sensitivity analysis – Sensitivity analysis aims to reveal the influence of model components and input parameters in the behavior of the model, identifying parameters that cause little or greater fluctuations in model outputs.

---

[5] Live fuel moisture effect is the ratio between the rate of spread with varying live fuel moisture and the rate of spread of average live fuel moisture. Average live fuel moisture as 84 % for Lindenmuth and Davis

Comparison with other models – Comparison of outputs of several models of the same phenomena provide an understanding of possible deficiencies in the models and their limits of applicability.

Predictive validation - Predictive validation consists in the comparison of model outputs with an independent dataset of the phenomena under study.

Statistical validation – Statistical validation consists in a variety of tests aimed to determine model efficiency, bias, and error characterization.

1.4.2.1. *Data validation*

For the various types of evaluation tests to be performed to Rothermel crown fire spread model several different kinds of data were used. For the sensitivity analysis, due to the fact that there are multiple interacting factors within the model being evaluated, and that their effect in fire spread rate is not linear, the analysis was performed under two distinct fire weather conditions. One selected situation [Kenshoe Lake experimental fire # 5 (Stocks 1989)] was conducive to crown fire spread in the lower spectrum of fire intensity. The second situation [Lily lake wildfire (Rothermel 1983; Alexander 1991)] was on the extreme side of the fire intensity spectrum (Table 1.1).

Table 1.1. Reference values used in sensitivity analysis

	Kenshoe Lake #5	Lily lake wildfire
Temperature (C°)	23	20.6
Rel. humidity (%)	39	16
10 m open wind (km/h)	29	37
1 hr. FM (%)[1]	8	5
10 hr. FM (%)[2]	9	6
100 hr. FM (%)	10	7
Live woody FM (%)[3]	75	75
Foliar moisture content (%)[4]	100	100

[1] - 1 hr fuel moisture values were estimated from FBA tables (Rothermel 1983).

[2] 10 and 100 hr fuel moisture contents were arbitrarily assigned plus one and two percent points of the value of the 1 hr fuels.

[3] Live woody moisture was arbitrarily assigned.

[4] - Foliar moisture of Kenshoe was estimated from FBP system (Fire Danger Group 1992). Foliar moisture of Lily lake was arbitrarily assigned.

(1973), 90 for Vega et al (1996) and an arbitrary value of 90 % for the BEHAVE system.

In order to compare the Rothermel crown fire model outputs with other crown fire models it was decided to compare model outputs for a particular site during a fire season. For this, the 13:00 h data from Moose Creek weather station, Montana was used for the year of 1994. Weather station selection was based on data availability (the data was available within the FIREFAMILY+ software). The year of 1994 was chosen from the available data (period 1980 to 1998) as it was the year characterized by higher fire danger indexes values and consequently higher potential for crown fire occurrence.

In order to evaluate the Rothermel crown fire spread model against crown fire spread data it was decided to compare Rothermel crown spread model with data from high intensity experimental fires. The choice of using experimental fires instead of data from wildfire case studies is due to the fact that the wildfire data is subject to non-quantifiable uncertainty, namely due to fuels heterogeneity, representativeness of weather data and difficulties in locating the flame front.

The choice of the experimental fire data for use in model evaluation was restricted by the relative small amount of such data available in the literature. The data used (Table A.1, Appendix) are the experimental crown fires available in the literature to the knowledge of the author. The database for model evaluation comprise the following fuel complexes:

- Immature Jack pine (Stocks 1987)
- Mature Jack pine (Quintilio et al. 1977; Van Wagner 1977; Stocks 1989)
- Red pine (Van Wagner 1977)
- Black spruce (Alexander et al. 1991)

Two wildfires, Gwatkin lake (Van Wagner 1965) and CR-6-82 (Alexander et al. 1991) were included in the database due to the weather station proximity, knowledge of stand and fuel characteristics, and reliable fire behavior documentation.

Fuel complex description

The various fuel complexes used in this evaluation cover a reasonable range of fuel complex characteristics. Stand structure of the various experimental fire plots are depicted in Table 1.2. The fuel complexes used in this analysis cover a range from well stocked stands with basal areas up to 35 m^2/ha to open stands with basal areas of 1.5 m^2/ha. Stand heights range from 20 meters in mature jack pine stands to 4 meters in the open black spruce stands. Figure 1.2.a through c characterize the variability in crown fuel load, canopy bulk density and height of crown base of the several plots. Canopy bulk density in the dataset covers a wide spectrum of this parameter, from 0.10 to 0.32 kg/m^3. Crown load and height of crown base data do not homogeneously cover the range of the data. Detailed information on the crown fuel characteristics of each experimental plot is summarized in Table A.5 in the Appendix.

Table 1.2. Forest stand structure for the various experimental fires

Site	Species	Stand density (Trees/ha)	DBH (cm)	Stand height (m)	Basal area (m^2/ha)
Kenshoe	Jack pine (Black spruce)	2057 (1093)	13.3 (5.9)	18-20 (1-13)	31.2 (4)
Sharpsand	Jack pine	9276	5.14	10	18.6
DL 4	Jack pine	1877	10.7	6 – 12	16.6
DL 6	Jack pine	532	18.4	12 - 18	14
PL 1	Black spruce	2220	5.2	4.1	6.77
PL 2	Black spruce	896	5.7	4.3	2.96
PL 3	Black spruce	1154	7.3	5.2	6.78
PL 4	Black spruce	1030	5.7	4.1	3.85
PL 5	Black spruce	877	8	5.6	7.41
C6	Red pine	3200	14	14	50
C4	Red pine	3200	14	14	50
R1	Red pine	3200	14	14	50
GL-A	Jack pine	1600	15	20	27
GL-B	Jack pine	1800	15	18	25
SC	Jack pine	890		18	15
ADK	Black spruce	597	5.6	4.4	1.5

Figure 1.2.d. illustrates the crown fire spread criterion distribution of the experimental fires dataset. Analysis of the spread rate criterion for active crowning (Figure 2.d) shows that the data is evenly divided into values above and below 1, the theoretical threshold that separates passive (criterion < 1) from active (criterion >1) crown fire spread conditions. This might have some influence on the scatter of observed versus predicted points, as we are facing two distinct modes of fire spread in terms of the contribution of each fuel strata to the propagating flux, and the crown fire model being evaluated does not consider this fire behavior characteristic.

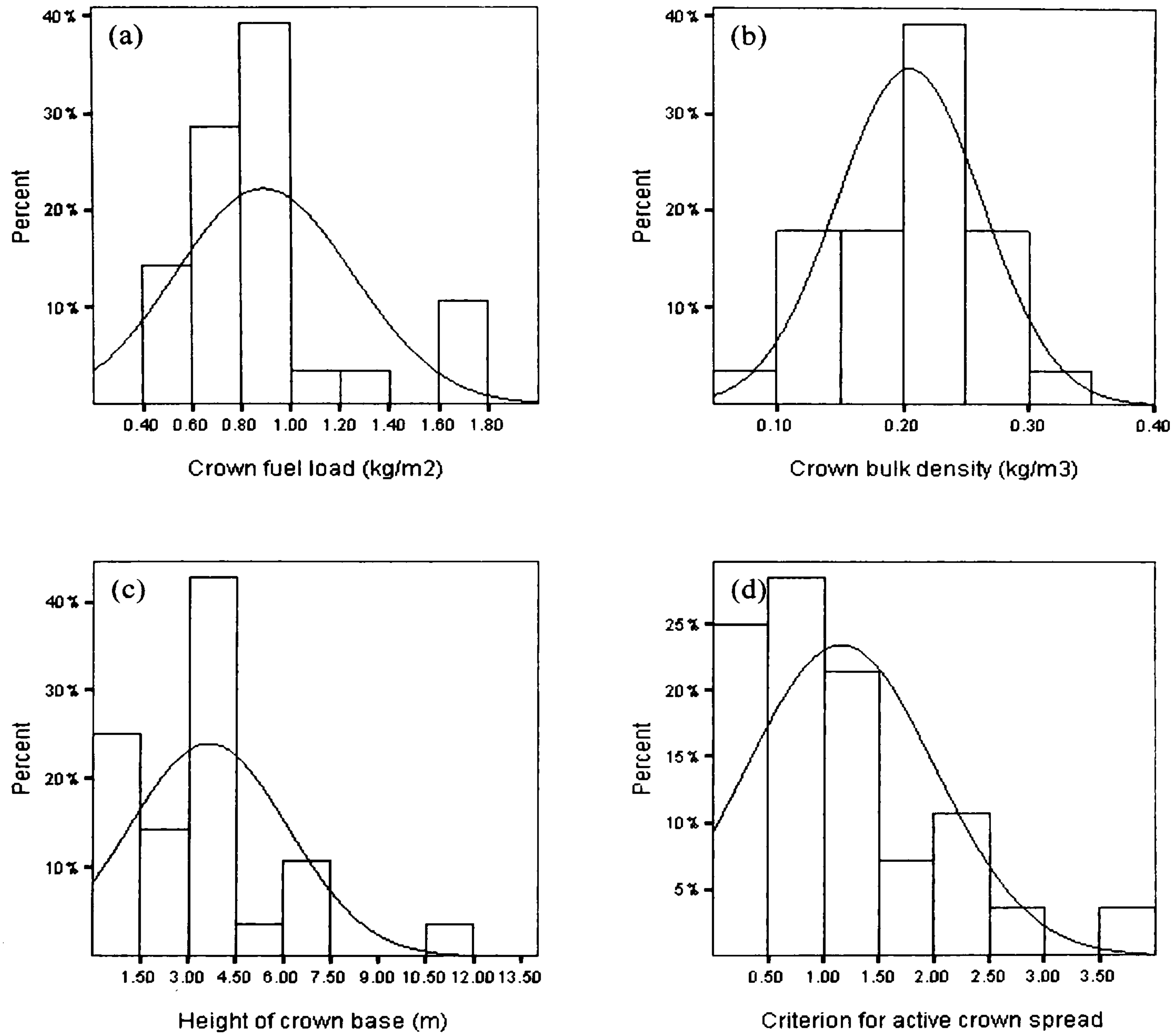


Figure 1.2. Distribution crown fuel strata structural variability (a, b, c) and crown fire spread criterion (d) for the experimental fires dataset.

Representativeness of fire behavior data

To assess the representativeness of the select experimental fire database of the range of fire behavior exhibited in crown fires, the experimental fire database was compared with wildfire crown fire data existent in the Canadian FBP system (Figure 1.3.a and b). Experimental fires spread data show a distribution skewed to the right, a consequence of several logistic and safety constrains that have limit past experimental crown fires to lower fire environment and behavior thresholds (Alexander and Quintilio 1990). It is also verified that the experimental fire data do not cover the range of behavior exhibited by crown fires in the wildfire database (Figure 1.3 b). Although this maybe considered a weakness in the selected test data, it was considered to be an acceptable compromise to evaluate model performance using highly reliable data while rejecting high intensity wildfire data.

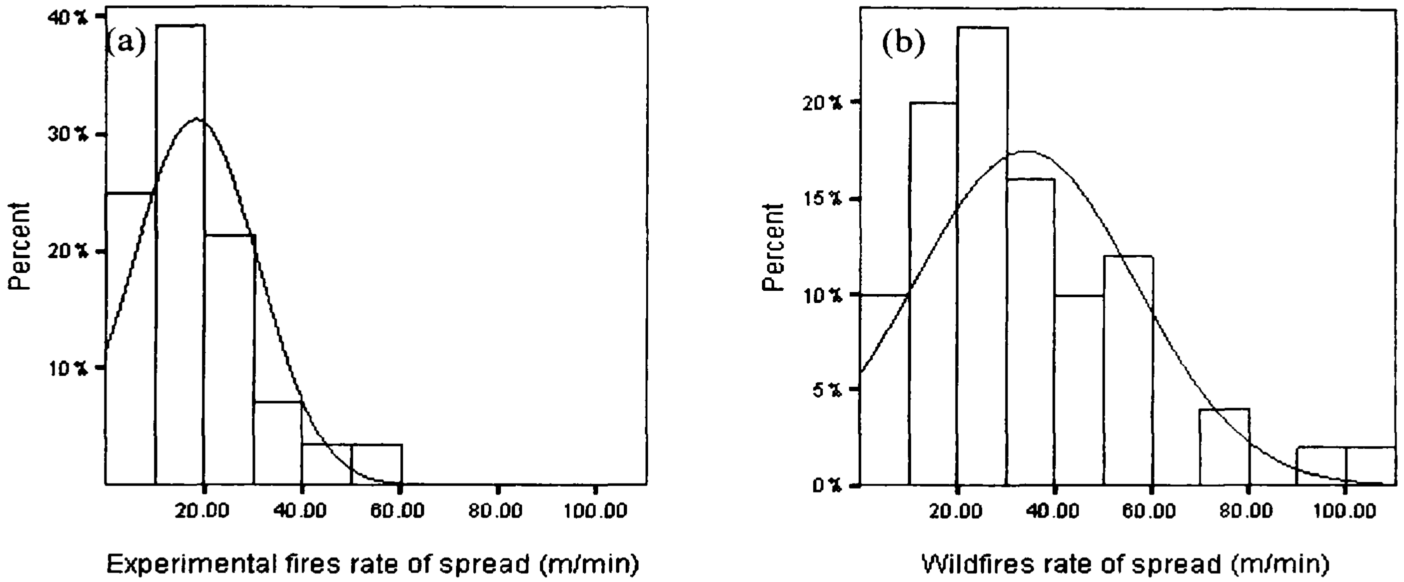


Figure 1.3. Frequency distribution of (a) experimental crown fire data used in Rothermel (1991a) crown fire model evaluation and (b) wildfire crown data in the FBP database.

1.4.2.2. *Sensitivity analysis*

When considering models one should be aware of the sensitivity that the model has to its several inputs. Sensitivity analysis is used in the identification of the degree of sensitivity of model components, attempting to reveal model parameters and sub-models which when perturbed cause the greatest fluctuations in model predictions (Vanclay and Skovsgaard 1997), revealing components with high and low sensitivity. Another important aspect of the sensitivity analysis is to assess the degree of uncertainty in the outputs that is associated with certain lack of precision in the inputs. This acquires great importance in fire behavior prediction as the interaction between certain variables under or above certain thresholds greatly magnifies the level of fire behavior exhibited. Trevitt (1988) illustrated this effect on a fire behavior database from McArthur (Cheney 1981), analyzing the combined effect of windspeed and dead fuel moisture on spread rate in a dry sclerophyll fuel complex.

Though the importance of sensitivity analysis in the modeling process has long been recognized, many models are presented in the literature without this kind of analysis. Such analysis may give insight about the need for adjustment or improvement of models, indicate future research, and allow the omission of insensitive components. This omission may be attributed to the complex process of sensitivity analysis and the difficulty to interpret results (Mahamah 1988). As pointed by Leemans (1991), the most complete sensitivity analysis scheme would combine the effect of all possible parameter combinations and their interaction in a factorial design. The complexity of this process leads to the use of simplified sensitivity analysis schemes (e.g. Bartlink 1998; Bevins and Martin 1978; Mahamah 1988, Dimitrakopoulos 1987).

For the present analysis the relative sensitivity test, RS (Bartlink 1998), was choose. RS is a dimensionless analysis using the following criteria:

$$RS = \frac{V_{+10\%} - V_{-10\%}}{V_{def} 0.2} \qquad [1.9]$$

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 percent; V_{def} is the resulting value of the critical parameter under default conditions, the value 0.2 is the relative range (1.1-0.9) of the parameter to be analyzed. The 10 % intervals were arbitrarily selected.

Table 1.3. Relative sensitivity (RS) of rate of spread output of several crown fire spread models to fine dead fuel moisture content, 10 m windspeed and live fuel moisture content. Reference situation is Kenshoe Lake #5.

Input parameter	Rothermel 1991	FBP C-3	FBP C-6	FBP C-7
1 hr Fuel Moisture	- 0.238	- 3.047	5.57	- 2.295
10 m Windspeed	1.428	2.930	5.402	2.213
Live FM	- 0.714	-	3.592	-

Table 1.4. Relative sensitivity (RS) of rate of spread output of several crown fire spread models to fine dead fuel moisture content, 10 m windspeed and live fuel moisture content. Reference situation is Lily Lake wildfire.

Input parameter	Rothermel 1991	FBP C-3	FBP C-6	FBP C-7
1 hr Fuel Moisture	- 0.224	- 0.545	- 0.150	- 0.606
10 m Windspeed	1.343	1.230	0.343	1.367
Live FM	- 0.597		- 1.725	

Relative sensitivity (RS) indicates the degree of variation in the output introduced by the change in the input parameter. A RS score of 0 indicates that there is no response in the output due to input variation. RS of *n* indicates that the relative response is *n*-fold. Analysis of Rothermel crown fire model RS scores (Table 1.3 and 1.4) show that the model produce similar scores for both situations. The results show that the model has greater sensitivity to windspeed, followed by live fuel moisture and fine dead fuel moisture. Canadian FBP fuel type C-3, C-6, and C-7 were included in the analysis for model comparison purposes and will be analyzed in Section 1.4.2.3.

1.4.2.3. *Crown fire models comparison*

Spread rates outputs from the Rothermel (1991a) crown fire spread model were compared with rate of spread computed by models of three FBP (Fire Danger group 1992) system fuel types. The three fuel types selected for the analysis were C-3 (mature Jack or Lodgepole pine), C-6 (Conifer plantation) and C-7 (Ponderosa pine – Douglas-fir). Output evaluation was made by analyzing the sensitivity of the various models to the parameters varied in Section 1.4.2.2 and through direct output comparison.

When considering the RS scores (Table 1.3 and 1.4), an important point to consider in the analysis is the fact that the FBP rate-of-spread is predicted through a sigmoid model. Hence the RS is function of the slope of the area in the ISI-ROS curve. This is evident when comparing RS for the three FBP fuel types between the two default conditions. The Kenshoe outputs show large RS scores, a function of the location of the situation close to the inflection point in the sigmoid curve. The Lily Lake situation show modest RS scores as the situation is near the horizontal asymptote. This variation has some theoretical justification, as in the Kenshoe situation, fire behavior is more sensitive to variation in environmental factors, which coupled with being in the transition area between surface and crown fire spread originates larger changes in the outputs. The extreme fire weather that characterizes the Lily Lake wildfire situation produces fire behavior levels that are expected to not respond to small changes in the fire environment. Results suggest that for the Kenshoe #5 situation, the Rothermel crown fire spread model is less sensitive to the variation in wind and fuel moisture than the FBP models analyzed. The large RS scores computed for the FBP fuel type models indicate that the introduction of small errors in the input create significant output variation.

The relative insensitivity of the Rothermel crown fire model might be explained by the laboratory and semi-empirical nature of the Rothermel (1972) surface fire spread model. The relative small range of fire environment conditions used in the development of the model might explain the limited model response to wind and fuel moisture variation. The magnitudes of variation of these factors in the two situations used in the present study are outside the range of the original model development conditions.

Rothermel crown fire spread model outputs were compared with outputs of the above-referred models of the C-3, C-6 and C-7 FBP fuel types. Output analysis was based on fire weather data from the Moose Creek weather station, Montana in 1994. Outputs were bounded by a lower rate of spread threshold limit of 5 m/min predicted by C-6 model (the model that exhibit faster rates of spread for the fire weather data used). From the scatterplots in Figure 1.4 through 1.6 it can be seen that the various models respond to the same conditions in different ways. FBP C-3 and C-6 models predict much higher rates of spread them Rothermel crown fire model. Figure 1.4.b and 1.5.b depict the distribution of the ratios Rothermel/C-3 and Rothermel/C-6 predicted spread rates. C-3 model predict rates of spread at least twofold higher than Rothermel crown fire model in 83 % of the cases, and C-6 model in 92 % of the cases. C-7 model is from the models tested the one that more closely approaches Rothermel crown fire output. From Figure 1.6.a it can be noticed that the FBP system models used predict lower spread rates. For C-7 model, in 36 % of the situations the Rothermel/C-7 spread rate ratio are within the interval 0.75 – 1.25. Nevertheless, 80 % of the spread rate ratios are below 1. The better fit found for C-7 may be explained by the fact that C-7 represents open stands of ponderosa pine and Douglas-fir, lodgepole pine, and other conifers (Fire Danger Group 1992), that more closely resemble the fuel types of the original data used in the Rothermel (1991a) model development. C-3 and C-6 are characteristic of fully stocked stands, which have higher amounts of available fuel in the canopy, and consequently can release higher amounts of energy for the same fire weather conditions.

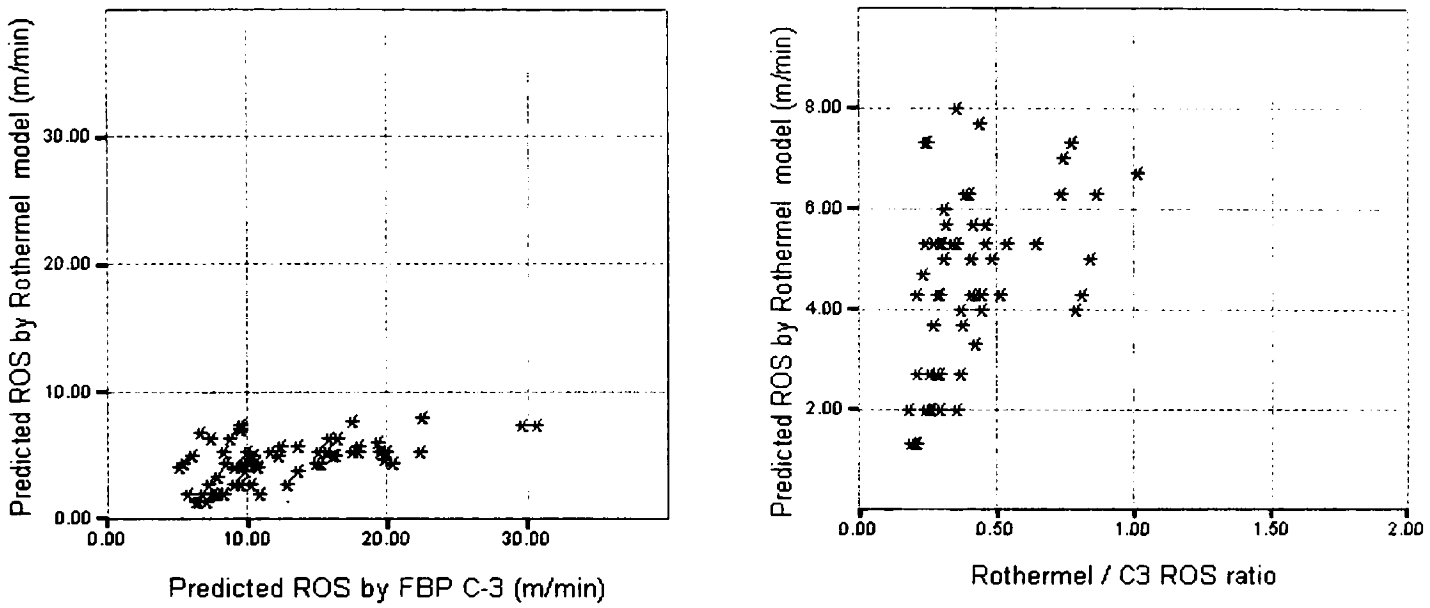


Figure 1.4. Scatterplot of predicted rate of spread by Rothermel crown fire model and FBP C-3 (a) and distribution of predicted spread rate ratios by predicted rate of spread by Rothermel (1991a) model.

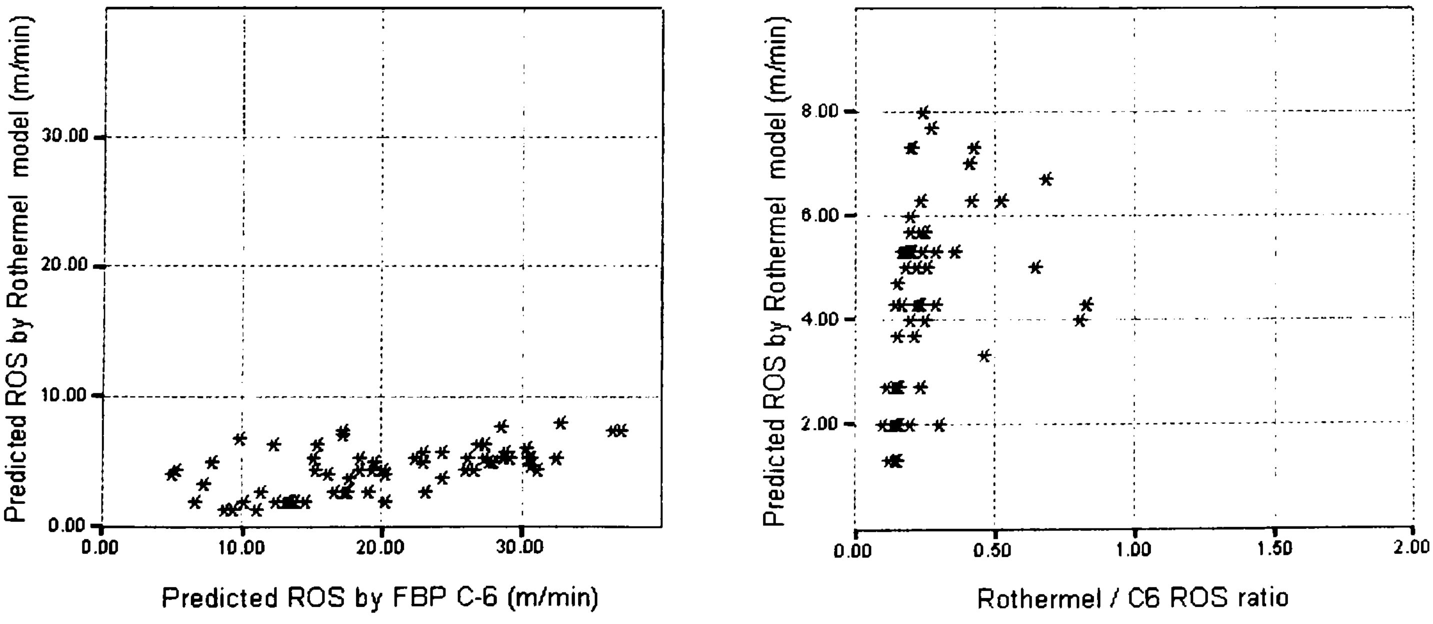


Figure 1.5. Scatterplot of predicted rate of spread by Rothermel crown fire model and FBP C-6 (a) and distribution of predicted spread rate ratios by predicted rate of spread by Rothermel (1991a) model.

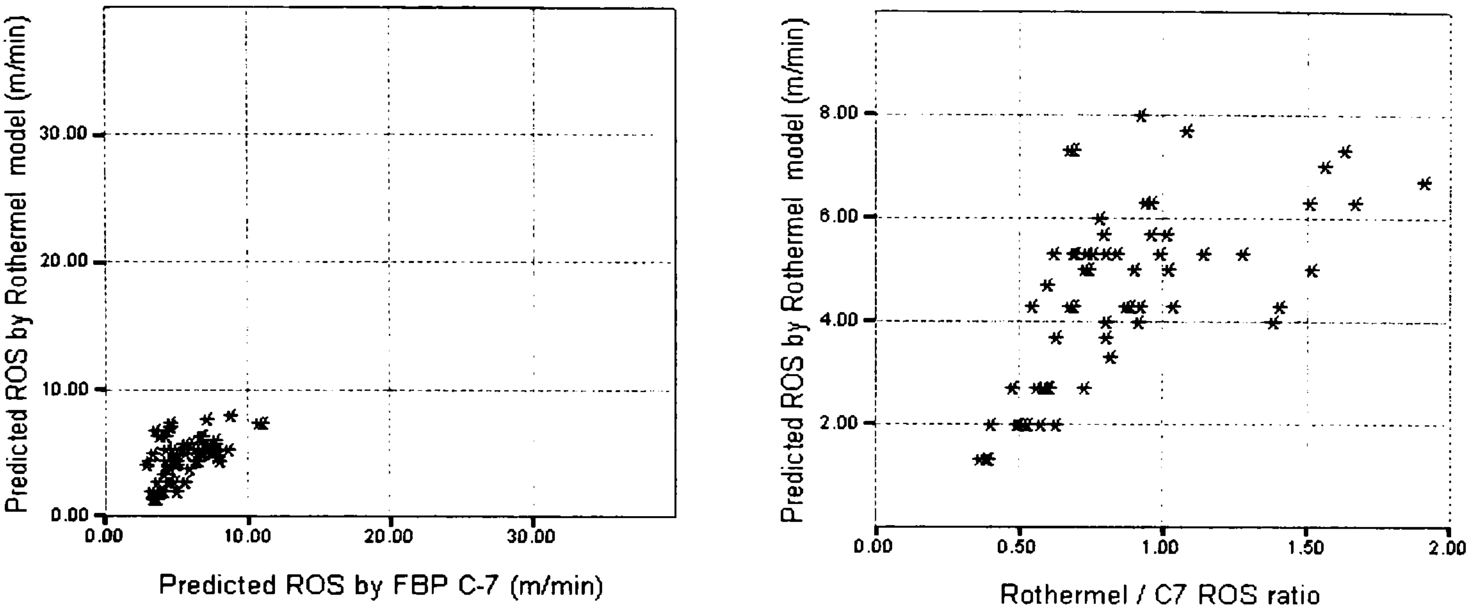


Figure 1.6. Scatterplot of predicted rate of spread by Rothermel crown fire model and FBP C-7 (a) and distribution of predicted spread rate ratios by predicted rate of spread by Rothermel (1991a) model.

1.4.2.4. *Predictive validation*

Predictive validation aims to assess how well a model forecast the behavior of real world systems. In the present work this was accomplished through comparison of model outputs with crown fire spread data from well-documented experimental fires referred previously.

The scatterplot (Figure 1.7.a) between observed and predicted[6] rates of spread show that Rothermel crown fire model tend to under-predict crown fire spread rates. Analysis of the spread data stratified by fuel type show that the model behaves reasonably well for the mature jack pine data (with the exception of wildfire GL-B). Model predictions for the other fuel types show consistent under-prediction trends.

The linearity of the trends, and their different slopes suggest that other factors that are not incorporated in the Rothermel crown fire model, as crown fuel structural

---

[6] Outputs from Rothermel crown fire spread model assume constant live woody fuel moisture content of 80 %. Fuel moisture of 10- and 100- hr timelag fuels was set to 12 and 13 %.

properties, might have a significant effect on crown fire spread rate. This lead to the hypothesis that a robust empirical crown fire spread model should discriminate major fuel complex characteristics. The linear under-predicting trends observed in the predicted-observed data points may also be explained by a lack of sensitivity of the model to the variation in wind, as indicated before.

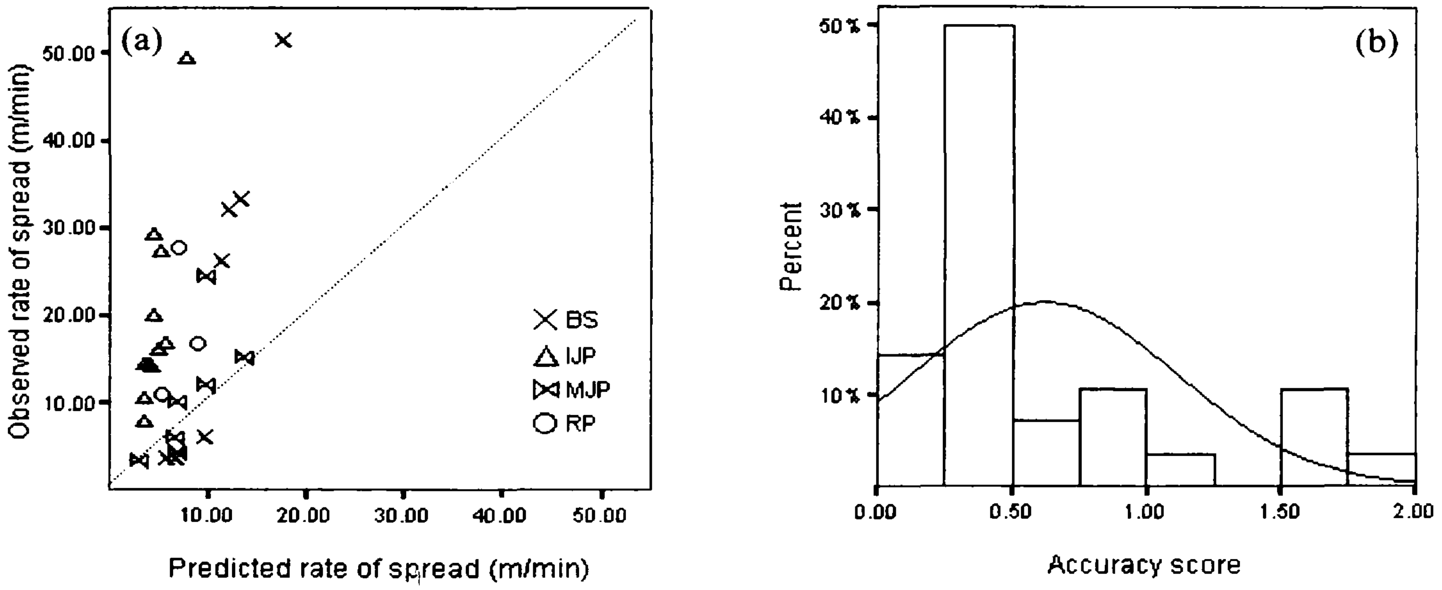


Figure 1.7. (a) Observed versus predicted crown fire spread rates. Dashed line is line of prefect fit. (b) Accuracy score distribution. BS – Black Spruce; IJP – Immature Jack Pine; MJP – Mature Jack Pine; RP – Red Pine.

The overall performance of the Rothermel crown fire spread model to the crown fire data used in this evaluation can be assessed through the analysis of an accuracy score (Figure 1.7.b) composed of a ratio between predicted and observed values. This accuracy score allows determining the degree of over and under prediction relative to the observed rate of spread. The model under-predict 82 % of the situations, within which 64 % have a degree of under-prediction with scores below 0.5, meaning that the model outputs under-predict fire spread by more than twofold

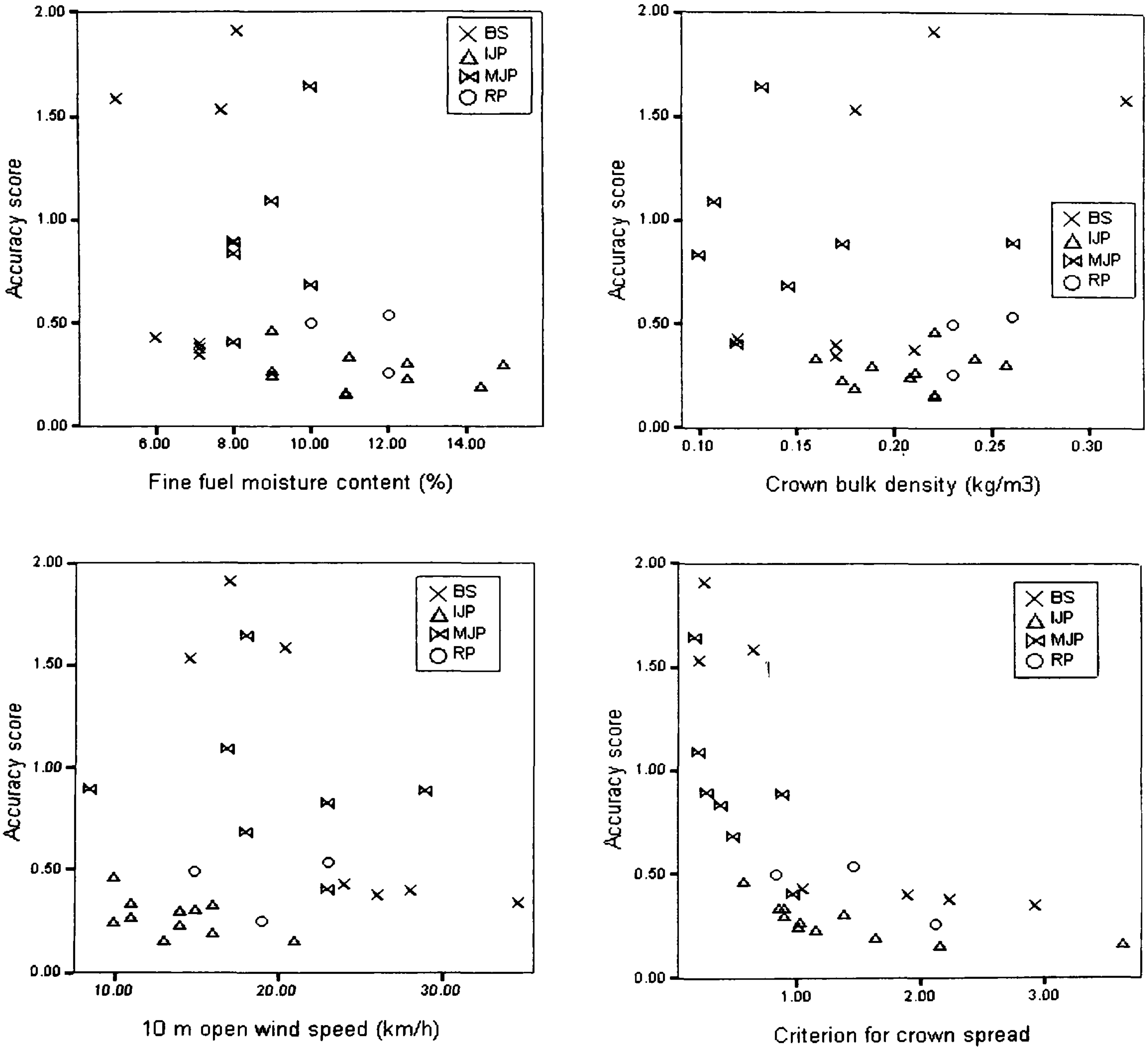


Figure 1.8. Distribution of accuracy scores with (a) fine dead fuel moisture, (b) canopy bulk density, (c) windspeed, and (d) crown fire spread criterion. BS – Black Spruce; IJP – Immature Jack Pine; MJP – Mature Jack Pine; RP – Red Pine.

Analysis of the distribution of computed accuracy scores with important fire environment variables, as fine dead fuel moisture, canopy bulk density, and windspeed do not suggest evident trends (Figure 1.8 a through c) that could explain some of the deviance produced by the Rothermel crown fire model. Analysis of the distribution of accuracy scores with the criterion for crown spread (Figure 1.8.d), shows that the over-prediction scores and scores within 0.5 and 1, with the exception of one data point, do not meet the criterion for active crown spread. These fires may be considered as passive crown fires, with the spread rate partially dependent on the surface spread phase. The data points that meet the active crown fire spread criterion are under-predicted by more than twofold. This shows that although both passive and active crown fires are consuming the crown fuel strata, their mechanisms of propagation and their sensitivity to the environment conditions might be different. Thus, requiring special attention when applying crown fire behavior models to situations where the criteria for active crown spread are not met (as modeled by Finney 1998).

1.4.2.5. *Statistical validation*

Statistical validation of models has some advantages over the subjective predictive validation due mainly to its quantitative nature. One of the main difficulties in establishing statistical validation criteria is the selection of technique and the degree of confidence interval that are meaningful for the phenomena being studied. Different tests may accept or reject simultaneously the same hypothesis (e.g. Mayer and Butler 1993; Mayer et al. 1994) leading to accept a type II error, i.e. accepting a model as valid when it is incorrect. As pointed by Rykiel (1996) probability levels of 0.05 are commonly accepted to test statistical significance in a variety of natural resources studies, but there is no objective basis for its selection mainly due to the nature and characteristics encountered in the system under study (Mayer et al. 1994). Being aware of these constraints, the following tests were arbitrarily selected for evaluate Rothermel crown fire spread model.

The statistical validation of Rothermel crown fire model was based on the analysis of the experimental fire data referred in Section 1.4.2.1, and qualitatively analyzed in Section 1.3.2.4. The model was evaluated through deviance measures and statistical tests.

Deviance measures

Two deviance measures used were mean absolute error, MAE (Mayer and Butler 1993), expressed as:

$$MAE = \frac{\sum |y_i - \hat{y}_i|}{n} \qquad [1.10]$$

being y_i the observed spread rate and $\hat{y}_i$ the predicted spread rate;

and mean absolute percent error (MA%E), expressed as:

$$MA\%E = \frac{\sum \left(\frac{|y_i - \hat{y}_i|}{y_i} \right)}{n} 100 \qquad [1.11]$$

Due to the difficulty in establish deviance criteria for model acceptability, these two deviance measures are better used as comparative measures between models, although the magnitude of the computed deviance give insight to model performance.

Statistical tests:

a) Computation of a modeling efficiency – EF (Mayer and Butler 1993), expressed as:

$$EF = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y}_i)^2} \qquad [1.12]$$

This parameter gives an indication of goodness of fit, having a lower theoretical bound of negative infinity and upper bound of 1. EF values close to 1 describe a good model. Negative EF values shows poor model performance.

b) Analysis of linear regression parameters

c) Simultaneous F-test for slope = 1 and intercept = 0 (Draper and Smith 1981; Mayer et al. 1994). This statistical test evaluate the hypothesis:

$$H_0 : (\beta_0, \beta_1) = (0,1)$$

being the alternate hypothesis:

$$H_1 : (\beta_0, \beta_1) \neq (0,1)$$

the hypothesis are tested by the following statistic:

$$Q = (\beta - b)' X'X(\beta - b) \qquad [1.13]$$

where, β are the population parameters to be tested;

$X'X$ the matrix term in the independent variable;

b vector of regression parameters;

The null hypothesis being accepted if:

$$Q \le ps^2 F(p, v, 1-\alpha) \qquad [1.14]$$

where, p is the regression degrees of freedom;

s^2 the variance;

v is $n-p$;

α is the probability level.

As could be expected from the previous qualitative analysis, results from the quantitative statistical tests performed reveal a poor performance of the Rothermel crown fire model to the database tested. Results in Table 1.5 display very high mean absolute error (11.6 m/min) and percentage error (57.8 %) scores., Computed negative modeling efficiency parameter (EF) reinforces poor model fit. Linear regression parameters show a lower R^2 (0.297), and intercept and slope coefficients quite distinct from the optimum 0 and 1 respectively.

Table 1.5. Validation parameters for the Rothermel crown fire model

Deviance measures		EF	Linear regression		
MAE	MA%E		R^2	β_0 (lower / upper 95%)	β_1 (lower / upper 95%)
11.6	57.8	- 0.848	0.297	4.60 (2.48 / 6.73)	0.16 (0.06 / 0.25)

The simultaneous statistical test for slope = 1 and intercept = 0 rejects the null hypothesis at the 95 % probability level tested, as the calculated Q statistic (333.7) exceeds the 40.9 value for $pS^2F(p,v,1-\alpha)$.

1.5. CONCLUSIONS

Crown fire phenomena modeling have been approach differently by several researchers along the last four decades. Mechanistic modeling has induced an increase in the understanding of the various processes controlling these phenomena, but has not been able to provide an operational crown fire model. Empirical approaches to model crown fires have been used throughout the world to build models to support fire management decision-making.

Rothermel (1991a) crown fire spread model was subject to detailed evaluation. From the several model evaluation approaches analyzed in Section 1.4, it is noted the inadequacy of Rothermel (1991a) crown fire spread model to predict crown fire behavior in fuel complexes with distinct structural characteristics from the one used in model development. Discussion of conceptual validity showed that important crown fuel strata characteristics and the type of crown fire spread are not considered in the model, which should limit its applicability. Comparisons between Rothermel crown fire spread model with Canadian FBP (Fire Danger Group 1992) models outputs showed a under-prediction trend by the Rothermel crown fire spread model. This trend was further reinforced by comparisons of Rothermel crown fire spread model outputs with an independent dataset. Statistical tests applied to quantitatively evaluate the performance of Rothermel crown fire model with the independent dataset showed large mean percentage errors, and lack of relationship between the predicted and observed data sets.

An important final consideration of the analysis of Rothermel crown fire spread model is that some of the fires used in the model construction might have been predominantly passive crown fires. This would explain why this model exhibits quite different trends from other crown fire models and under-predict considerably spread rates observed in experimental crown fires.

These conclusions reinforce the need of developing a crown fire spread model for U.S. fuel complexes, which is attempted within this thesis.

CHAPTER II

LOGISTIC CROWN FIRE INITIATION MODELING

2.1. OBJECTIVES

Due to the need to have a model to predict the onset of crowning in coniferous stands in the U.S., and due to the fact that the models currently developed are not parameterized for U.S. fuel complexes, a different approach to model the phenomena was followed. Following the Alexander (1998) remark regarding the adequacy of modeling the onset of crowning phenomena through a probabilistic approach, this line of thought was followed and data from several experimental fires were gathered to assess the viability of this approach. One advantage of the probabilistic approach is the fact that it gives a rational method to deal with certain "*randomness*" of fire phenomena (Ramachandran 1988) and unexplained uncertainty in the data due to natural variability of fire environment variables. Probabilistic models are used throughout the world as operational tools to support decision-making in fire management related problems. As examples, Wilson and Ferguson (1986) predict probabilities of house survival in Australia, Wilson (1988) estimated the effectiveness of firebreak width in grass fires, Lawson et al. (1994) estimate thresholds of sustained people caused ignition, Lawson et al. (1997) modeled the probability of sustained smoldering combustion, and Latham and Schlieter (1989) modeled the ignition probabilities of wildland fuels from simulated lighting discharges.

The objective of this chapter is to build a probabilistic model for the prediction of the onset of crowning based on easily measured fire environment variables.

2.2. REVIEW OF PERTINENT VARIABLES INFLUENCING CROWN FIRE INITIATION

From the previous discussion on the state of the art on crown fire initiation (Section 1.2), the following fire environment and behavior characteristics were identified as having a strong influence in crown fire initiation phenomena:

- Foliar moisture content;
- Fuel complex vertical continuity;
- Available fuel in surface fuelbed;
- Foliage chemical properties;
- Wind speed;
- Fireline intensity.

To better understand the influence of each of these variables on crown fire initiation, a review of their effect on fire behavior will be presented.

Foliar moisture content

Theoretically moisture content of forest fuels affects fire spread in several ways. It acts as a heat sink in the combustion process due to: (i) need to heat the existent water to the boiling point, (ii) vaporize the water, and (iii) give up the heat of desorption of the water in the fuel (Van Wagner 1972). The moisture content also affects flame emissivity by changing the amount of water vapor, carbon dioxide and soot particles in it (Johnson 1992), and combustion due to the dilution of the available oxygen by the water vapor that surrounds the fuel (Simard 1968). Restricting the analysis to the effect of foliar moisture content on crown fire ignition, the problem can be divided into: (i) a heat balance calculation, and (ii) a ignition delay (i.e. the time required to ignite a certain fuel when subject to a determined heat flux) of the foliage. A purely physical approach to calculate a heat balance within the lower branches of the crown when subjected to convective/radiative heating from a surface fire source seems difficult considering the present knowledge of heat transfer and combustion processes in wildland fires.

The calculation of an ignition delay of the foliage, as approached by Xanthopoulos (1990) and other "flammability" studies (e.g. Valette 1990; Dimitrakopoulos and Mateeva 1998), based on foliage moisture content seems a valid alternative to estimate crown fire ignition under the present limitations on the knowledge of the processes involved. The coupling of ignition delay relationships with time above a certain temperature, or the heat flux from a surface fire, as modeled by Xanthopoulos (1990), Weber et al. (1995) and Alexander (1998), should close the problem for practical applications.

Although reasoning on fuel ignition logic, as from the analysis of Equation [1.2] and laboratory experiments (as indicated above), shows an effect of foliar moisture content on foliage ignition, its effect on wildfires has been difficult to quantified. Several studies have related crown fire activity with the seasonal foliar moisture variation of coniferous trees of North America with conflicting conclusions. Van Wagner (1967) and Funglem (1979) report an increase in fire activity during the periods of low foliar moisture content that occur in spring in Canadian forests. Kill et al. (1977) in a Fire Weather Index calibration study in Alberta, report that although the spring period, where 75 % of fire greater than 202 ha occur, might be characterized by low foliar moisture contents, it is also the period where higher values of fire danger indices, namely ISI and FWI, are more frequent. Certain authors, e.g. Hough (1973), found a relationship between the crown fire activity and the period of low foliar moisture content, others did not found any relationship (e.g. Johnson 1966; Philpot and Mutch 1971). Van Wagner (1998) noted that the fire behavior database of the Canadian FBP did not shown a statistical effect of FMC on crowning. This lack of physical evidence of the effect of foliar moisture content on crowning in wildfires may be due to stronger effects of other variables, as discussed in this section, have in the phenomena under study.

Fuel strata gap

The importance of the distance between the surface and crown fuel strata is well understood from equation [1.1] develop by Thomas (1963) in still air conditions. Although, to the author knowledge, there are no published relationships of the decay of the heat flux with height, several theoretical and empirical studies (e.g. Van Wagner 1975; Xanthopoulos 1990; Fendell et al. 1990; Mercer and Weber 1994) quantitatively characterized the variation in temperature with height above surface fires. One of the main problems with the estimation of the vertical fuel gap is the definition of what are the limits of the two fuel strata under consideration, and mainly the lower limit of the crown fuel stratum. Several authors (e.g. Kilgore and Sando 1975; Van Wagner 1977; McAlpine and Hobbs 1994; Scott 1998) defined the vertical fuel gap as the crown base height (CBH), although the definition of the CBH parameter varied. Some authors defined CBH as the lower insertion point of branches in a tree. Sando and Wick (1972) defined CBH arbitrarily as the lower vertical 0.3 m (1 ft.) section with a weight greater than 112.4 kg/ha (100 lbs/acre), based on the reasoning that there is a minimum amount of fuel required to support combustion vertically. Ottmar et al. (1998) defined CBH as "the height of the lowest continuous branches of the tree canopy" and refined their description of the crown fuel strata identifying ladder fuels as "the height of the lowest live or dead branch material that could carry fire into the crown".

From the reasoning that, in terms of crown fire initiation, the bottom of an aerial fuel stratum should be defined as a layer which has a minimum fuel density to allow fire to be carried vertically, this study defines a new variable, fuel strata gap. Fuel strata gap (FSG) is defined as the lower limit of the aerial fuel stratum constituted by the ladder and live crown fuels, that can carry fire vertically. Although open to subjective interpretation, as the previous definitions of CBH (or surface fuelbed depth (Brown et al. 1982; Burgan and Rothermel 1984)), the author believe that a trained and experienced fire behavior analyst can objectively identify FSG in a fuel complex where he/she has previously observed fire behavior under various levels of fire intensity.

Available fuel in surface fuel stratum

The amount of fuel consumed within the active combustion phase, defined as a solid flaming zone (Alexander 1982), is expected to have a strong influence in flame characteristics (length, height, angle, depth and emissivity), on the velocity and temperature of the buoyant gases in the convection plume, and consequently on the heat flux reaching the base of the aerial fuel stratum. For a particular fuelbed, the amount of available fuel to be consumed in active combustion is mainly function of fuelbed structure (expressed as bulk density or packing ratio), fuel particle size (expressed as surface area to volume ratio), and fuel moisture content gradient (Byram 1957; Anderson 1969; Rothermel 1972; Wilson 1982, 1990).

Assuming that within a fuel complex, fuelbed structure and particle size are constant through a period of time that can extend for several years, the amount of fuel available to be consumed through flaming combustion depends on fuel load and moisture content. Fuel load is dependent on several factors such as site productivity, species present, fuel accumulation dynamics, and past disturbances, and can be estimated by fuel sampling (e.g. Brown et al. 1982), photo series (e.g. Sandberg and Ward 1981; Stocks et al. 1990) and models (e.g. Marsden-Smedley and Catchpole 1995; Fernandes and Rego 1998). Within drought periods, there is an increase of the fuel available for flaming combustion (Gill and Moore 1990; Rothermel 1993) due to the lower moisture content of the medium size fuels, which will have a substantial effect on the temperature and rate of vertical momentum within the convection plume.

Surface fuel consumption (SFC) can be used as a surrogate of available fuel consumed within flaming combustion within a statistical approach to estimate the probability of the onset of crowning, although some assumptions need to be made. It needs to be assumed that there is a relationship between the fuel consumed within flaming combustion and the total fuel consumption. It must be also assumed that fuel consumption is not dependent on fireline intensity. This is in agreement with several studies (e.g. Van Wagner 1971; Weber et al. 1987) that refer that surface fuel consumption is mainly a function of the dryness of fuels and in a certain way a measurement independent of fire intensity (Alexander 1982).

Wind speed

Wind affects fire behavior through the increase in (i) the rate of energy production and (ii) in the propagating heat flux by exposing the unburned fuel to additional radiative (due to flame tilting) and convective heating (Rothermel 1972). The increase in the amount of fuel being consumed in the flaming zone of a surface fire due to wind will produce higher forward and upward heat fluxes, and consequently faster pre-heating of aerial fuels.

Fuel heat content – chemical properties

Foliar moisture effect on foliage ignition might be overshadowed by the effect of low-temperature volatiles, e.g. terpenoid hydrocarbons and lipids, on the combustion processes. For certain species, the complexity of the chemical characteristics of forest fuels and its variation between and within species led to inconclusive results relative to its effect on forest fuel combustion. This group of compounds, know also as ether extractives, contain about twice the heat content of the extracted fuel and appear to be located near the surface of fuels, facilitating rapid release (Philpot 1969). Philpot and Mutch (1971) hypothesized the importance of these extractives on crown fire phenomena since: (i) their very high energy content (up to 45 MJ/kg for some components (Sussot 1980)); (ii) their high vapor pressure and location makes them easily available to combustion; and (iii) terpenes have one of the lowest fuel/air ratio of any organic fuel.

Much of forest fuel chemical characterization has been restricted to quantify high heat content and its seasonal variability within species (e.g. Philpot 1969; Philpot and Mutch 1971; Hough 1973; Chrosciewicz 1986; Van Wagtendonk et al. 1998). These studies showed that for crown fuels, interspecies heat content variations are comparable to intraspecies variations due to site characteristics, weather and seasonal changes. Due to this conclusion, several researchers, e.g. Van Wagner (1972) and Albini (1976), refer that the heat content variability in forest fuels is not a determinant factor in explaining fire behavior variability. The assignment of a constant heat of combustion for all forest fuels is justified by some authors (e.g. Albini 1993) because other fuel complex properties, with a stronger influence in fire behavior, have a higher variability. The restricted interspecies variability in high heat content does not explain differences in burning characteristics of live fuels. Pompe and Viries (1966) refer the effect that low-temperature volatiles may have in the early stages of burning when the rate of combustion is slow, particularly due to the presence of water. These components will be volatilized at low temperatures, and release large amounts of heat energy from relatively small heat inputs, and can have a biochemical kindling function (Pyne 1984) inducing the combustion of fuels that would not be available due to their higher moisture content.

Due to the fact that a variable part of the fuel heat content will be not released as volatile but remain as char (Sussot et al. 1975), several studies (Shafizadeh et al. 1977; Sussot 1980a, 1982a, 1982b) aimed to characterize which fraction of the heat content is released as volatiles, contributing to flaming combustion, and the rate of heat release as function of temperature. These studies reveal that a large proportion of the total heat content is not available to flaming combustion, remaining trapped as char, and that just a small percentage of the volatile products are release at low-temperatures.

Although it is believe that the heating rate of wildland fuels conditions the decomposition pathways, namely, rapid volatilization and flaming combustion, or dehydration and charring reactions (Shafizadeh 1968), Sussot (1980b) found through a series of experiments where heating rate was changed from 20 °C/min to about 3000 °C/min (Albini 1980) that relative char production in forest fuels was nearly independent of heating rate.

No conclusive results on the effect of low temperature volatiles on crown fire phenomena can be inferred, remaining this subject open to discussion.

Fireline intensity

The concept of fireline intensity, I_B, as defined by equation [2.1] (Byram 1959) has been accepted by the fire research and operational community as one of most important fire behavior descriptors. This measure of fire intensity, also called Byram's fireline intensity and frontal fire intensity (Merril and Alexander 1987) estimates the "rate of energy released per unit time per unit length of the fire front" from:

$$I_B = R w_a H \qquad [2.1]$$

where,

I_B is fire intensity expressed in kW/m;

R is the fire rate of spread (m/s in this equation for units compatibility);

w_a the fuel consumed within active flaming combustion (kg/m^2);

H heat of combustion (kJ/kg) after reductions due to fuel moisture content.

Since the introduction of the fireline intensity concept, it has been used as a fire behavior characteristic explaining a large array of phenomena. Fireline intensity has been related to fire related phenomena such as crown scorch height (e.g. Van Wagner 1973, 1975; Gould et al. 1997), fire impact on a site (Moreno and Oechel 1989), difficulty of fire control (Rothermel 1983; Alexander and Cole 1994) fire interaction with wind field (Byram 1959; Rothermel 1991a; Nelson 1993), flame length and height (e.g. Byram 1959; Thomas 1963; Marsden-Smedley and Catchpole 1995), and crowning potential (Van Wagner 1977; Alexander 1998).

The use of fireline intensity from a surface fire in estimating temperature in the canopy space or ignition of tree crowns have required the determination of a constant (e.g. Van Wagner 1973, 1977; Alexander 1998) that normally differ between fuel complexes. The relationship between fireline intensity and flame length and height has been found to change depending on the fuel being burn. Alexander (1998) plotted 14 different published models of fire intensity – flame size relationships, and revealed "noticeable differences" between model outputs. Cheney (1990) remarked that the intensity-flame dimensions relationships should be only applied to fuel types with similar structural properties. It can be inferred from this statement that the applicability of intensity-flame dimensions relationships is also restricted to fuel moisture gradients and fuel availability for flaming combustion.

Fireline intensity is not directly measurable in a fire (Alexander 1998) but just estimated from equation [2.1]. The form of this equation suggests that fireline intensity is related to the rate of heat transfer across the area of fire inception, i.e. boundary between burning and non-burning combustibles. Relationships of the type of equation [1.2] should hold for relatively limited ranges of fire environment and behavior, as the upward heat flux is expected to vary with available fuel for flaming combustion, fuelbed structure and fuel moisture content gradients. When considering the quantification of thermal fluxes to stand canopies, it seems that a more fundamental form to describe radiative and convective heat fluxes would be more appropriate. Although the utility of the use of fireline intensity or flame dimensions continue to be extremely useful to fire behavior information users in the field, their use in a scientific sense seems limited. The variability of fuel complexes and fire environment conditions existent on a fire would require an extensive evaluation of the empirically determined constants as used in equation [1.2] and [1.8].

2.3. METHODS

2.3.1. Database construction

The crown fire initiation modeling approach used in this study was based on the premise that there exists a sufficient available database on forest fire behavior in different fuel complexes that would allow the modeling of the phenomena without biasing the results to certain fuel and fire environment characteristics. Given this notion a fire behavior database was compiled from existent published data, and unpublished data from the Canadian Fire Behavior Prediction (FBP) system database provided by M.A. Alexander (1999). The compiled crown fire initiation database consists primarily of experimental fires set with the objective of quantifying fire behavior. It offers a high degree of reliability. Two wildfires (GL-A and B (Table A.2 in the Appendix) were included in the analysis because of the good description of the fuel complex and fire behavior provided by Van Wagner (1965). No other fire data from wildfire case studies were used, mainly due to the fact that they do not provide accurate information on the fuel complex characteristics and fire environment conditions during transition phases. The author used all the experimental fire behavior data know to him for the analysis of crown fire initiation. The dataset consists of data on surface and crown fires. A summary of the compiled dataset by fuel complex is provided in Table 2.1.

Table 2.1. Fuel complexes and fire type distribution in the database used for building the crown fire initiation model.

Fuel complex	Crown fires	Surface fires
Immature jack pine	12	2
Mature jack pine	11	19
Red pine	4	2
Black spruce	9	2
Maritime pine	4	-
Lodgepole pine	-	8
Total	40	33

Since one of the primary objectives in this study was to build a crown fire initiation model that could be applied to a wide spectrum of fuel complexes, the fuel complex characteristics identified in Section 2.2 were described physically. Within the dataset, some fires did not have all the information required to satisfactorily evaluate the effect of certain variables on crown fire initiation phenomena. There was a need to estimate fine dead fuel moisture content, foliar moisture content, and FSG for some fires. The following procedure was adopted:

Estimation of foliar moisture content

Foliar moisture content for the several species was estimated through two different procedures, model output (Fire Danger Group 1992) and graphs (Van Wagner 1967). The use of the Van Wagner graphs was justified as they were relative to the same time period and same location (Petawawa Forest Experiment Station) as some of the experimental fires (Table A.2 in Appendix). For other experimental fires conducted at different locations, the model embodied in the Canadian FBP system (Fire Danger Group 1992) was used to estimate foliar moisture content.

Estimation of fine dead fuels moisture content

Since no information was recorded on surface fuelbed structure (fuel load by type and size classes), it was decided to use estimated fine fuel moisture content as a surrogate of fuel moisture content of fuels controlling surface fire spread. From the various available models to estimate fine fuel moisture content (Rothermel 1983; Rothermel et al 1986; Van Wagner 1987; Lawson et al. 1996) it was decided to use the Rothermel (1983) FBA tables based on the following reasoning:

- Although the Rothermel et al. (1986) refinements for the effect of radiation on fuel drying resulted in more reliable fuel moisture predictions when compared with the FBA tables (Rothermel et al. 1986), this model is cumbersome to compute (43 input variables), and most of the input variables were not available.
- The use of a Fine Fuel Moisture Code transformation (Van Wagner 1987; Lawson et al. 1996) to yield fine fuel moisture content has not proven reliable, mainly due to the effect of other variables, such as radiation, in fuel drying.

The FBA tables are based on work by Fosberg and Deeming (1971) for mid-afternoon fuel moisture content modeling, and include the effect of slope, aspect, season and time of day on fine fuel moisture content. Reliability of the FBA tables in estimating fine dead fuel moisture content as been assessed by several authors. Hartford and Rothermel (1991) obtained good results for the peak burning period (defined here as the afternoon period of the day with maximum fire activity) when comparing measured with predicted fine fuel moisture content with the FBA tables. Burgan (1987) also obtained good agreement between fuel moisture content of a fine fuel moisture analog and outputs from the FBA tables.

Fuel strata gap

Due to the difference in concept of the FSG and CBH, as discussed in Section 2.2, a new value to describe fuel vertical continuity needed to be estimated for some of the experimental fires. For the immature jack pine experimental fires (Stocks 1987) the 4 meters CBH estimated by Van Wagner (1993) was reduced to 2 meters based on the photographic evidence (Stocks 1987) of a continuous layer of ladder fuels constituted by dead fine fuels. This alteration is supported by Stocks (1987) who refer that in this fuel complex crown involvement will occur even on fires spreading under moderate intensities.

Detailed information on fuel complex characteristics, fire environment, and fire behavior for each fire in the dataset is provided in Tables A.2 and A.3 in Appendix.

2.4. RESULTS

2.4.1. Variables analysis

Correlation matrices, using Pearson correlation coefficient, were computed for the various available variables identified as pertinent in order to evaluate relationships between variables. Histograms of variable distributions were examined to analyze the representative coverage of the data. Scatterplots were also examined to identify relationships between pertinent variables.

Table 2.2. Correlation matrix for significant fire environment and behavior variables in the dataset

	ROS	U_{10}	SFC	FSG	EFFM	DC	FMC	DMC
ROS	1.000	0.446**	0.312**	-0.282*	-0.146	0.015	-0.003	0.001
U_{10}	0.446**	1.000	0.248*	-0.012	-0.127	-0.129	0.033	0.126
SFC	0.312**	0.248*	1.000	-0.111	0.004	0.396**	0.129	0.232
FSG	-0.282*	-0.012	-0.111	1.000	0.133	0.287*	-0.024	0.653**
EFFM	-0.146	-0.127	0.004	0.133	1.000	0.105	0.047	0.207
DC	0.015	-0.129	0.396**	0.287*	0.105	1.000	0.314**	0.260*
FMC	-0.003	0.033	0.129	-0.024	0.047	0.314**	1.000	0.217
DMC	0.001	0.126	0.232	0.653**	0.207	0.260*	0.217	1.000
DMC	0.001	0.126	0.232	0.653**	0.207	0.260*	0.217	1.000

ROS – Rate of spread; U_{10} – Windspeed at 10 meters; SFC – Surface fuel consumption; FSG – Fuel strata gap; EFFM – Estimated fine fuel moisture; DC – Drought code; FMC – Foliar moisture content; DMC – Duff moisture code.

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

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

Foliar moisture content

Foliar moisture content in the dataset is not significantly correlated with any of the variables described in Section 2.2 (Table 2.2). It is correlated with the drought code DC although no relationship should be expected based on results from past studies (e.g. Viegas et al. 1998).

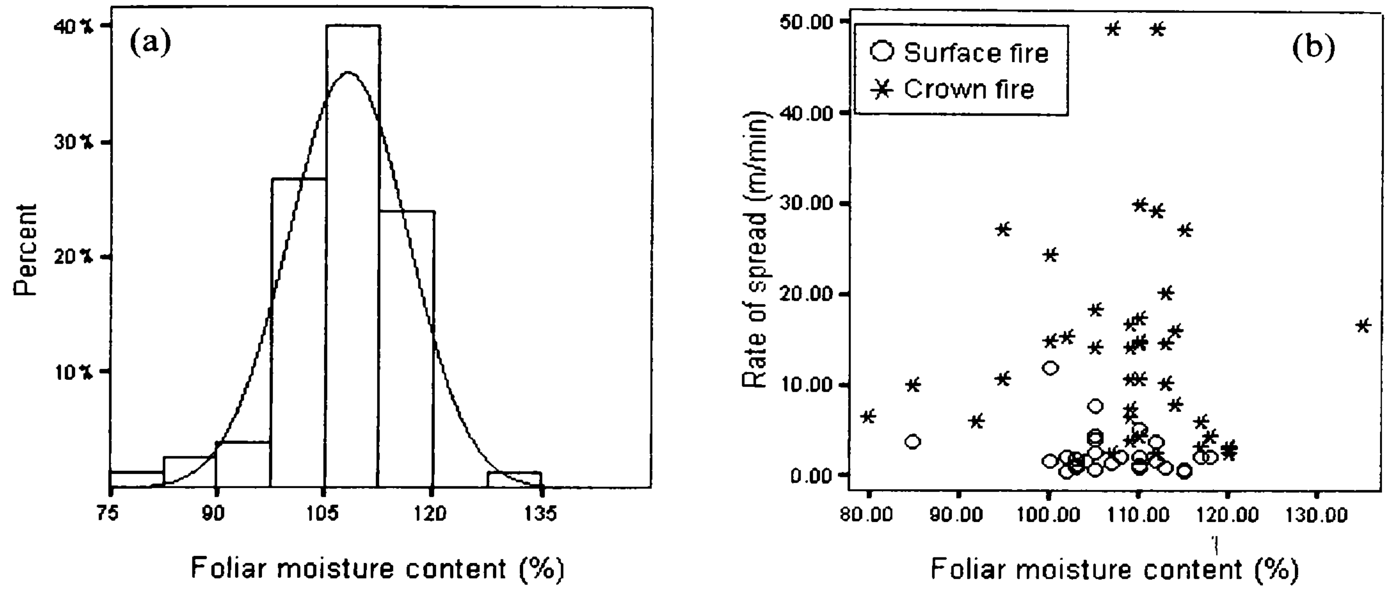


Figure 2.1. (a) Frequency distribution of FMC data, (b) Scatterplot of FMC effect on rate of spread by fire type.

Figure 2.1.a display the frequency distribution of the FMC data on the database gathered to model crown fire ignition. It can be seen that most of the data is within a limited range of 105 –115 %. Figure 2.1.b is a scatterplot of rate of spread and FMC with data categorized by surface and crown fires. Analysis this scatterplot shows no conclusive trend of an effect of FMC on the type of fire. There are two main reasons that may explain this result:

- The influence of FMC on crowning is limited, and is overshadowed by the effect of other variables, namely windspeed and amount of fuel available to flaming combustion in the surface fuel stratum.

- FMC data is estimated from graphs (Van Wagner 1967) or equations (Fire Danger Group 1992; Hirsch 1996), which result in average FMC for a site and may confound results.

Fuel strata gap

Fuel strata gap data in the dataset is significantly correlated with fire rate of spread, (Table 2.2) which was expected from the effect of this variable on transitional fire behavior, and consequently on overall rate of spread. FSG is positively correlated with DC and DMC. As there is no theoretical relationship between the FSG and the drought codes, this correlation can be assumed to be fortuitous.

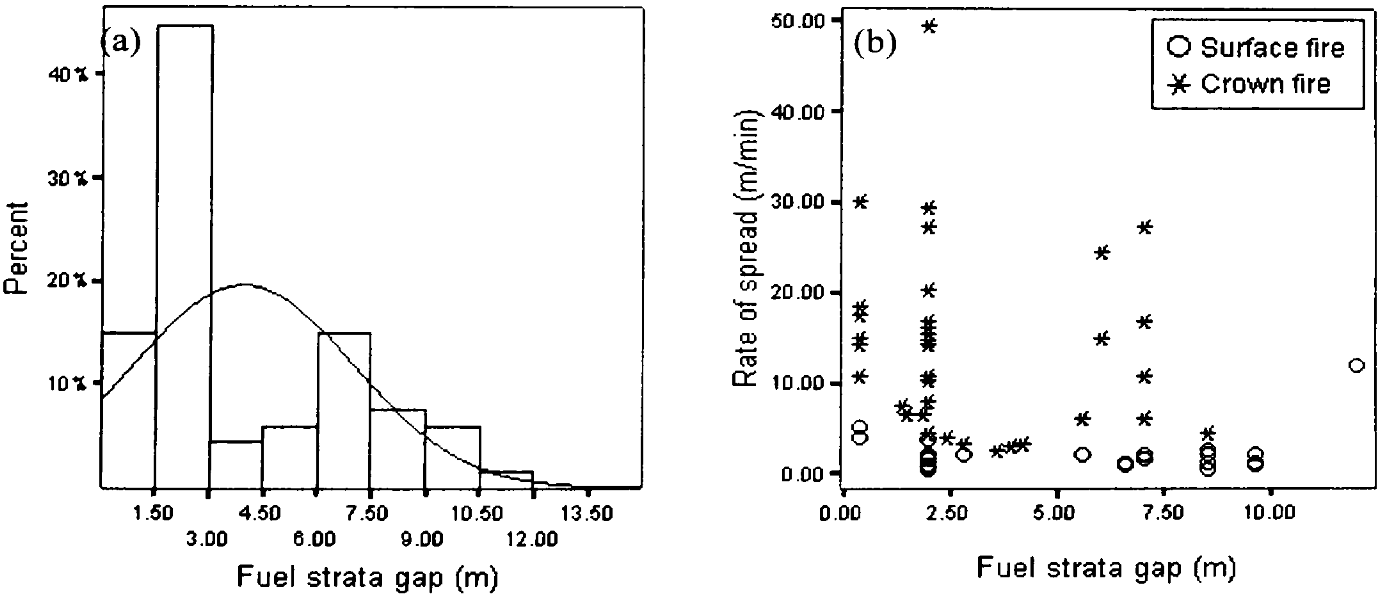


Figure 2.2. (a) Frequency distribution of FSG data, (b) Scatterplot of FSG effect on rate of spread by fire type

Figure 2.2.a presents the frequency distribution of FSG in the database. Although not evenly distributed, FSG covers the range where it is expected that crown initiation is expected. Analysis of Figure 2.2.b show that above an FSG of 7 m the proportion of crown fires drop considerably due to the higher energy requirements to ignite the crown fuels.

Surface fuel consumption

Surface fuel consumption (SFC) is significantly correlated with windspeed, fire rate of spread and DC (Table 2.2). The relationship between SFC and DC is expected as DC is a measure of drought conditions, and higher DC values are indicative of higher amounts of fuel available for combustion. The correlation of SFC and rate of spread is somewhat expected, as larger amounts of fuel available for flaming combustion will result in higher spread rates. This relationship can not be easily assessed due to the correlation between windspeed and SFC, which confounds the analysis.

Figure 2.3.a displays the distribution of the surface fuel consumption data within the dataset, and Figure 2.3.b displays a scatterplot of rate of spread versus surface fuel consumption categorized by type of fire spread. Note that there exists a differentiation between surface and crown fires, with the crown fires occupying the upper spectrum of the surface fuel consumption and most of the surface fires having fuel consumption values lower than 1.6 kg/m^2. Very few crown fires occurred with SFC values below 0.9 kg/m^2.

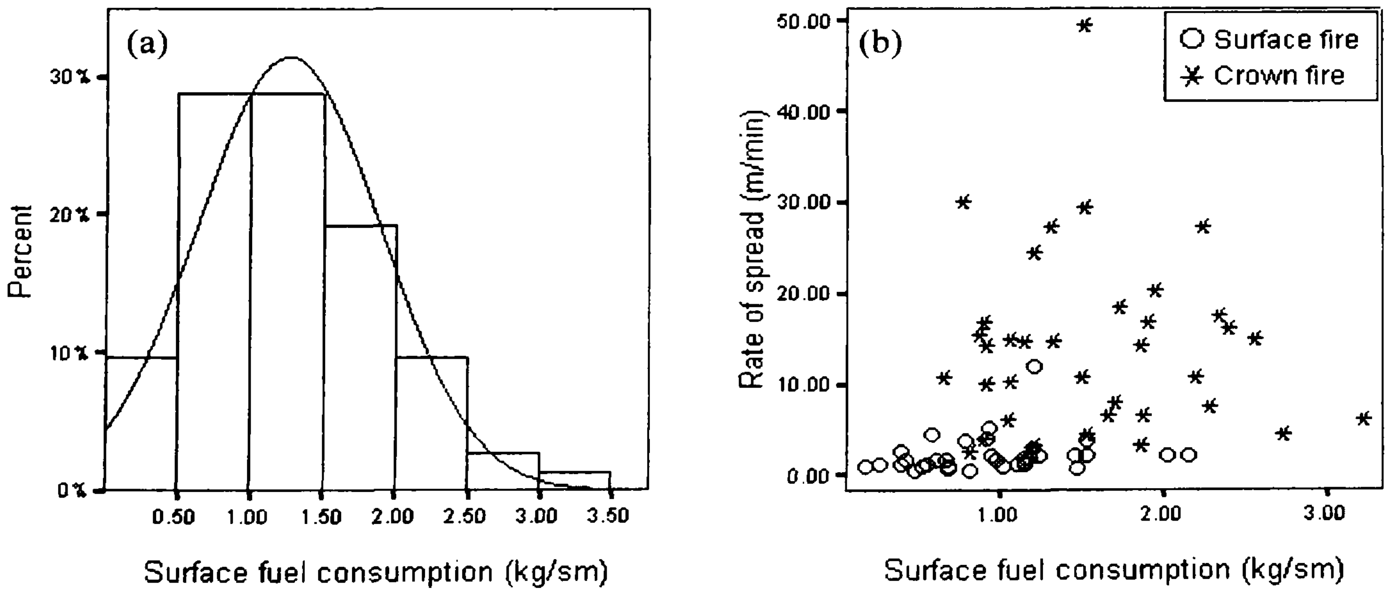


Figure 2.3. (a) Frequency distribution of SFC data, (b) Scatterplot of SFC effect on rate of spread by fire type

Wind speed measured at 10 meters in the open

As expected wind speed measured at 10 meters in the open was significantly correlated with rate of spread. Windspeed is also significantly correlated with SFC (Table 2.2) although this relationship can be expected to be fortuitous.

The histogram of 10 m wind speed for the crown fire initiation database (figure 2.4.a) covers the lower spectrum of wind speeds where crown fire initiation is expected to occur. The scatterplot of rate of spread with wind speed show that there is a strong effect of wind on fire type. A marked differentiation between the two types of fire spread can be identified, with most of the crown fires occurring at 10 m wind speeds above 10 km/h. Almost all surface fires are located below the 15 km/h threshold.

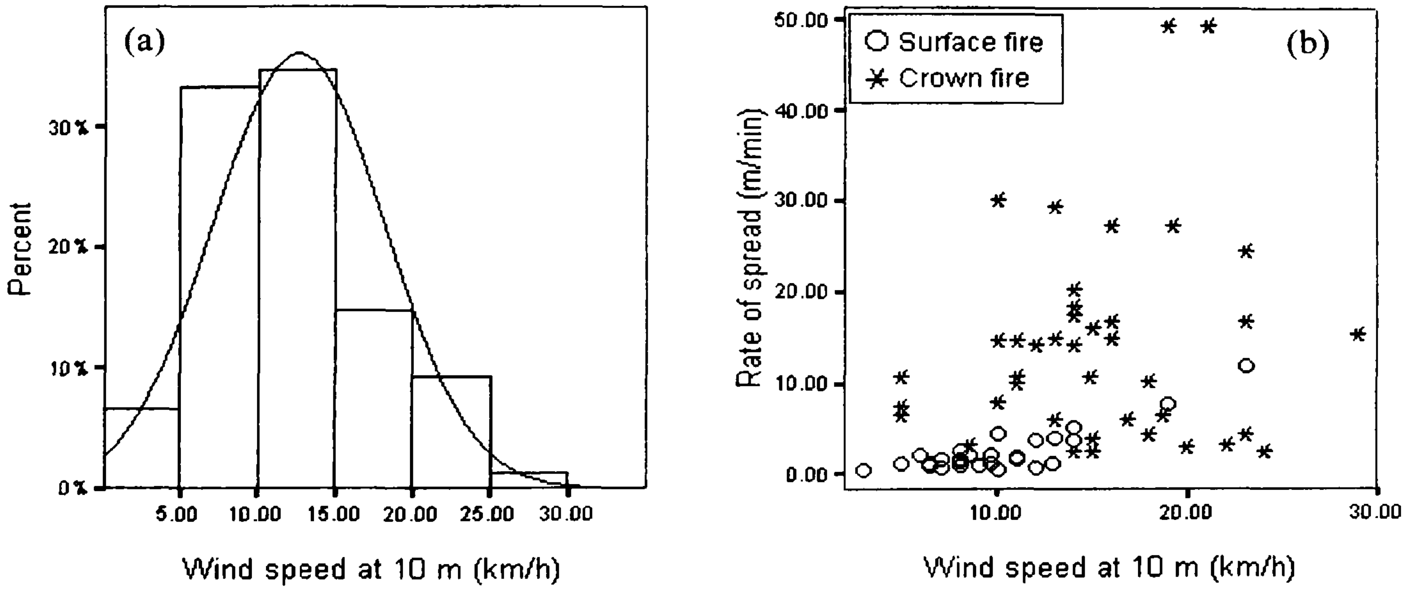


Figure 2.4. (a) Frequency distribution of wind speed data, (b) Scatterplot of wind speed effect on rate of spread by fire type

Estimated fine fuel moisture content

Estimated fine fuel moisture content is not significantly correlated with fire rate of spread or any other variable referred in Table 2.2. As for FMC, the estimates of fine fuel moisture content are concentrated within a limited range of data (Figure 2.5.a). The lack of fires with lower fine fuel moisture contents can be explained due to the difficulties of executing experimental fires under extreme fire weather conditions. Although the overall estimated fine fuel moisture content values are not related to fire rate of spread, Figure

2.5.b show the damping effect of this variable on crown fire spread rate. The existence of measured fuel moisture content data by size classes instead of estimated fine fuel moisture content would be expected to help better understand the dependence of crown fire in the available fuel for flaming combustion in the surface fuelbed.

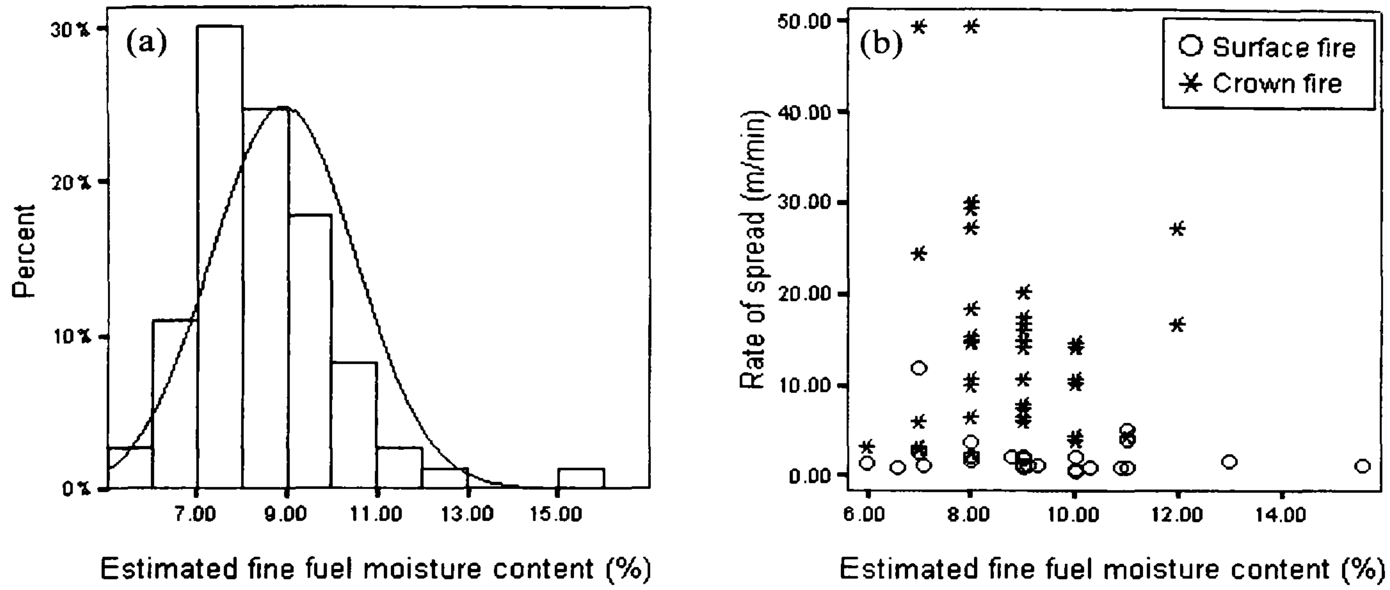


Figure 2.5. (a) Frequency distribution of estimated fine fuel moisture content data, (b) Scatterplot of estimated fine fuel moisture content effect on rate of spread by fire type

2.4.2. Model building

2.4.2.1. *Methods*

Due to the fact that the dependent variable, occurrence or not of crowning, has a dichotomous outcome, a logistic regression approach allowing the estimation of the probability of an event occuring from a combination of fire weather/environment factors was chosen. The multiple logistic regression model has the following form (Hosmer and Lemeshow 1989):

$$P(y_i = 1) = \frac{e^{g(x)}}{1 + e^{g(x)}} \qquad [2.2]$$

Being the logit given by the equation:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i \qquad [2.3]$$

where,

$P(y_i=1)$ is the probability of a crown fire occurs;

β_i are the coefficients estimated from the data;

x_i are the independent variables.

From the previously presented variables, the following were selected to test their influence in the proposed model:

Wind speed (U_{10}) measured at 10 meters in the open expressed in km/h;

- Fuel strata gap (FSG) expressed in meters;
- Surface fuel consumption (SFC) expressed in kg/m^2;
- Foliar moisture content (FMC) expressed as a percentage of ovendry weight;
- Estimated fine fuel moisture content (EFFM) expressed as a percentage of ovendry weight.

The data used in model construction are shown in Table A.2 and A.3 in Appendix.

Since the post-fire measured surface fuel consumption reflects fuels consumed in both flaming and glowing combustion, limits the hypothetical use of this model. Surface fuel consumption is an *a posteriori* measure of fire behavior, although there exist models that predict total fuel consumption (Reinhardt et al. 1997) or fractional fuel consumption by size classes (e.g. Albini 1996; Call and Albini 1997). Due to the difficulty of estimating available fuel for combustion and possible model errors, it was decided to use the variable SFC as a categorical variable in order to simplify the use of this variable. Three classes encompassing broad ranges of SFC were defined: SFC < 1 kg/m^2; 1 < SFC < 2 kg/m^2; SFC > 2 kg/m^2. The limits of these classes were based on trends on scatterplot of Figure 2.3.a. Since the classes of SFC are broad and might not reflect a physical reality, it was decided to code the SFC variable. The newly created categorical variable SFC (SFC_CAT) was coded through two design variables (D1 and D2). The statistical package SPSS 8.0 (Norusis 1997) used in the logistic analysis generated the following design variables (Table 2.3).

Table 2.3. Coding scheme of the SFC category design variables

Surface fuel consumption (kg/m^2)	Parameter coding of SFC_CAT	
	D_1	D_2
SFC < 1	1	0
1 < SFC < 2	0	1
SFC > 2	0	0

Since the values of the design variables are assumed nominal scaled as opposed to interval scaled, the logit equation [2.3] is altered to (Hosmer and Lemeshow 1989):

$$g(x) = \beta_0 + \beta_1 x_1 + \ldots + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_i x_i \qquad [2.4]$$

Where j^{th} variable is SFC, with k_j levels (two in the present formulation), and D_{ju} are the design variables.

The method of estimation of the parameters in equation [2.4] is the maximum likelihood, which will produce coefficients that maximize the probability density as function of the original set of data (Hosmer and Lemeshow 1989).

2.4.2.2. *Model results*

Several possible model solutions were analyzed, with various combinations of the independent variables. A model including all the variables listed above was tested for the significance of the variables (Table 2.4).

Table 2.4. Estimated parameters and statistics for the probabilistic crown initiation model

Variable	β	S.E.	Wald	Df	S.L.	R
U_{10}	0.3704	0.1233	9.0259	1	0.0027	0.2761
FSG	-0.6610	0.2266	8.5077	1	0.0035	-0.2657
SFC_CAT			9.6103	2	0.0082	0.2467
SFC_CAT(1)	-4.3423	1.5824	7.5304	1	0.0061	-0.2450
SFC_CAT(2)	-1.7801	1.3876	1.6458	1	0.1995	0.0000
EFFM	-0.2852	0.3427	0.6924	1	0.4054	0.0000
FMC	0.0034	0.0574	0.0036	1	0.9522	0.0000
Constant	2.9970	7.5059	0.1594	1	0.6897	

S.E. – St. error; Wald – Wald statistic; S.L. – Sig. level for the Wald statistic; R – R statistic.

Using the Wald statistic (Table 2.4) the coefficients of the variables wind speed, fuel strata gap and surface fuel consumption all show a significant effect on the model. The positive sign of the FMC coefficient indicates an increase in the likelihood of crowning with higher values of FMC. This effect is opposite of what would be expected and probably reflects the small influence of FMC in crowning activity in the dataset used. The Significance level for the Wald statistic for this variable reinforces this conclusion. The relevance of variable EFFM in the model is also open to question. The test that the coefficient of EFFM is 0 based on the Wald Statistic, reveals that it is not significantly different from 0 (Table 2.4).

Although statistically it seemed not important to include EFFM as a variable in the model, it was decided to include it in the model based fire behavior reasoning. Since FSG and SFC are assumed constant during a burning day, and wind speed varies randomly during the same period, fine fuel moisture content is the variable that will discriminate the peak burning period, when fuel dryness is at its lower value, and crowning activity has the highest probability of occurring.

Based on these considerations, a new logit model was fitted to the data:

$$g(x) = \beta_0 + \beta_1 U_{10} + \beta_2 FSG + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_5 EFFM \qquad [2.5]$$

where, D are the two design variables for SFC from Table 2.3.

The estimated parameters for equation [2.5], their standard errors, and significance levels are displayed in Table 2.5.

Table 2.5. Estimated parameters and statistics for the probabilistic crown fire initiation model

Variable	β	S.E.	Wald	Df	S.L.	R
U_{10}	0.3702	0.1232	9.0302	1	0.0027	0.2762
FSG	-0.6640	0.2217	8.9736	1	0.0027	-0.2751
SFC_CAT			9.7709	2	0.0076	0.2250
SFC_CAT(1)	-4.3543	1.5747	7.6464	1	0.0057	-0.2475
SFC_CAT(2)	-1.7869	1.3867	1.6605	1	0.1975	0.0000
EFFM	-0.2859	0.3420	0.6991	1	0.4031	0.0000
Constant	3.3969	3.4061	0.9946	1	0.3186	

S.E. – St. error; Wald – Wald statistic; S.L. – Sig. level for the Wald statistic; R – R statistic.

The model have a –2 Log Likelihood (-2LL) of 40.040, against the –2LL of the initial log likelihood function of 92.149, yielding a model chi-square of 52.109. Hence we reject the null hypothesis that the coefficients estimated in the model are 0. Due to the fact that the maximum likelihood theory applies strictly to large samples (Smith 1969 in Wilson 1988), the statistical results reported in this section should be analyzed with care.

The model yields a goodness of fit statistic of 36.98. The Nagelkerke R^2, which has a similar interpretation of the coefficient of determination in linear regression, yields a value of 0.72. The Wald statistic shows that the coefficients for Wind speed, FSG and SFC categories (SFC_CAT) are significantly different from 0 at a significance level of 0.05. Once again the null hypothesis that the EFFM coefficient is significantly different from 0 was not rejected by the Wald statistic at the 0.05 significance level.

Analysis of the R statistic in Table 2.5, shows that an increase in windspeed and SFC increase the likelihood of the occurrence of the event crown fire. Increase in the FSG and EFFM values decreases the likelihood of crowning due to the negative sign of the statistic. The classification table (Table 2.6) of positive predictions with a cutoff value of 0.5[7] shows that the model predicted correct scores 85 % of the situations.

Table 2.6. Classification table for logistic model fire type prediction.

		Predicted		Percent correct
		Surface	Crown	
Observed	Surface	24	6	80.0 %
	Crown	4	33	89.2 %
			Overall	85.1 %

An Holmer and Lemeshow goodness-of-fit test, using a chi-square test to assess differences between the observed and predicted number of events, was applied (Norusis 1997), although the small sample size used limit conclusive results. A calculated chi-square value of 2.73 has a significance level of 0.95, thus the null hypothesis that there is no difference between the observed versus predicted scores is not rejected.

---

[7] Probabilities below 0.5 indicate a surface fire, whereas a crown fire is assumed to occur when the estimated probabilities are above 0.5.

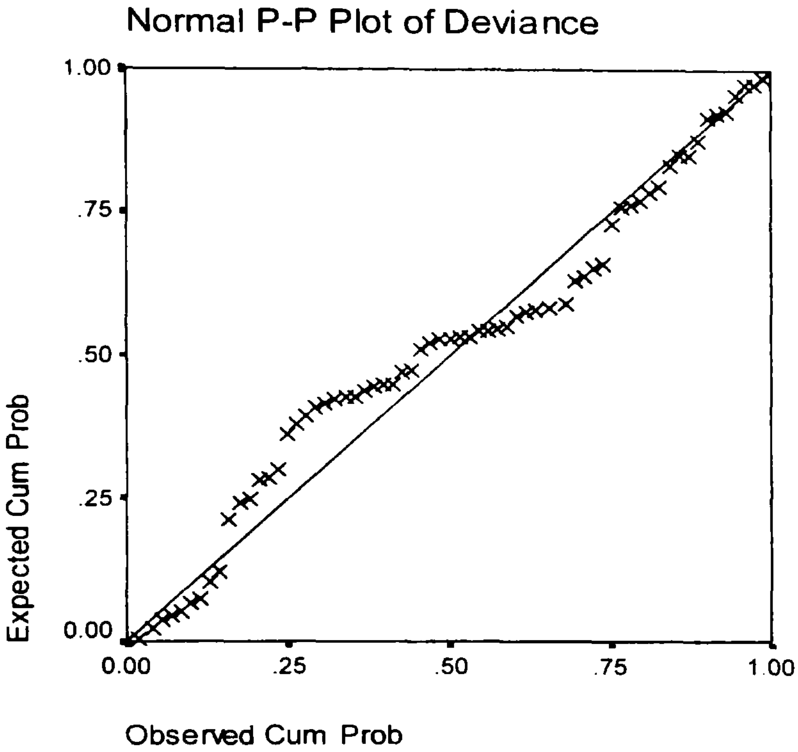


Figure 2.6. Plot of the observed cummulative deviance versus the cummulative expected deviance under the normal distribution.

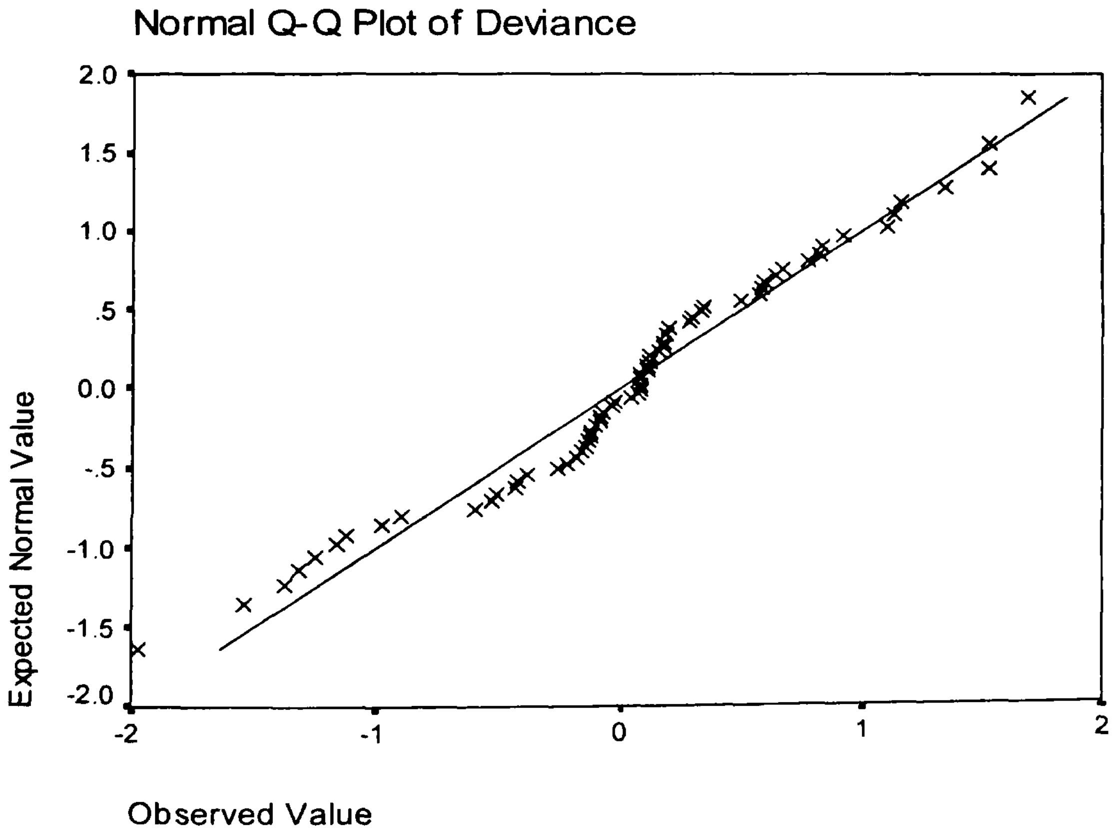


Figure 2.7. Plot of the observed absolute deviances versus the expected deviances under the normal distribution.

```
                 Observed Groups and Predicted Probabilities

      16 +                                                            +
         I                                                           CI
         I                                                           CI
F        I                                                           CI
R     12 +                                                           C+
E        IS                                                          CI
Q        IS                                                          CI
U        IS                                                          CI
E      8 +S                                                          C+
N        IS                                                          CI
C        IS                                                          CI
Y        IS                                                          CI
       4 +S                                                          C+
         ISS                                                 C       CI
         ISS   S S          C             C         C       CS    CC CI
         ISS  SS S S    C   CS  S C   SSCCS S S  C SC C   CCCS C  CCCCI
Predicted --------------+--------------+--------------+---------------
  Prob:   0            .25            .5             .75             1
  Group:  SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

Figure 2.8. Histogram of estimated probabilities for crown fire occurrence for the crown fire initiation database.

Normal cumulative deviance (Figure 2.6) and absolute deviance (Figure 2.7) plots show normality of deviances and small absolute deviances. These results support the good fit of the model, and lower probability of occurrence of large errors. Figure 2.8 display an histogram of estimated probabilities for the data used in the model. Each S or C refers to a model prediction of a surface or crown fire respectively. Optimum results would locate all surface fires below the 0.5 probability cutoff, and all crown fires above 0.51. From Figure 2.8 it can be seen that wrong scores are mostly in the middle section of the probability scale, where naturally a higher level of uncertainty is expected relatively to the occurrence or not of crown initiation. Individual probability scores for all fires in the dataset used to build the crown fire initiation model are in Table A.3.

2.4.3. Model evaluation

Although the probabilistic crown fire initiation model build in Section 2.4.2 should be subject to an evaluation procedure as the one described in Section 1.4, it will be subject in this section to a more limited evaluation due to three reasons:

- A conceptual validity of the model would be a repetition of Section 2.2. It is the believe of the author that the model build follow the theoretical considerations and assumptions made in that section. A conceptual validity evaluation should be made by someone other than the model author, as the model build is based on the validity of relationships assumed by the author. A different and independent approach might be needed to perform and unbiased evaluation of the relationships existent in the model.
- To the knowledge of the author there is no independent database to which a predictive and statistical evaluation, as done in Section 1.4, could be made to the probabilistic crown fire initiation model build in this section.
- The modeling approach used in other models aimed to predict crown fire initiation (e.g. Van Wagner 1977 and Alexander 1998), in which fireline intensity are used to predict crown initiation thresholds are not comparable to the approach followed in this study. This fact makes that the comparison between those models and the one build in this study unrealistic.

Outputs from the crown fire initiation model were compared with a wildfire crown fire spread dataset constituted from published wildfire case studies know to the author. The selected case studies (Table A.7) have complete and detailed information on crown fire runs, fuel type and fire weather conditions, but no information on FSG and SFC. FSG data was inferred from values assumed for Canadian Fire behavior Prediction system fuel types (Fire Danger group 1992). SFC data was estimated from models using BUI as independent variable (Fire Danger group 1992). The computation of the crown fire initiation probabilities for crown fire runs from a wildfire dataset yield high crown fire initiation probabilities for all the fires. The crown fire initiation model [Equation 2.5] produced probabilities higher than 0.96 for all cases except one (0.86). This result could be somewhat expected, as the case studies analyzed are from fires burning in extreme fire weather conditions, where the combination of fire environment variables originate crown fire initiation and spread. Fires spreading under less severe fire environment conditions and that barely meet the requirements for crown fire initiation do not present significant crown fire runs susceptible for analysis as case studies. It would be under these conditions that a better evaluation of the crown fire initiation model should be made.

The crown fire initiation model evaluation will be restricted to sensitivity analysis and analysis of model behavior.

Sensitivity analysis

As referred in Section 1.4.2.2, a comprehensive sensitivity analysis scheme should combine the effect of all possible parameter combinations. As for Section 1.4.2.2, the sensitivity analysis to be performed to the probabilistic crown fire initiation model will be restricted to the model behavior within a limited input range. Due to the S shaped form of the probabilistic output curve (e.g. Figure 2.9), and its shifting on the x scale function of the variation of other variables, it was defined to perform the sensitivity analysis in a situation where the probabilistic curve would be at its maximum slope. The selected combination of variables was: U_{10} – 15 km/h; FSG – 6 m; SFC between 1 and 2 kg/m^2; EFFM – 10 %. Relative sensitivity (RS) scores (Equation [1.9]) were calculated for an input variation of plus or minus 10 % of the above values.

Estimated RS scores were 2.33 for wind speed, 1.64 for fuel strata gap, and 1.21 for estimated fine fuel moisture content. Surface fuel consumption was not subject to sensitivity analysis due to its categorical nature. The calculated RS scores reflect the importance of each variable in the model. As expected the by the R statistic of Table 2.5, the model is very sensitive to wind speed, which can be explained by the effect of wind speed in surface fire behavior. A change of 10 % in wind result in a 23 % higher probability score. The computed RS scores for fuel strata gap and estimated fuel moisture content show variation of these variables induce a proportionally higher response by the model. The calculated sensitivity scores also help us analyze the effect that errors in estimating the input variables can cause on the output. The 1.21 RS score for estimated fine fuel moisture suggests a change of 12 % for a 10 % input error. Errors in the estimation of wind speed would result in much higher proportional errors as shown above.

Model behavior

Analysis of model behavior will help understand how the crown fire initiation model responds to the variation of the input variables, identify model limitations and unacceptable results. Several runs of the model were done to evaluate model behavior. Table 2.7 indicates the variable values used in the evaluation. These runs try to cover not just the normal range of variation of the variables, but test the model output in extreme situations.

Table 2.7. Values of input variables used for the evaluation of model behavior

Variable being analyzed	Wind speed (km/h)	FSG (m)	SFC (kg/m^2)	EFFM (%)
Wind speed	0 - 37	2; 4; 6	< 1	12
FSG	10; 15; 20	0 – 16	1 – 2	7
SFC	0 - 37	5	3 classes	10
EFFM	10; 15; 20	5	1 – 2	2 - 25

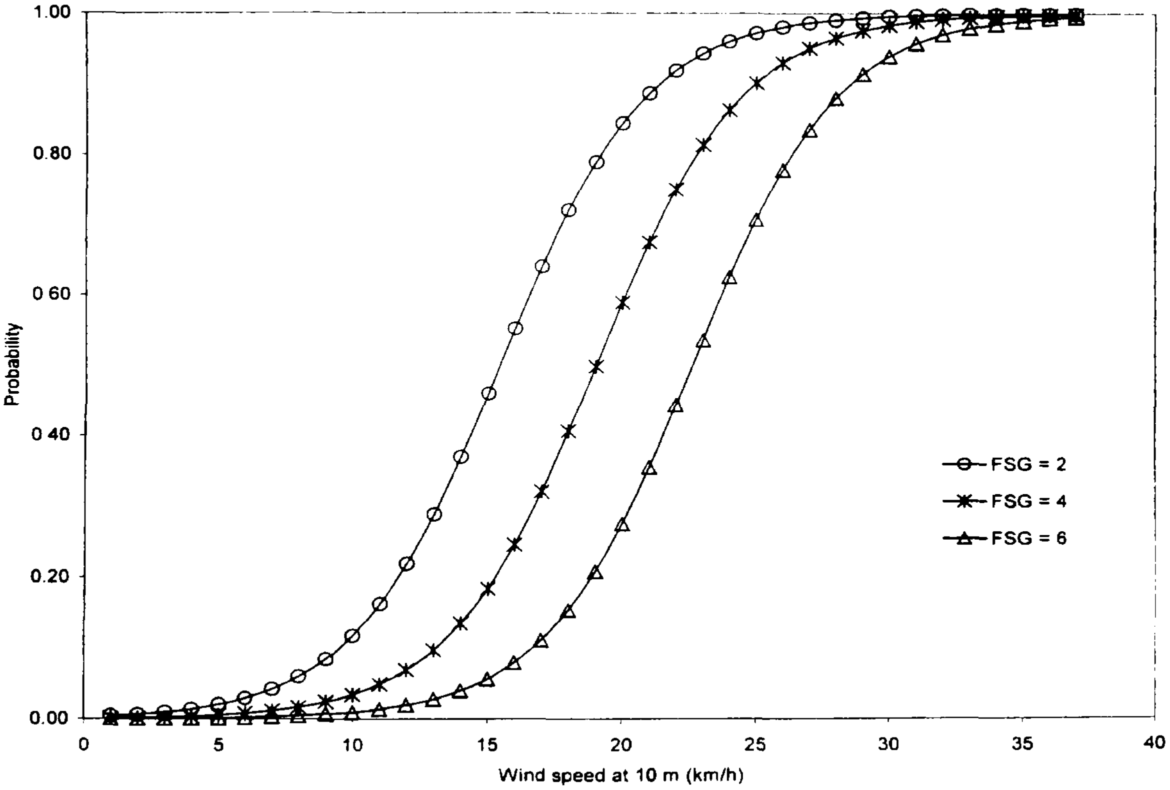


Figure 2.9. Behavior of the probabilistic crown fire initiation model. Effect of wind speed variability. Values for SFC and EFFM in Table 2.7.

Figure 2.9 illustrates model response to wind variation under three FSG levels. As referred before, the model output is an S-shaped curve that reflects the non-linear relation between *g(x)* and the probability. The S-shaped curve for the wind variable is characterized by a slow increasing area below probability < 0.1, followed by a steep region that will cover the 0.1 – 0.9 range in a less than 15 km/h wind speed range. This steep region illustrates the dependence of the onset of crowning in wind speed. For the three FSG levels tested, a change of windspeed between 6 to 10 km/h change a lower probability (≈ 0.1) of crown fire initiation to a positive probability (> 0.5) of crown fire occurrence. The three curves in Figure 2.9 have very similar shapes. Changes in input variables other than wind speed originate a shift of the curve along the x-axis, not significantly affecting the shape of the curve

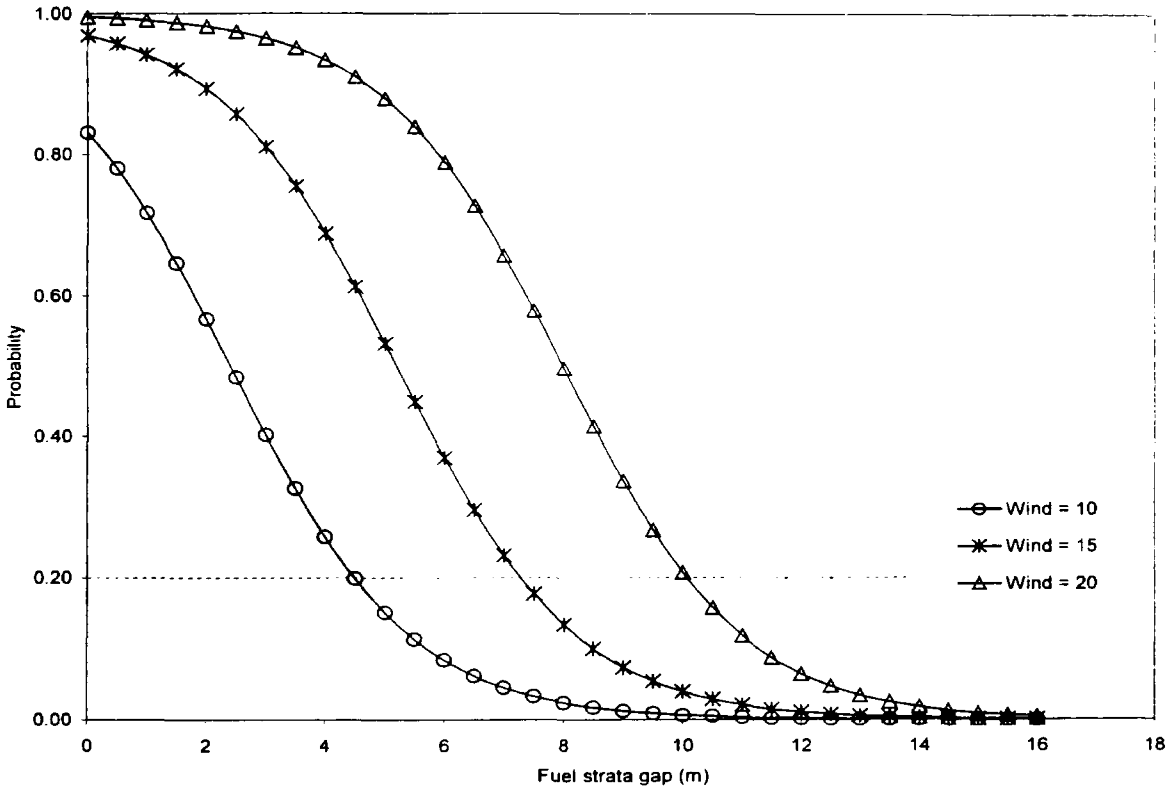


Figure 2.10. Behavior of the probabilistic crown fire initiation model. Effect of fuel strata gap variability. Values for SFC and EFFM in Table 2.7.

Figure 2.10 show the damping effect that the increase in fuel strata gap has on the probability of crowning. As in the results of the sensitivity analysis, the slope originated by changes in FSG is lower than for wind speed. This is due to the smaller effect of FSG variation in the probability score. An increase in FSG of 1.5 - 2 meters will reduce the probability of crown fire occurrence by 0.25, which would take a fire in the 0.5 threshold to a lower probability of 0.25. From the reasoning that outside the probability interval 0.25 – 0.75 the model responds quite well (Figure 2.8), it could be estimated that an increase in FSG by approximately 3.5 meters would significantly decrease the probability of crowning to occur. The model identifies an area with FSG below 3 meters of critical sensitivity to crowning. Under the simulation conditions (SFC between 1 - 2 kg/m^2; EFFM = 7 %), FSG levels below 3 meters have high probabilities for occurrence of crowning.

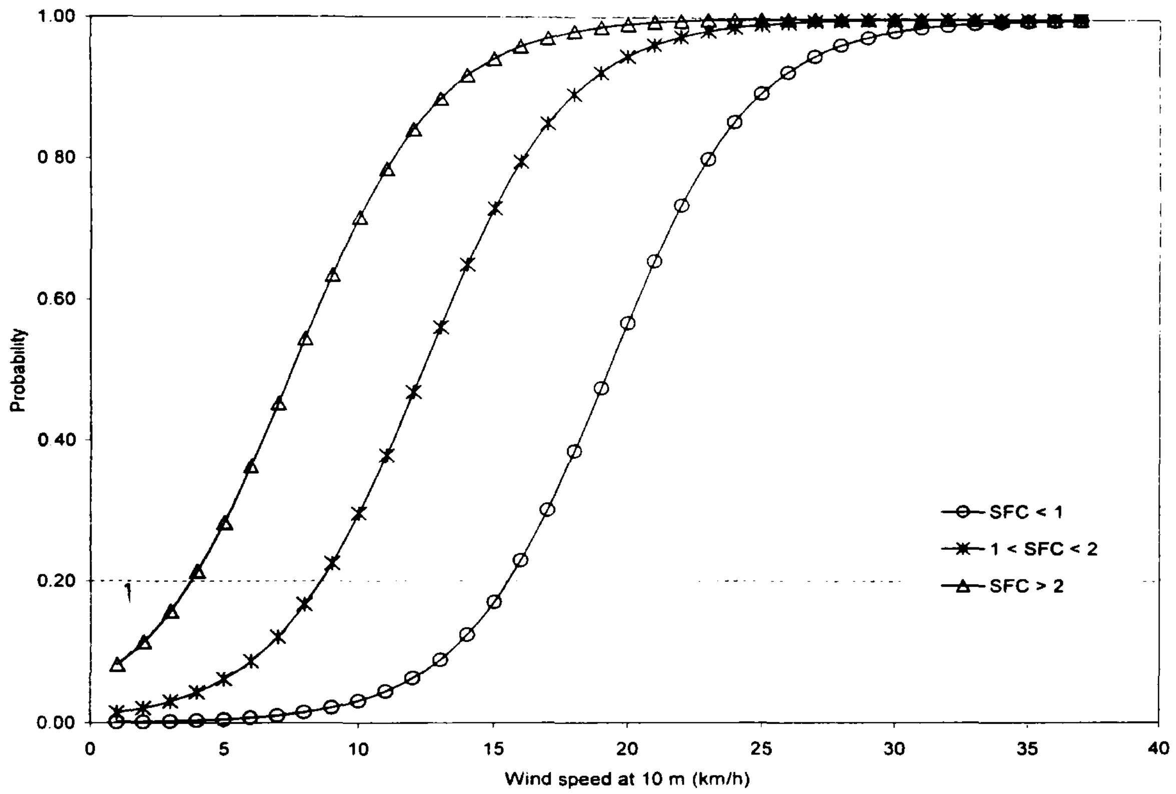


Figure 2.11. Behavior of the probabilistic crown fire initiation model. Effect of Surface fuel consumption class. Values for FSG and EFFM in Table 2.7.

The effect of the variability in SFC class on the probability score is displayed in Figure 2.11. The relative wide interval between the curves illustrates the importance of this variable in the crowning phenomena. For the same windspeed, e.g. 15-km/h, a change from the lower SFC class to the medium increases the probability of crowning occurrence from 0.17 to 0.73. In terms of probability of crowning occurrence, the distance between the lower and the higher SFC class in the probability interval 0.2 – 0.8 is roughly equivalent to a 12-km/h windspeed change. The significance of this variable has particular importance when evaluating different fuel management options, as fuel reduction or thinning with or without slash removal.

Estimated fine fuel moisture content is the variable with smaller effect on crowning potential, evidenced by the lower grade of the curves in Figure 2.12. A reduction from a 0.5 to a 0.25 probability of crowning requires an increase of EFFM of 4 %. The effect of EFFM variation in crowning activity is well perceived during wildfires, when crowning activity is normally restricted to the peak burning period, when fine fuel moisture levels attain their daily minimum. Although the daily cycle of fine fuel moisture varies greatly depending on the fire weather conditions, a daily variation between 5 and 11 % as reported by Hartford and Rothermel (1991) would result in a variable reduction of crowning probability depending in wind speed. For a wind speed of 10 km/h the reduction would be 0.4, whereas for a wind speed of 20 km/h the reduction would be just 0.06 due to the flat area of the curve for those conditions.

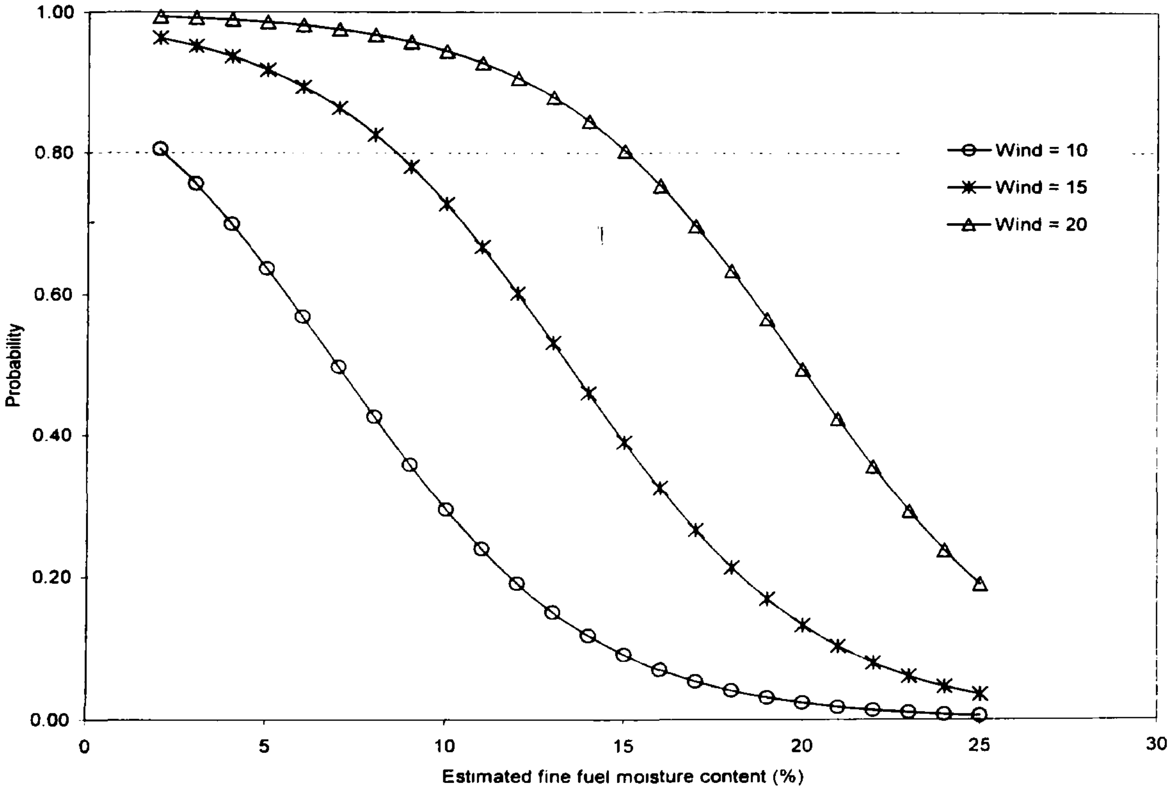


Figure 2.12. Behavior of the probabilistic crown fire initiation model. Effect of fine fuel moisture variability. Values for FSG and SFC in Table 2.7.

2.5. CONCLUSIONS

The present study approached the problem of predicting the phenomena of crown fire initiation differently from previous studies. Previous modeling approaches of the crowning initiation phenomena (e.g. Van Wagner 1977, Alexander 1998) were based on the combination of surface fire intensity and ignition requirements at the base of the crowns, yielding a dichotomous answer. The incorporation of heat transfer theory with empirical data gives these models wide applicability. As a disadvantage of these models, the use of fire intensity as a variable in the crown fire initiation process requires the estimation of empirically determined coefficients that encompass the effect of several variables. This fact requires the estimation of new coefficients when trying to apply the models to fuel complexes with different fuel arrangements and burning characteristics. A further inconvenience of the use of fire intensity as a variable, is that it is a parameter that needs to be estimated from other models outputs, namely rate of spread and fuel consumed in flaming combustion, that can be predicted but with variable error. The combination of the theory underlying these models with a more realistic fire intensity measure would improve greatly the applicability of these models.

My model predicts the likelihood of crowning from a combination of fire environment and behavior parameters, yielding a probability of occurrence of a crown fire. The probability score for crown fire initiation allows a user to interpret the results differently from the dichotomous answer of the other models. Based on user experience in a particular fuel type, threshold scores can be locally defined for the probability of crowning. The non use of fire behavior model outputs, as rate of spread or fire intensity, as variables in the present model can be seen as an advantage, as there will be no error propagation in the process of predicting crown initiation.

The input variable in the model that is not easily estimated is surface fuel consumption. Although the use of this variable as a categorical one, with three broad classes should allow coherent decisions based on the available fuel in the surface fuelbed and fuel moisture. The use of a model as the Albini et al. (1995) burnout model can support with a deterministic basis the choice of surface fuel consumption class to use.

The model is the result of the relationships existent in the dataset used in its construction, and so, it might be biased to some extent by the distribution of the original variables. As example, the fuel strata gap data was greatly concentrated in the lower part of its spectrum of variability. Crown fire initiation in stands with large fuel strata gap would require burning conditions under which fire researchers are normally not allowed to burn. Foliar moisture content is another variable that might have some effect on the crowning initiation phenomena, but in this study did not yield any relationship with crowning, which may be explained by the use of estimated instead of measured foliar moisture content values.

The variability in fuel complex characteristics used in the model construction and the incorporation in the model of key physical variables influencing crown fire initiation suggests that the model should be applicable to other fuel complexes different from the ones used in the model construction. Evaluation of the model against an independent dataset constituted by crown fire runs from wildfires yielded good results. The crown fire initiation model produced high probabilities of crown fire initiation for all the fires.

CHAPTER III

CROWN FIRE SPREAD MODELING

3.1. OBJECTIVES

Chapter I presented the current limitations of empirically and physically based models to predict crown fires spread rates in U.S. fuel complexes to support fire management decision making. The objective of this chapter is to build an empirically based crown fire spread model applicable to the wide variety of fuel arrangements found in fuel complexes that support crown fires. The model to be constructed will be based on highly reliable experimental crown fire data and should discern fire spread of fires spreading as either active or passive crown fires.

3.2. REVIEW OF PERTINENT VARIABLES INFLUENCING CROWN FIRE SPREAD

From the previous discussion on the state of the art on crown fire spread modeling (Section 1.3), the following fire environment and behavior characteristics were identified as influencing crown fire spread.

- Wind speed;
- Available fuel for flaming combustion (in surface and crown strata);
- Crown fuel bulk density
- Fuel complex vertical continuity;
- Foliar moisture content;
- Moisture content of surface fuels

To better understand the influence of each of these variables on crown fire spread, a review of their effect on fire behavior will follow.

Wind speed

As noted in Section 2.2 wind speed is one of the fire environment variables with a stronger effect on fire spread due to its effect on (i) the rate of energy output and (ii) heat transfer efficiency through the increase on radiative and convective heat fluxes. The magnitude of this effect (relative to a non-wind, non-slope spreading fire) has been subject to theoretical (e.g. Baines 1990), laboratory (e.g. Thomas 1967; Rothermel 1972; Beer 1995), field experimental (Marsden-Smedley and Catchpole 1995; Cheney et al. 1998) and wildfire (McArthur 1967) evaluation.

Due to the difficulties in quantifying the wind effect on fire behavior from a physical standpoint (e.g. limits and proportion of each heat transfer mechanism to the total heat flux) the form of this wind function in fire behavior models has been estimated from empirical studies. Luke and McArthur (1978) conclude that the rate of spread in forests (Eucalyptus fuel complexes) vary as the square of wind speed. Noble et al. (1980) evaluate the wind function on the McArthur MK V in forests (McArthur 1973) as:

$$ROS = ROS_0 \exp(0.04003 U_{10}) \qquad [3.1]$$

where, U_{10} is windspeed in km/h measure at 10 meters.

One common approach in quantifying the wind effect on fire spread rate is the use of a power function of the form ROS $\propto U^n$. Rothermel (1972) establish a wind coefficient to quantify the wind effect on spread rate based on laboratory and wildfire data with the following power function:

$$\phi_U = CU^B \left(\frac{\beta}{\beta_{op}} \right)^{-E} \qquad [3.2]$$

where,

β, and β_{op} are respectively the fuelbed packing ratio and optimum packing ratio;

C, B and E are coefficients determine experimentally function of σ, the surface area to volume ratio of fuel particles.

The dependence of the wind function on β and σ is due to the speculation based on laboratory fires (Rothermel 1972) that the fire response to wind is function of fuel particle size and fuelbed compactness. Marsden-Smedley and Catchpole (1995) based on a 68 fires parameterized the effect of wind in Tasmanian buttongrass moorlands through a power function with an exponent of 1.3. Cheney et al. (1998) in a refined analysis of the effect of wind on fire spread, considered that there is a critical wind speed (after Beer

1995) that establish a threshold between heat transfer mechanisms, justifying different parameterization of empirical models for quantifying wind effect on spread rate. This critical windspeed, which should be a function of the fuel complex, was determined to be 5 km/h in grasslands. Cheney et al. (1998) determined a linear function of ROS on wind speed below the critical wind threshold and a power function (exponent of 0.844) for fires above the critical wind speed. Grishin (1997) analyzing outputs from his mathematical crown fire spread model refers an almost linear relation between spread rate and wind speed.

As shown by Cheney et al. (1998), the exponent used in the wind function might have several values, depending on the fuel complex and on the range of wind speeds encountered. It would be expected that experimental data on the lower spectrum of the wind speed scale would yield higher exponents in the power function. For a experimental fire behavior database covering the upper scale of wind speed values encountered in wildfires should yield lower exponents due the asymptote reached by the rate of spread curve, as modeled in Fire Danger Group (1992).

Available fuel

When analyzing the effect of the available fuel for flaming combustion in crown fire rate of spread, a distinction must be made between the fuels within the surface and crown fuel strata. From current experimental (e.g. Van Wagner 1967) and theoretical (Albini 1996) considerations it is assumed that crown fire spreading in a quasi-steady state is dependent on the heat provided by the combustion of the surface and crown fuel strata, in order to develop a continuous flame from the surface to tree top. From this standpoint the equilibrium spread depends on the available fuel for flaming combustion within the two fuel strata. The modeling approach followed by Albini and Stocks (1986) where crown fire spread is a function of crown fuels and assuming the surface fuel strata as thermally inert seems in opposition to empirical evidence. It is empirically accepted that crown fires entering areas where the surface fuelbed has been pre-treated tend to change to a surface spread phase, due to the dependence of a spreading crown fire on the radiation within the sub-canopy space (Van Wagner 1967).

It is normally assumed that crown fuel load, W_c, available for combustion in a crown fire flaming front is restricted to foliage and dead twigs (Van Wagner 1977; Stocks 1980; Albini and Stocks 1986). The estimation of the amount of fuel available for consumption within the surface fuelbed is dependent on the fuelbed structural properties and fuel moisture gradients. Discussion on its effects on fire behavior and crowning are in Section 2.2. The available data do not give information about the structure of the surface fuelbed. Information on the litter fuels (W_l in Table A.5 in Appendix) is incomplete and do not discriminated distribution by particle sizes classes.

Canopy bulk density

Fuel bed bulk density, i.e. the amount of fuel per unit volume, has been recognized as an important variable influencing fire rate of spread in laboratory (e.g. Thomas and Simms 1963; Rothermel 1972; Wilson 1982) and experimental fires (Thomas 1970; Van Wagner 1977). Various conclusions have arisen from the analysis of the effect of this variable on fire behavior. Several authors, e.g. Thomas (1971) and Van Wagner (1974) suggested from the analysis of the fundamental fire spread equation (a.k.a. basic heat transfer equation) that fire spread is inversely proportional to fuelbed bulk density. Rothermel (1972) identified two distinct effects of fuel bed bulk density, where if bulk density was below an optimum value (function of fuel particle size), its increase would result in an increase in reaction velocity and fire spread rate. If bulk density is above the optimum bulk density, its increase will have a damping effect on fire spread rate. Catchpole et al. (1998) determined, from a laboratory fires database covering a wide range of fuel and environment conditions, that an increase in bulk density will increase the fire propagating flux, and consequently, surface fire rate of spread. Grishin (1997) concluded through the analysis of his mathematical model that an increase in canopy fuel bulk density, CBD, (within a 0.15 – 0.4 kg/m^3 range) would decrease rate of spread due to the increase of heat energy necessary to pre-heat unburned fuels.

GIven the Van Wagner (1977) crown fire spread theory (Section 1.3), it can be inferred that under certain fire environment conditions, an increase in canopy fuel bulk density, will induce an earlier active crown fire spread phase, and consequently faster spread rates. This phenomena can be seen from the analysis of Figure 3.1.b, where for the same wind speed, active crown fires have higher spread rates than passive crown fires.

Agee (1996) analyzed post-fire data from several forest stands and identified a canopy bulk density threshold of 0.10 kg/m^3, below which crown fire spread is greatly limited. In FARSITE (Finney 1998) canopy bulk density is used to determine if a fire that meet the critical surface intensity threshold is treated as a crown fire or a surface fire. If the fire is considered a passive crown fire, fire spread is assumed as to be equal to the surface fire spread rate. If the fire is classified as an active crown fire, fire spread rate is estimated through a combination of Rothermel (1991a) and Van Wagner (1993) crown fire spread models.

Fuel strata gap

From the previously assumed dependency of crown fire spread on the interaction of the result of the combustion of the surface and crown layers of the fuel complex, it is inferred that the distance between these two layers, the fuel strata gap, has an effect on the way they interact. An increase in the distance between the strata would require larger heat outputs from the combustion of the surface and crown layers to constitute a solid and thick flame that will occupy the sub-canopy space.

Foliar moisture content

The theoretical considerations on the effect of foliar moisture content in the ignition of forest fuels and heat transfer phenomena were given in Section 2.2. Although the damping effect of fuel moisture in fire spread in dead fuels is easily observed through laboratory experimental fires (e.g. Rothermel 1972; Catchpole et al. 1998) and reasonable to quantify (Van Wagner 1972; Frandsen 1973), its effect on fire spread in live fuels, namely in crown foliage, has been found to be more difficult to assess.

Van Wagner (1967) noticed a significant effect of foliar moisture content in reducing radiant heat fluxes in a experimental setting where single trees (Christmas trees) were burn at variable foliar moisture content levels. Butler (1993) did not find any correlation between radiant heat flux and moisture content of dead fuels in a limited set of experimental laboratory fires. Data from prescribed and experimental fires in shrub dominated fuel complexes indicate that the live fuel moisture content effect on fire behavior varies in this fuel type due to species intrinsic properties, namely fuel chemical composition. Marsden-Smedley and Catchpole (1995), Vega et al. (1996), and Fernandes (1998) found no significant effect of live fuel moisture content in fire spread rate in prescribed and experimental fires in heathland fuels. Fire behavior data from Lindenmuth, and Davis (1973) in Arizona oak chaparral and from Van Wilgen et al. (1985) in South African Fynbos show a damping effect of live fuel moisture content in fire spread rates.

An important consideration in analyzing the foliar moisture content effect on spread rate in experimental fires is the magnitude of fire intensity. It might be hypothesized that in phenomena as crown fires, the amount and rates of released radiant energy are so high, with its impact on combustion phenomena due to the extremely rapid preheating, that the possible effect of an increase in foliar moisture content is canceled. Some well documented wildfires spreading as crown fires with very high rates of spread had high foliar moisture content levels. The Mack Lake fire (Simard et al. 1983) made a 4 hour crown fire run in jack pine stands with maximum estimated spread rates of 11 km/h although the estimated foliar moisture contents were around 120 %. Hartford and Rothermel (1991) refer that during the 1988 Yellowstone fires foliar moisture content was within normal values (within 96 – 118 % range) for the time of the year for various conifers.

Cohen et al. (1989) and Cohen and Omi (1991) hypothesized that certain tree species under non-water stress conditions may have a heating related water transport mechanism that would transport substantial water quantities to the branches subject to heating. This theory was based on the idea that under drought periods woody plants increase their propensity to ignite. Their theory was supported by the fact that under their experimental setup, non-stressed tree branches exhibited water uptake rates up to 50 times greater than prior to heating. Further tests, under more realistic heating rates shown that the increment moisture in foliage was restricted to 1 to 2 % (Sussot 1998), not influencing combustion processes.

Of the crown fire spread models presently used, the model build by Van Wagner (1993) for the C-6 (conifer plantation) fuel type of the Canadian FBP system is the only model that incorporates foliar moisture effect on the estimation of crown fire spread rates.

Van Wagner combined the effect of moisture content on (i) the energy of ignition and (ii) on flame radiation intensity, through the following foliar moisture effect (FME) function based on the basic heat balance equation (Thomas 1971):

$$FME = \frac{(1500 - 2.75FMC)^4}{h} \qquad [3.3]$$

where, the numerator incorporates the effect of fuel moisture in lowering flame temperature, and consequently flame emissivity through the Stefan-Boltzmann law (Van Wagner 1974). The denominator represents the heat of pre-ignition, calculated from Equation [1.4]. The FME is used in a relative sense, being normalized using an average FME relative to the supposed average foliar moisture content for Jack pine plantations.

Although the theoretical reasoning behind this formulation might be considered valid, its damping effect on spread rate seems excessive (Alexander 1998). This can be partially attributed to the fact that present theories of moisture content effect on fire behavior have been evaluated under laboratory experiments, but not in full scale experimental fires, where the heat transfer mechanisms and the magnitude of radiant fluxes are different. Van Wagner (1998) acknowledges the lack of a relationship of FMC on fire spread rates within the Canadian FBP database, but justifies his approach (Equation [3.3]) from a theoretical stand point

Foliar moisture variation in tree crowns

Moisture content of foliage of North American conifer trees show a seasonal variation due to several physiological and environment factors. Much of this variation has been attributed to patterns in carbohydrate accumulation (Chrosciewicz 1986;Tunstall 1988), species physiological controls, and environmental conditions that influence water supply and transpiration demand. Water movement within conifer trees is the result of pressure gradients between the leaves and the soil. When water supply in the soil reach certain lower limits, the rate of water uptake by the roots from the soil is reduced and the plant controls water transfer from the leaves to the environment through stomatal closure.

Several studies were conduct to evaluate seasonal moisture variation in coniferous trees in North America (Table 3.1). As an average, the foliar moisture range measured for the various species correspond to an increase in the heat requirements (Δh) for igniting fuels of 1400 kJ/kg (from Equation 1.4). It is difficult to estimate what will be the damping effect of this figure in crown fire spread.

Table 3.1. Variability of foliar moisture content (%) of several conifers in North America

Species	Year	Max. (month)	Min. (month)	Range	Reference	Origin	Δh (kJ/kg)
Pinus strobus	63-65	128(8)	102(6)	26	Van Wagner 1967	ON	1132
Pinus banksiana	63-65	118(8)	102(6)	16	Van Wagner 1968	ON	874
Pinus resinosa	63-65	112(8)	91(6)	21	Van Wagner 1968	ON	1003
Abies balsamea	62-64	123(8)	90(5)	33	Van Wagner 1968	ON	1313
Picea glauca	62-64	113(8)	87(5)	26	Van Wagner 1968	ON	1132
Pinus ponderosa	1962	125(7)	103(5)	22	Philpot 1963	CA	1029
Pinus resinosa	1963	125(8)	98(5)	27	Johnson 1966	MI	1158
Pinus banksiana	1963	120(7)	100(4)	20	Johnson 1966	MI	977
Pinus radiata	80-90			25	Pook and Gill 1993	NZ	1106
Pinus banksiana	1974	129(4)	84(6)	45	Chrosciewicz 1986	AL	1623
Picea mariana	1974	124(4)	73(6)	51	Chrosciewicz 1986	AL	1778
Picea glauca	1974	139(4)	78(6)	61	Chrosciewicz 1986	AL	2037
Abies balsamea	1974	140(4)	75(6)	65	Chrosciewicz 1986	AL	2140
Pinus banksiana	1975	123(4)	79(5)	44	Chrosciewicz 1986	AL	1597
Picea mariana	1975	126(5)	79(7)	47	Chrosciewicz 1986	AL	1675
Picea glauca	1975	126(3)	80(5)	46	Chrosciewicz 1986	AL	1649
Abies balsamea	1975	135(7)	83(5)	52	Chrosciewicz 1986	AL	1804
Pinus clausa	1971	150(9)	120(3)	30	Hough 1973	FL	1236
Pinus ponderosa	1968	118(8)	85(6)	33	Philpot and Mutch 1971	MT	1313
Pseudotsuga menziesii	1969	120(8)	72(6)	48	Philpot and Mutch 1971	MT	1701
Pinus ponderosa	1968	110(8)	87(6)	23	Philpot and Mutch 1971	MT	1055
Pseudotsuga menziesii	1969	120(9)	86(6)	34	Philpot and Mutch 1971	MT	1339

Δh is the heat of ignition calculated from equation [1.4]; ON –Ontario, Canada; CA – California; MI – Michigan; NZ – New Zealand; AL – Alberta, Canada; FL – Florida, MT – Montana.

Although for some marginal burning conditions (considered here as near some limiting threshold in relation to the contribution of live fuels to fire spread as a source or sink) it may be theoretically feasible that the increase in the heat sink due to high foliar moisture content will have a significant damping effect on fire spread, under the fire environment conditions required to sustain active crown fire spread the natural variation in foliar moisture content may not induce significant changes in spread rate.

Moisture content of surface fuels

Given the assumed dependence of a crown fire on the heat output of the surface phase, the moisture content of surface fuels acquire an important role in the phenomena under study as it will control surface fuel availability (as discussed in Section 2.2), combustion rates, and consequently the overall amount and rates of heat output. The analysis of fuel moisture effects on crown fire spread within the present database is somewhat impractical, as not all fires in the dataset had information on fuel moisture content discriminated by type and size classes of fuel.

3.3.METHODS

3.3.1. Database construction

After a review of the available crown fire spread data present in the literature it was decided to approach the modeling of crown fire spread based on experimental crown fire data. This preference of experimental fire data over wildfire case studies data is based on the inaccurate and uncompleted nature of most of the data from wildfire case studies. Some of the fuel complex variables identified in Section 3.2, e.g. canopy bulk density, with an effect on crown fire behavior, are not described and are difficult to estimate in most of the published wildfire case studies (e.g. Wade and Ward 1973; Simard et al 1983; Rothermel and Mutch 1986; Alexander and Lanoville 1987; Hirsch 1989). Furthermore, crown fire behavior data originated from wildfires is characterized by deficient information relative to various aspects of fire environment and behavior, which can be summarized as:

- Difficulties in monitoring fire front displacement, due to smoke, lack of reference points, or remoteness of the area, normally hamper the monitorization of fire spread and originate incorrect locations of the fire perimeter in time. In these situations, *a posteriori* personal and subjective accounts, characterized by exaggeration in stress situations, are sometimes used inducing further errors. The inability to view the fire front due to smoke make that certain extreme fire behavior phenomena, such as massive short range spotting or medium range spotting, can not be identified which will cause further unexpected variation. Crown fire runs are sometimes not precisely documented in their beginning and end, increasing error.

Weather data is normally recorded at a nearby or remote weather station, but the data may not be representative of the crown fire run location, due to topographic effects on the wind field or local wind patterns. Fire induced buoyancy may interact with the wind field, originating local wind patterns near the fire, that are not captured by nearby weather stations.

Quantification of fuel complex properties, i.e. live and dead fuel moisture variation, and surface and crown fuel strata structure, are normally not made. Often such data are estimated in simplified ways based on assumptions as weather conditions, and stand history and structure.

As with the crown fire initiation model, the database gathered for the construction of a crown fire spread model comes mainly from published experimental crown fires and some unpublished data found in the Canadian FBP database provided by M.E. Alexander (1999). As for the dataset described in Section 2.3.1, data in the crown fire spread database comprise all the experimental crown fire data in coniferous stands known to the author. The assembled dataset covers a smaller range of fuel complex variability than the dataset used for crown initiation modeling (Section 2.3.1). Nevertheless, the variability of fuel complex physical characteristics seems adequate to allow building a model without biasing the outputs to certain input variables. Fuel complexes selected for crown fire spread model building are presented in Table 3.2. Fire data sources are described in Table A.5 in Appendix.

As for the crown fire initiation model, due to the objective of building a model applicable to a wide spectrum of fuel complexes, the fuel complex characteristics of each fire are physically described. Detailed information on fuel complex characteristics, fire environment, and fire behavior for each fire is provided in Tables A.4, A.5 and A.6 in the Appendix.

Table 3.2. Fuel complexes used for building the crown fire spread model.

Fuel complex	n
Black spruce	16
Immature jack pine	12
Mature jack pine	12
Red pine	3
Total	43

As in the crown fire initiation dataset, information on measured surface fuels moisture content and foliar moisture content was not available with all the data. To cope with this limitation, values for these variables were estimated as indicated in Section 2.3.1.

3.4. RESULTS

3.4.1. Variables analysis

Correlation matrices, using Pearson correlation coefficient, were computed for the various available variables identified as pertinent in order to evaluate relationships between variables. Histograms of variable distributions were examined to analyze the representativeness of the data within the range of fire environment conditions found in wildfires. Scatterplots were also examined to identify relationships between the selected variables and crown fire rate of spread.

When considering the spread of crown fires two phenomena should be separated due to their different controls, namely passive and active crown fires. As discussed previously (Section 1.3) passive crown fires are in a large way controlled by the surface phase, whereas in active crown fires the main control should be in the crown phase. Accepting this premise, the crown fire spread database was divided into fires spreading as active and as passive crown fires and the effect of the fire environment variables separately analyzed for each fire type (Table 3.3 and 3.4) The criterion used to divide the dataset into active and passive crown fires was the achievement of a crown fire spread criterion (Section 1.3) above 0.9. Although this approach is open to question because of limited experimental support for the assignment of 3 kg/m^2-min for the critical mass flow rate (Van Wagner 1977), it is to the knowledge of the author the only way to determine how a crown fire is spreading.

Table 3.3. Correlation matrix for significant fire environment and behavior variables of active crown fires within the crown fire spread database (n=25).

	ROS	U_{10}	EFFM	CBD	FMC	W_c	SFC	FSG
ROS	1.000	0.695**	-0.400*	-0.397*	-0.376	-0.197	-0.156	-0.107
U_{10}	0.695**	1.000	-0.078	-0.508**	-0.528**	-0.245	-0.091	0.182
EFFM	-0.400*	-0.078	1.000	0.078	0.230	0.632**	0.109	0.769**
CBD	-0.397*	-0.508**	0.078	1.000	0.211	0.188	0.175	-0.119
FMC	-0.376	-0.528**	0.230	0.211	1.000	0.393	0.191	0.044
W_c	-0.197	-0.245	0.632**	0.188	0.393	1.000	0.125	0.589**
SFC	-0.156	-0.091	0.109	0.175	0.191	0.125	1.000	0.203
FSG	-0.107	0.182	0.769**	-0.119	0.044	0.589**	0.203	1.000

ROS – Rate of spread; U_{10} – Windspeed at 10 meters; SFC – Surface fuel consumption; FSG – Fuel strata gap; EFFM – Estimated fine fuel moisture; CBD – Canopy bulk density; FMC – Foliar moisture content; Wc – Crown weight;

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

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

Table 3.4. Correlation matrix for significant fire environment and behavior variables of passive crown fires within the crown fire spread database (n=14).

	ROS	U_{10}	CBD	EFFM	SFC	W_c	FSG	FMC
ROS	1.000	0.433	-0.408	-0.265	-0.246	0.158	0.156	-0.001
U_{10}	0.433	1.000	-0.498	-0.046	-0.262	0.020	0.351	-0.190
CBD	-0.408	-0.498	1.000	0.007	-0.220	0.183	-0.446	-0.243
EFFM	-0.265	-0.046	0.007	1.000	0.148	0.238	0.084	0.276
SFC	-0.246	-0.262	-0.220	0.148	1.000	-0.465	0.446	0.407
W_c	0.158	0.020	0.183	0.238	-0.465	1.000	-0.451	0.443
FSG	0.156	0.351	-0.446	0.084	0.446	-0.451	1.000	0.202
FMC	-0.001	-0.190	-0.243	0.276	0.407	0.443	0.202	1.000

ROS – Rate of spread; U_{10} – Windspeed at 10 meters; SFC – Surface fuel consumption; FSG – Fuel strata gap; EFFM – Estimated fine fuel moisture; CBD – Canopy bulk density; FMC – Foliar moisture content; Wc – Crown weight;

Wind speed

Wind speed is significantly correlated with active crown fire spread rate (Table 3.3). The high correlation coefficient between these two variables shows the strong control that wind speed has on the spread rate of active crown fires. Wind speed is significantly correlated with foliar moisture content and canopy bulk density in the active crown fire spread dataset. Non-independence of these variables limits the inferences that can be made through regression analysis.

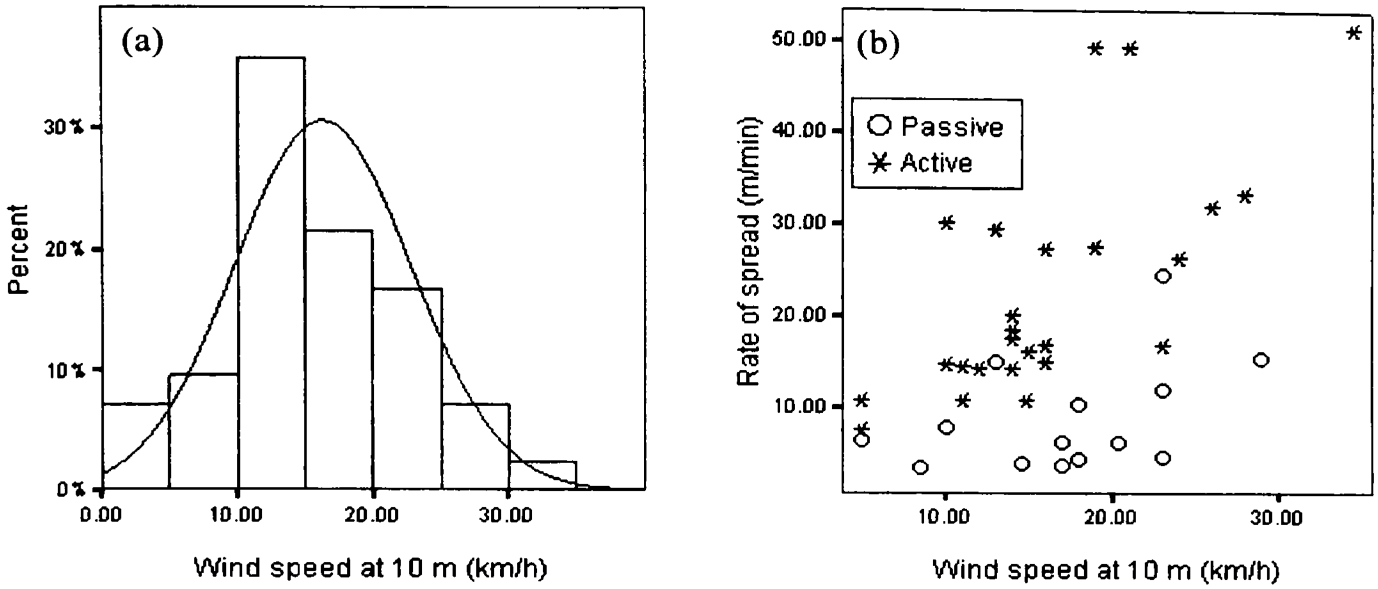


Figure 3.1. (a) Distribution of wind speed data within the crown fire model database; (b) Scatterplot of rate of spread with windspeed.

For the passive crown fire spread dataset, wind is not significantly (at the 0.05 level) linearly correlated with rate of spread. The fact that a passive crown fire is to a variable extent controlled by the surface phase, makes it difficult to know which wind speed is affecting the fire. Apart from not knowing the wind profile and the factors that control it, the unknowns relatively to the proportion of each phase, surface and crown, controlling fire spread makes extremely difficult to estimate the wind velocity that was affecting fire spread for each experimental fire.

From the observation of figure 3.1.a it is noted that the range of wind speeds of the experimental fires used in the database is limited, with the majority of the data within the 15 – 20 km/h range. Although wind is recognized as being the environment variable with a stronger effect on fire rate of spread, the scatter in figure 3.1.b illustrate the variation that might be explained by other variables, as fuel complex structure and fuel availability, in crown fire spread rate. Differences in what controls fire spread in passive and active crown fires are illustrated in the scatter on figure 3.1.b. The different effect of wind speed on fire spread in the two fire types are observed by the different trends exhibited by the two crown fire types.

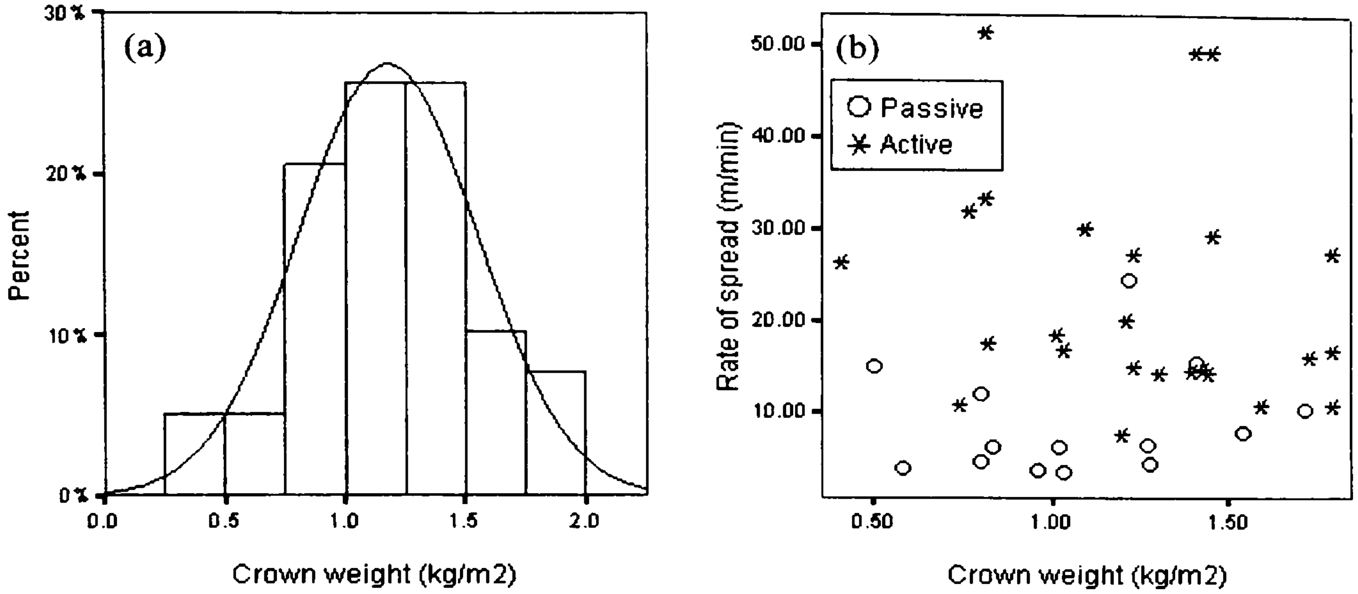


Figure 3.2. (a) Distribution of crown weight data within the crown fire model database; (b) Scatterplot of rate of spread with crown weight.

Available fuel

Neither crown weight (foliage and dead fine fuels) nor surface fuel consumption, used here as a surrogate of available fuel in the surface fuel stratum were significantly (at the 0.05 level) correlated with active or passive crown fire spread rate (Table 3.3 and 3.4). Crown weight was significantly correlated with fuel strata gap and estimated fine fuel moisture content for the active crown fire dataset. Figure 3.2.a shows the distribution of crown weight within the crown fire spread database. The database did not yield meaningful relationships between crown weight and active and passive crown fire rate of spread (Figure 3.2.b).

The use of surface fuel consumption as a surrogate of available fuel (Figure 3.3.a and b) as used in Section 2.4.1 did not yield any meaningful trend for both types of crown fire spread.

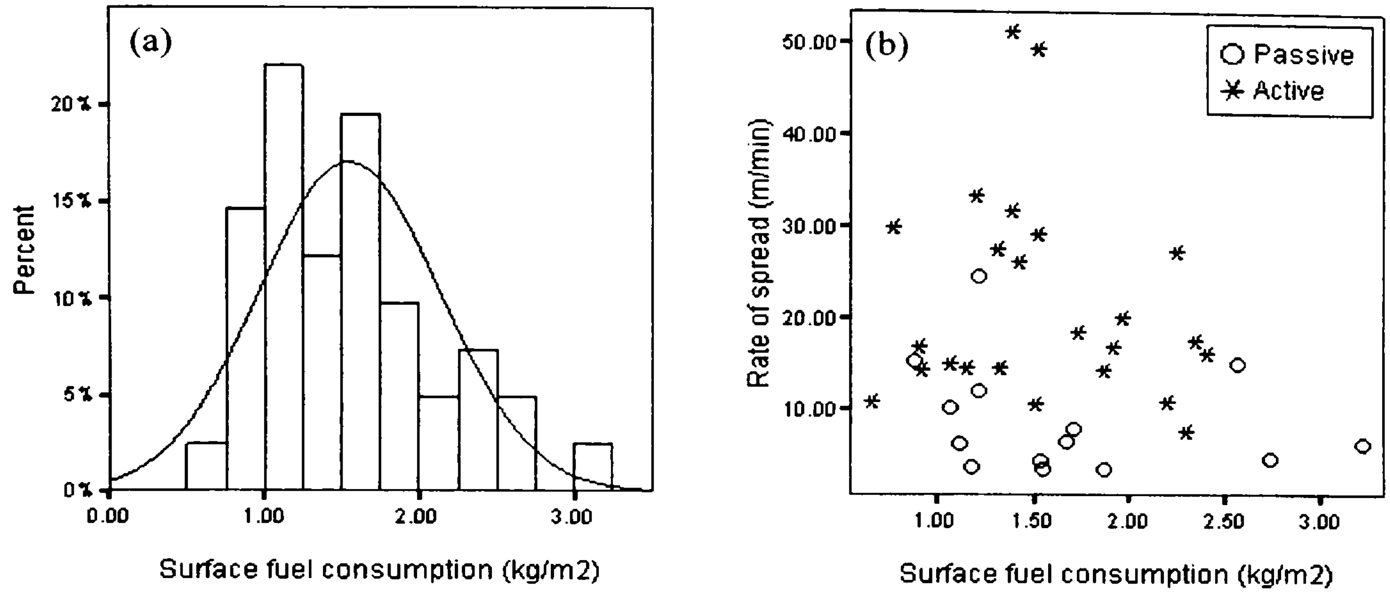


Figure 3.3. (a) Distribution of surface fuel consumption data within the crown fire model database; (b) Scatterplot of rate of spread with surface fuel consumption.

Canopy bulk density

Canopy bulk density assumes an important role in the crown fire modeling process as the separation of crown fires into active/passive are based on this fuel complex characteristic (Section 1.3). Canopy bulk density is significantly (at the 0.01 level) negatively correlated with fire spread rate of active crown fires. This relationship should be analyzed with care, as although it follow theoretical considerations of Thomas (1971) and Van Wagner (1974), canopy bulk density is also significantly negatively correlated with wind speed within the active crown fire dataset. It is expected that through the regression analysis to be done to the dataset in Section 3.5.1 the relation between canopy bulk density and active crown fire spread be clarified. Within the passive crown fire dataset canopy bulk density is not significantly correlated (at the 0.05 level) with any other variable being analyzed.

Data on the present crown fire spread database cover a wide range of canopy bulk density (Figure 3.4.a). A scatterplot of crown fire spread rates with canopy bulk density (Figure 3.4.b) show no clear trend of the effect of bulk density on fire spread rate. There are no active crown fires below the 0.10 kg/m^3 threshold, which support findings from Agee (1996) in defining such canopy bulk density threshold to support fuel management aimed to reduce the occurrence of crown fires. The high passive crown fire spread rates shown in Figure 3.4.b indicate that fires spreading under the defined passive crown fire phase can achieve high spread rates, contrary to the assumption by Finney (1998) to model passive crown fire spread as a surface fire.

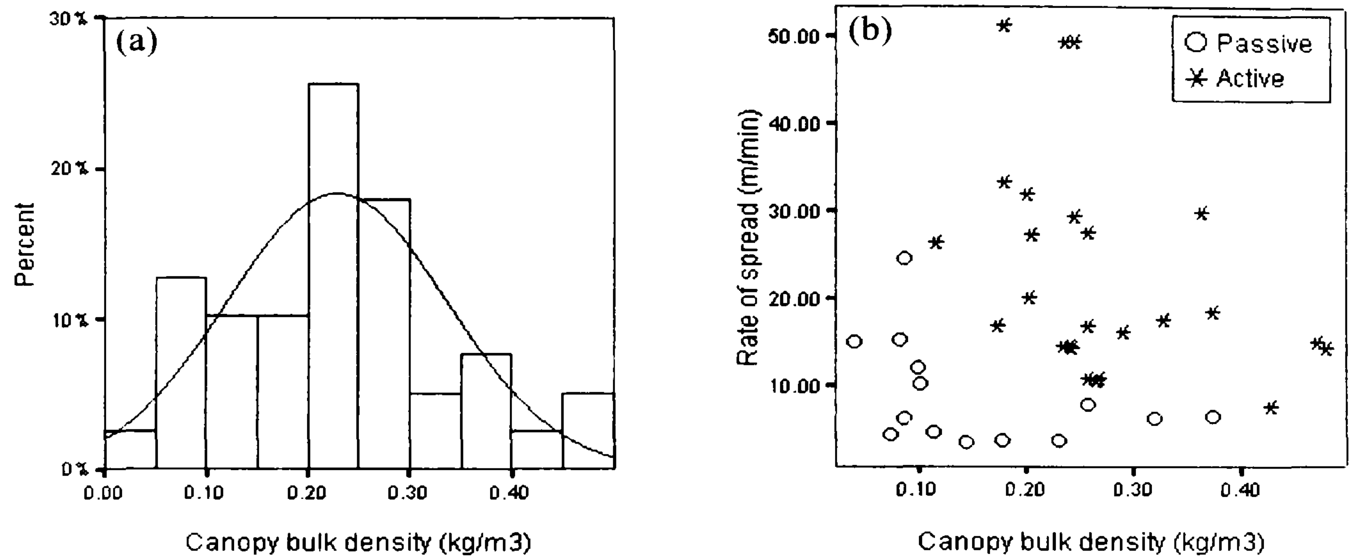


Figure 3.4. (a) Distribution of canopy bulk density data within the crown fire model database; (b) Scatterplot of rate of spread with canopy bulk density.

Fuel strata gap

Fuel strata gap is not significantly correlated (at the 0.05 level) with rate of spread of either passive and active crown fires (Table 3.3 and 3.4). The characteristics of the active crown fire dataset (Figure 3.5.b), with most of the data having FSG below 2.5 m, limit the analysis of the effect of this variable on the rate of spread of active crown fires. Overall the distribution of this variable (Figure 3.5.a) within the crown fire spread database, with more than 75 % of the fires with distances between the two strata under 2.5 meters, make difficult to yield conclusions concerning the effect of fuel strata gap on crown fire spread rate.

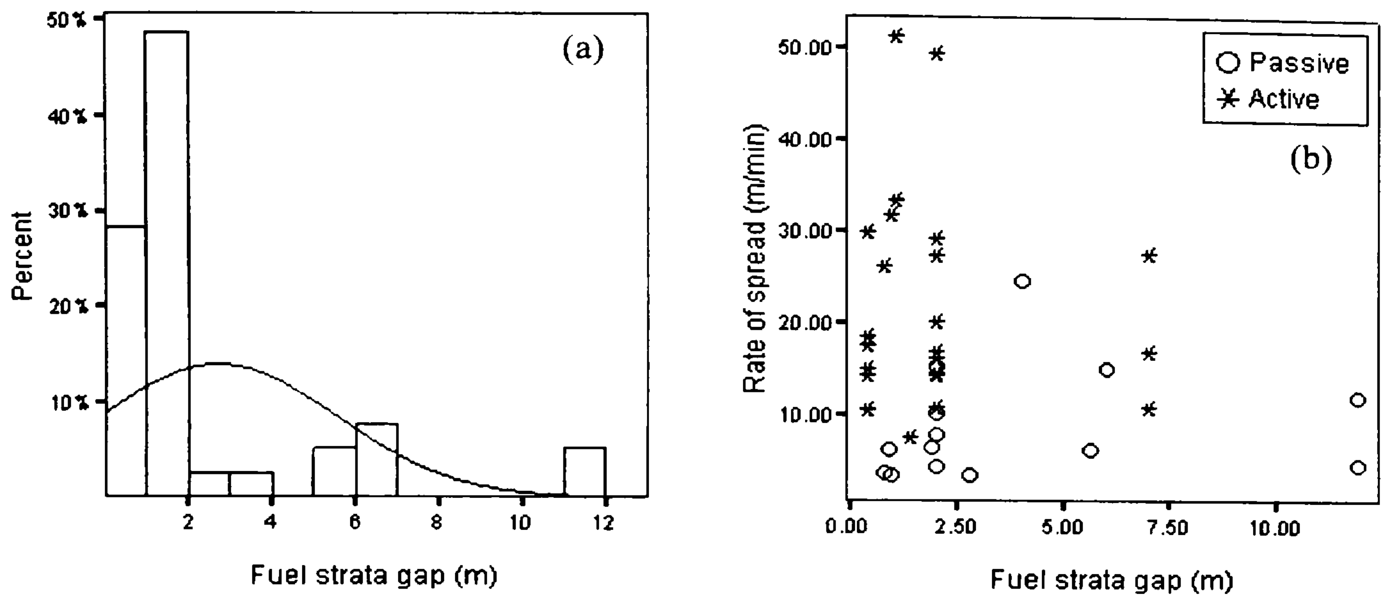


Figure 3.5. (a) Distribution of fuel strata gap data within the crown fire model database; (b) Scatterplot of rate of spread with fuel strata gap.

Foliar moisture content

Within the active and passive crown fire datasets there were no significant correlations between fire spread rate and foliar moisture content (Table 3.3 and 3.4). There exists a significant (at the 0.01 level) correlation between FMC and wind speed within the active crown fire dataset, but it is believed to be circumstantial, as there is no physical relation between the two.

Figure 3.6.a depicts the distribution of the estimated foliar moisture content in the crown fire spread database. Note the lack of variability, with most of the data within the 105 – 115 % range. A cause of this clustering within this short range can be pointed to the common period when most of the experimental fires were set (Table A.4 in Appendix for burn dates) and the fact that the FMC calculation (Fire Danger Group 1992) is a function of site location and the time of the year. The distribution of data points in Figure 3.6.b reflect the considerations previously made, where the possible effect of FMC on spread rate is confounded by the effect of other fire environment variables and the fact that the FMC value used is an estimate and not a measured one.

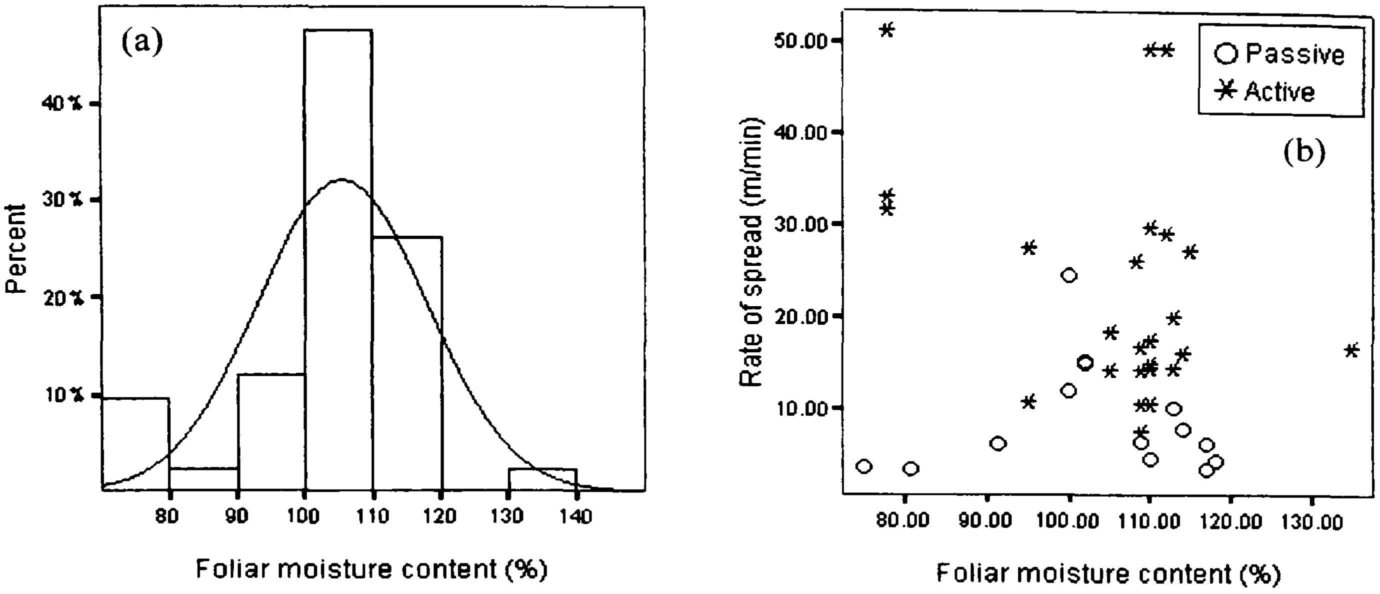


Figure 3.6. (a) Distribution of foliar moisture content data within the crown fire model database; (b) Scatterplot of rate of spread with foliar moisture content.

Estimated fine fuel moisture content

Estimated fuel moisture content was significantly correlated (at the 0.05 level) with active crown fire rate of spread. It was also significantly (at the 0.01 level) correlated with FSG and crown weight, although circumstantially.

Figure 3.7.a display the distribution of the estimated fine fuel moisture content within the database, where most of the data is within the limited range 7 to 10 %. This is a result of the low fuel moistures content needed to perform experimental crown fires, and also the social and operational limitations imposed to burning under more extreme fire weather conditions (Stocks 1987; Alexander and Quintilio 1990). The scatter of Figure 3.7.b shows a clear damping trend in active crown fire spread rate due the increase in the estimated fine fuel moisture content. The two 12 % data points, that are outside the trend are not estimated values but measured ones, as there were no temperature or relative humidity information for those fires. Estimated fine fuel moisture content is not correlated with passive crown fire spread rate.

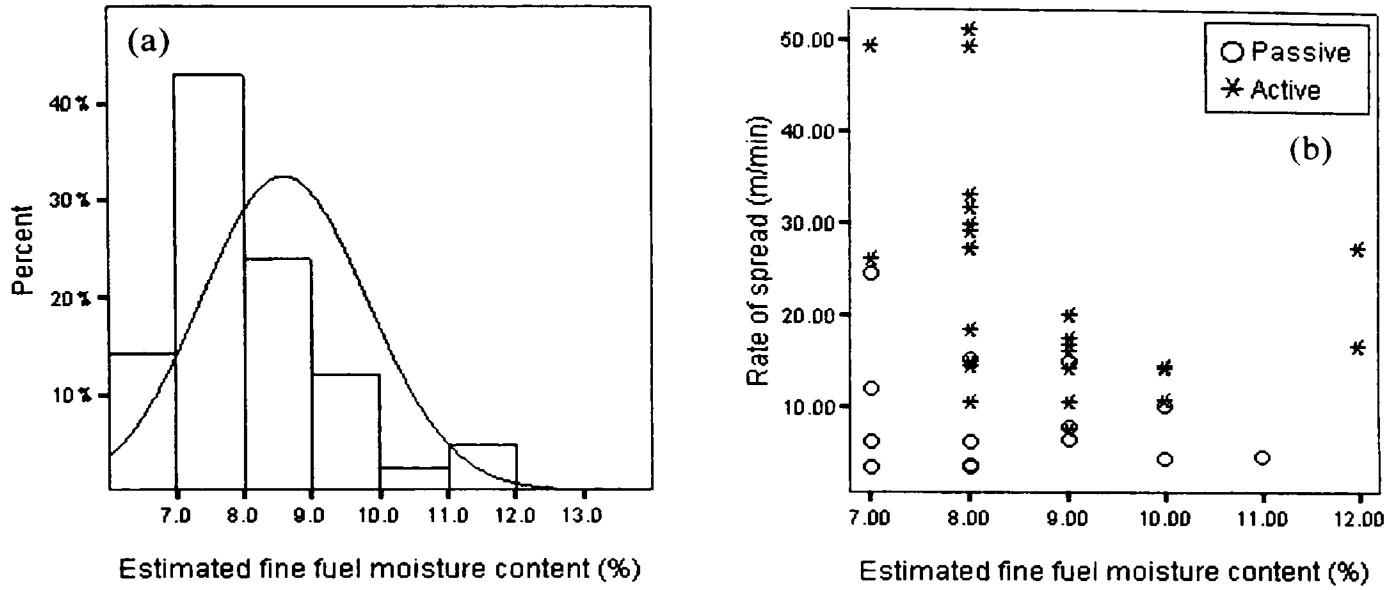


Figure 3.7. (a) Distribution of estimated fine fuel moisture content data within the crown fire model database; (b) Scatterplot of rate of spread with estimated fine fuel moisture content.

3.5. MODEL BUILDING

From the analysis of the previous section showing the differences between fires spreading as active or passive crown fires, the modeling of their spread rate will be done separately.

3.5.1. Modeling active crown fire spread rates

In order to produce a robust model applicable to different fuel complexes and under a wide spectrum of fire weather conditions, the focused modeling approach used in this study was an approach based as much possible in fundamental physical relations between the variables and the processes they influence. With this intent Thomas and Simms (1964) simple form of the heat balance equation was selected to model fire spread:

$$Q = R\rho_b \Delta H \qquad [3.3]$$

Where, Q is the forward heat flux per unit vertical cross section of the fuel bed, *R* the fire rate of spread, ρ_b is the fuel bulk density; and ΔH the difference in thermal enthalpy between the fuel at its ignition temperature and the virgin fuel. ΔH can be viewed as the heat of ignition. This equation links the rate of spread with fuel bulk density (variable describing the fuel complex), and the heat of ignition (function of foliar moisture content, dead fuel moisture content and amount of fuel) as a function of the net horizontal heat flux to the unburned fuels. Conceptually this net horizontal heat flux should depend mainly on windspeed and slope, and can be modeled also as a function of some fire spread index that incorporates windspeed and slope.

Although this equation is based on the assumption that the most important mode of heat transfer is radiation through the fuel bed (Thomas and Simms 1964), several authors (e.g. Van Wagner 1967, 1977; Thomas 1971; Rothermel 1972) based their analysis of the fire spread phenomena on this equation. The rearrangement of equation [3.3] in terms of fire rate of spread yield:

$$R = Q\rho_b{}^{-1}h^{-1} \qquad [3.4]$$

This equation assumes that rate of spread is inversely proportional to fuelbed bulk density and the heat of ignition. Considering that the bulk density, ρ_b, of crown fuels is below what would be considered an optimum due to site and biological limitations, it is expected that its increase would increase fire spread rate. As comparative values, canopy bulk density values in the crown fire spread database vary between 0.04 and 0.48 kg/m^3 (Figure 3.4.a for its distribution), where as in the laboratory surface fires used by Catchpole et al. (1998) bulk density in ponderosa pine needles fuelbeds varied within 10.2 and 47.9 kg/m^3. Under the physiological constraints in a tree that limit the amount of foliage it can support, it is expected that an increase in bulk density is related to an increase in foliage load, and respectively an increase in available energy to be released by a fire.

Based on the relationships described in Section 3.2, and the type of effect that the selected variables are expected to have in fire spread, two models were fitted to the data using SPPS (Norussis 1997) statistical analysis software:

$$ROS_A = \beta_1 U_{10}{}^{\beta_2} \cdot \rho_b{}^{\beta_3} \cdot \exp(-\beta_4 EFFM) \qquad [3.5]$$

$$ROS_A = \beta_1 U_{10}^{\beta_2} \cdot \rho_b^{\beta_3} \cdot EFFM^{\beta_4} \qquad [3.6]$$

3.5.1.1. *Modeling results*

The model of equation [3.5] produced a R^2 of 0.61, whereas equation [3.6] yield an R^2 of 0.63. The model [3.5] was preferred since the power function of the fine fuel moisture term used in equation [3.6] yields unacceptably high rates of spread under extremely low fuel moisture conditions. The exponential form of the fine fuel moisture term used in Equation [3.5] agrees with findings from laboratory fires on the fine fuel moisture damping effect on surface fire spread rate (e.g. Wilson 1991; Catchpole et al. 1998).

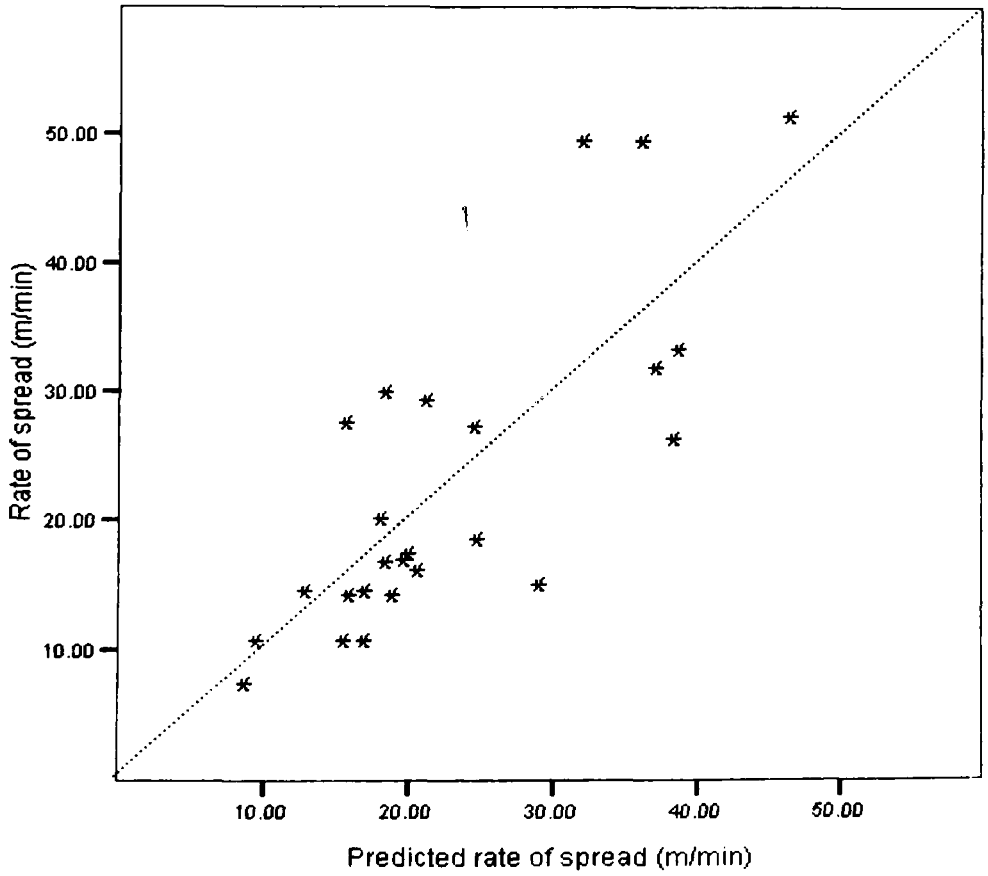


Figure 3.8. Plot of observed versus predicted active crown fire spread rate. Predicted values are from equation [3.5]. Dashed line is 1:1.

For equation [3.5] the constants $\beta_1 \ldots \beta_4$ are respectively (with asymptotic standard errors in brackets), 11.76 (10.62), 0.86 (0.23), 0.18 (0.26), and 0.17 (0.07). The model accounted for 61 % of the variability of spread rate within the dataset. Model predictions are compared with the data used in its construction in Figure 3.8. As pointed by other authors (Cheney et al. 1998) the scatter encountered in Figure 3.8 can be explained by the nature of the phenomena under study. Apart from effect of other variables (Section 3.2) that are not included in the model due to the nature of the database, it would be expect that certain phenomena, as interaction of convection plume with the fire and the occurrence of short range spotting, would be responsible for the scatter.

A plot of residuals versus predicted rate of spread (Figure 3.9.a) and the normal probability plot (Figure 3.9.b) indicate that error assumptions done when performing regression analysis, i.e. $\varepsilon_i \approx N(0,\sigma^2)$, are not violated.

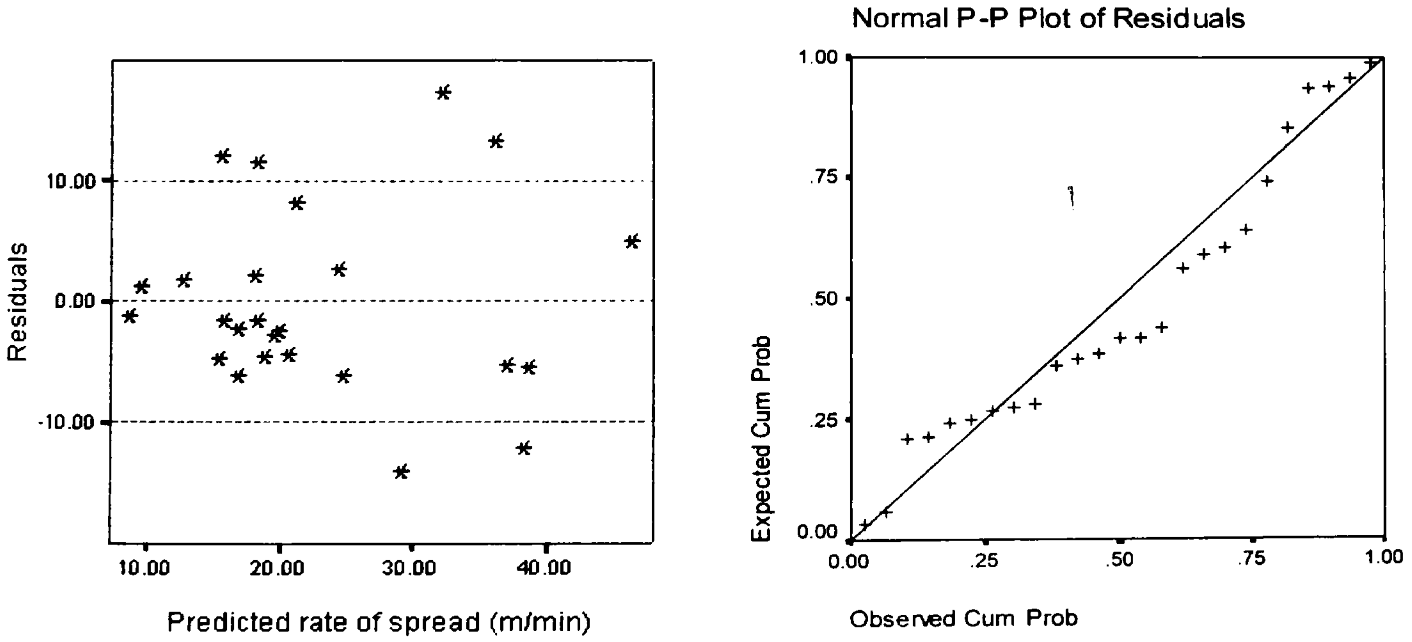


Figure 3.9. (a) Plot of residuals and predicted rate of spread, (b) Normal probability plot for residuals of crown fire spread model.

3.5.1.2. Model behavior

Analysis of model behavior will help understanding how the crown fire spread model responds to the variation of the input variables, identify model limitations and unacceptable results. Several runs of the model were done to evaluate model behavior within reasonable range of fire environment conditions. Table 3.5 present the range of variables values used in the evaluation.

Table 3.5. Values of input variables used for the evaluation of model behavior

Variable being analyzed	Wind speed (km/h)	CBD (kg/m^3)	EFFM (%)
U_{10}	5 - 60	0.10; 0.25; 0.40	8
CBD	20; 40; 60	0.05 – 0.65	8
EFFM	20; 40; 60	0.2	3 - 20

As expected from the theoretical discussion in Section 3.2, wind speed is the variable with the strongest effect on the spread rate of active crown fires (Figure 3.10). The 0.86 coefficient in the wind power function is similar to the 0.844 coefficient determined by Cheney et al. (1998) for grasslands, and lower than the 1.312 determined by Marsden-Smedley and Catchpole (1995) for shrublands. It is expected that in empirical studies this coefficient would vary within a certain limited range, a function of the representativeness of the dataset, namely the spectrum covered by wind speed, and the interaction between fire behavior and the wind field in a particular fuel complex. The significance of the wind effect on the spread rate of active crown fires is illustrated in Figure 3.10. The variation of the canopy bulk density variable within a likely range found in natural stands has a moderate effect on rate of spread comparatively with wind speed.

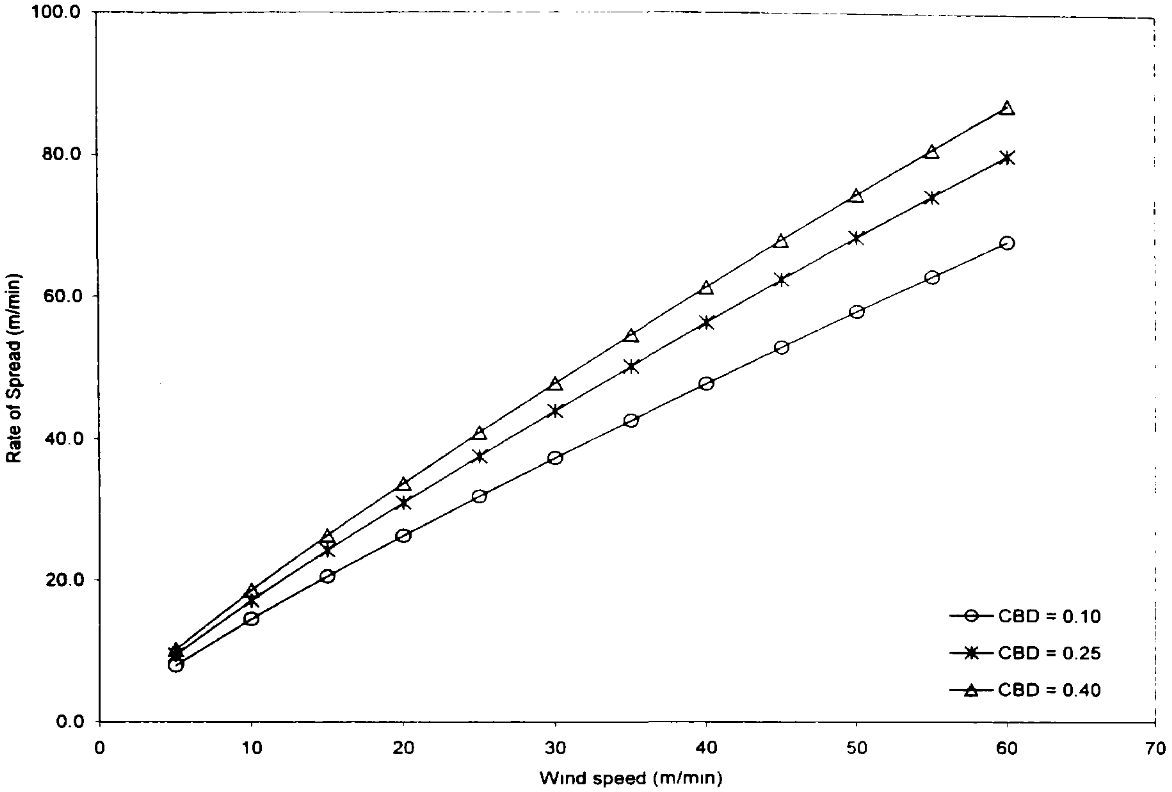


Figure 3.10. Windspeed effect on active crown fire rate of spread as predicted by model of equation [3.5]. EFFM set at 8 %.

The canopy bulk density function in the model induces a slight increase in rate of spread of active crown fires (Figure 3.11). As the model is a multiplicative one, the higher the spread rate induced by wind and fine fuel moisture, the higher will be the absolute effect of canopy bulk density in the final output. This is somewhat in opposition to the accepted notion that the more severe the burning conditions, the less will be the effect of fuel complex variability on fire behavior. The increase in canopy bulk density above 0.5 kg/m^3 induces small relative changes in active crown fire spread rate. Due to the fact that wind speed and canopy bulk density are linearly correlated within the dataset, it is difficult to identify the real effect of canopy bulk density in crown fire spread.

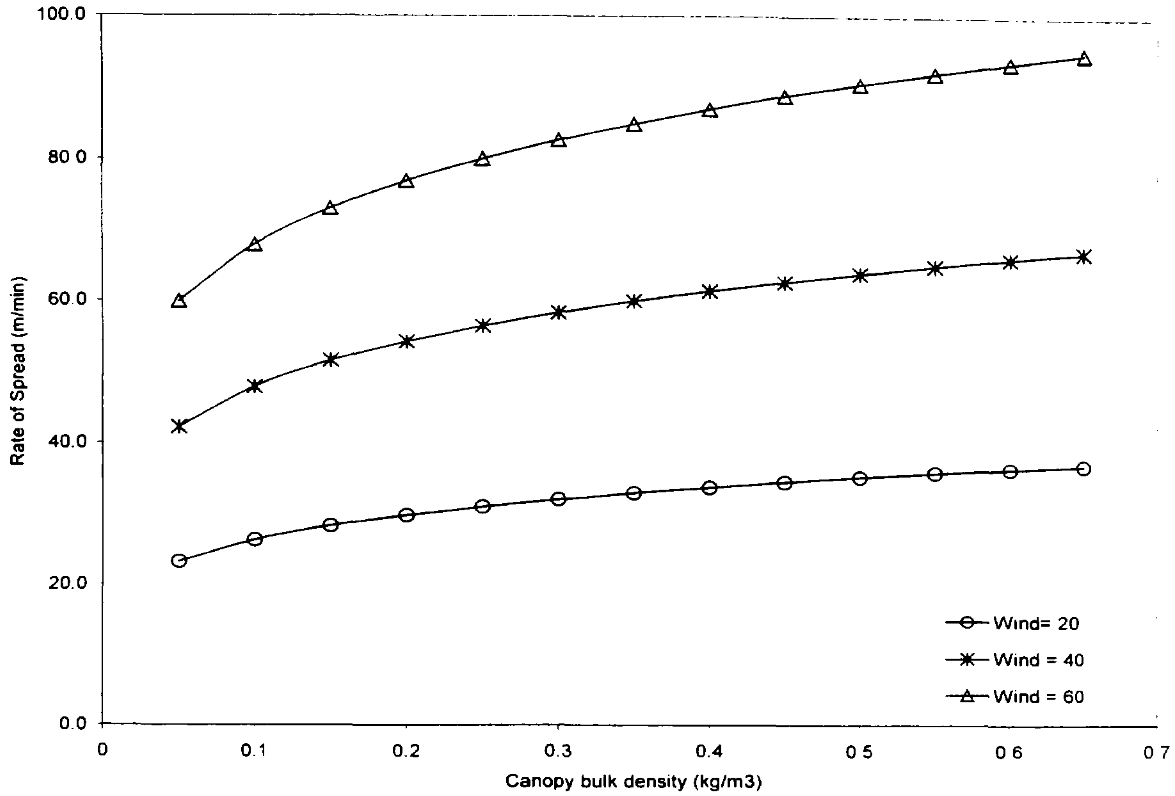


Figure 3.11. Canopy bulk density effect on active crown fire rate of spread as predicted by model of equation [3.5]. EFFM set at 8 %.

As expected, the variation of estimated fine fuel moisture content within the natural range of burning conditions has a strong impact on the spread rates of active crown fires (Figure 3.12). Crown fires under high fuel moisture contents are unlikely to occur, but if a certain combination of environment factors would induce crowning, it would be expected that the heat requirements for the surface phase would limit fire spread, resulting low crown fire spread rates. Under extreme burning conditions, characterized by very low dead fine fuel moisture contents (e.g. below 7 %), it is expected that small variations in fine fuel moisture content induce relatively large changes in spread rate (McArthur 1967). It seems that the model mimics this behavior relatively well.

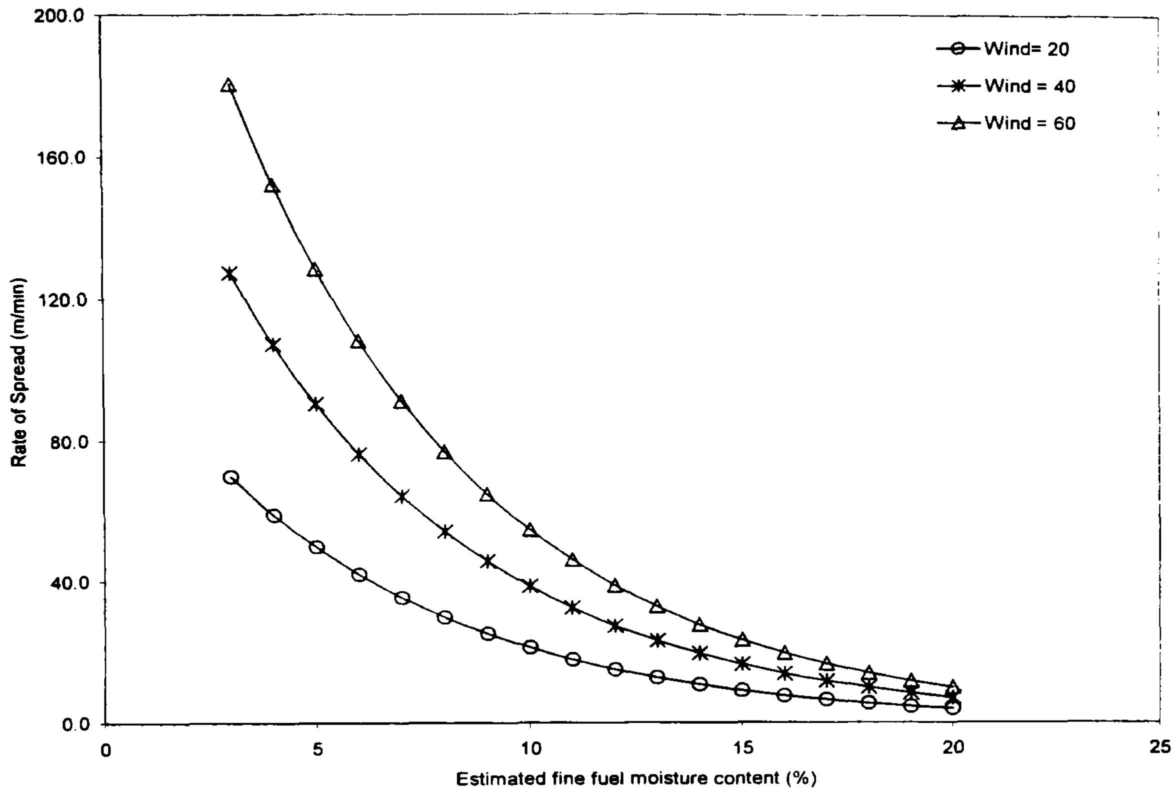


Figure 3.12. Estimated fine fuel moisture content effect on active crown fire rate of spread as predicted by model of equation [3.5]. CBD set at 0.2 kg/m^3.

The 0.17 coefficient of the moisture damping function is higher than similar coefficients found for grasslands (0.097) by Cheney et al. 1993 and shrublands (0.02) by Marsden-Smedley and Catchpole (1995), but within the range of values found for laboratory surface fires (Catchpole et al. 1998). Assuming that the estimated fine fuel moisture content value is representative of the fine fuel moisture existent during the experimental fires, it can be hypothesized that the effect of this variable on crown fire spread is similar to the one found in the model, as this variable is not related with the other variables used in the model.

3.5.1.3. Model evaluation

As for the probabilistic model built in Chapter II, the evaluation of the crown fire spread model will not follow the same procedure as the one described in Section 1.4. A more restricted evaluation of the active crown fire spread model build in Section 3.5.1.1 will be based on a sensitivity analysis and predictive and statistical validation using an independent crown fire dataset. This dataset consists on data published as wildfire case studies. No conceptual validation of the model will be performed as it would be a repetition of Sections 1.3 and 3.2.

Sensitivity analysis

Sensitivity analysis procedures and objectives have already been discussed in Section 1.4.2.2. The sensitivity analysis performed on the active crown fire spread model is based on the same fire environment conditions used for the sensitivity analysis of Rothermel (1991a) crown fire spread model (Table 1.1). A canopy bulk density of 0.09 kg/m^3 was assigned to the Kenshoe Lake fire situation based on the average bulk density found for the Kenshoe experimental fire plots. Since there is no data on canopy bulk density for the Lily Lake situation, an arbitrary value of 0.20 kg/m^3 was used in the sensitivity analysis. The relative sensitivity (RS) scores (Equation [1.9]) computed for the active crown fire model are in Table 3.6.

Table 3.6. Relative sensitivity scores for the active crown fire spread model.

Input parameter	Kenshoe Lake #5	Lily Lake
U_{10}	0.86	0.86
CBD	0.18	0.18
EFFM	- 1.38	- 0.89

The RS scores for wind speed and canopy bulk density reflect the coefficients used in the power functions of the active crown fire spread model (Equation 3.5). Depending on the fine dead fuel moisture content, the EFFM exponential damping function will originate different RS scores for fuel moisture variation. For the two situations tested for EFFM, the 10 % changes in the input yield relatively proportional (- 14 and - 9 %) changes in rate of spread. In comparison with the RS scores for the Rothermel (1991a) model (Table 1.3 and 1.4), the active crown fire model is less sensitive to wind variation but more sensitive to changes in the moisture content of dead fine fuels. Relative to the FBP (Fire Danger group 1992) fire models, for the Kenshoe Lake situation, the present model is less sensitive to the wind and fine fuel moisture content variation. Looking at the Lily Lake situation, the FBP models are less sensitive to changes in dead fuel moisture, whereas they continue to be more sensitive to wind speed (with exception of C-6).

Predictive validation

As described in Section 1.4.2.4, the predictive validation intents to assess how a model predict the behavior of a real world system. The evaluation performed on the active crown fire model (Equation [3.5]) in this section is not based on experimental crown fire data, since all the available data was used to build the model. It is based on data from published wildfires. A wildfire crown fire spread dataset was constituted from published wildfire case studies know to the author. The selected case studies have complete and detailed information on crown fire runs, fuel type and fire weather conditions. As for the crown fire initiation and spread datasets, the wildfire dataset does not have a complete description of dead fine fuel moisture content. This parameter was estimated by the FBA tables (Rothermel 1983) as for the two others datasets. All the fires are assumed to spread as active crown fires.

There was no information on canopy bulk density for the wildfire data. It is also important to consider that some of the crown fire runs used actually burned in several different fuel types making it difficult to define a canopy bulk density for each run. Based on this data limitation, a single canopy bulk density value of 0.15 kg/m^3 was assumed for all the fires. Summary of the wildfire data used in the predictive validation and their sources is presented in Table A.7 in Appendix.

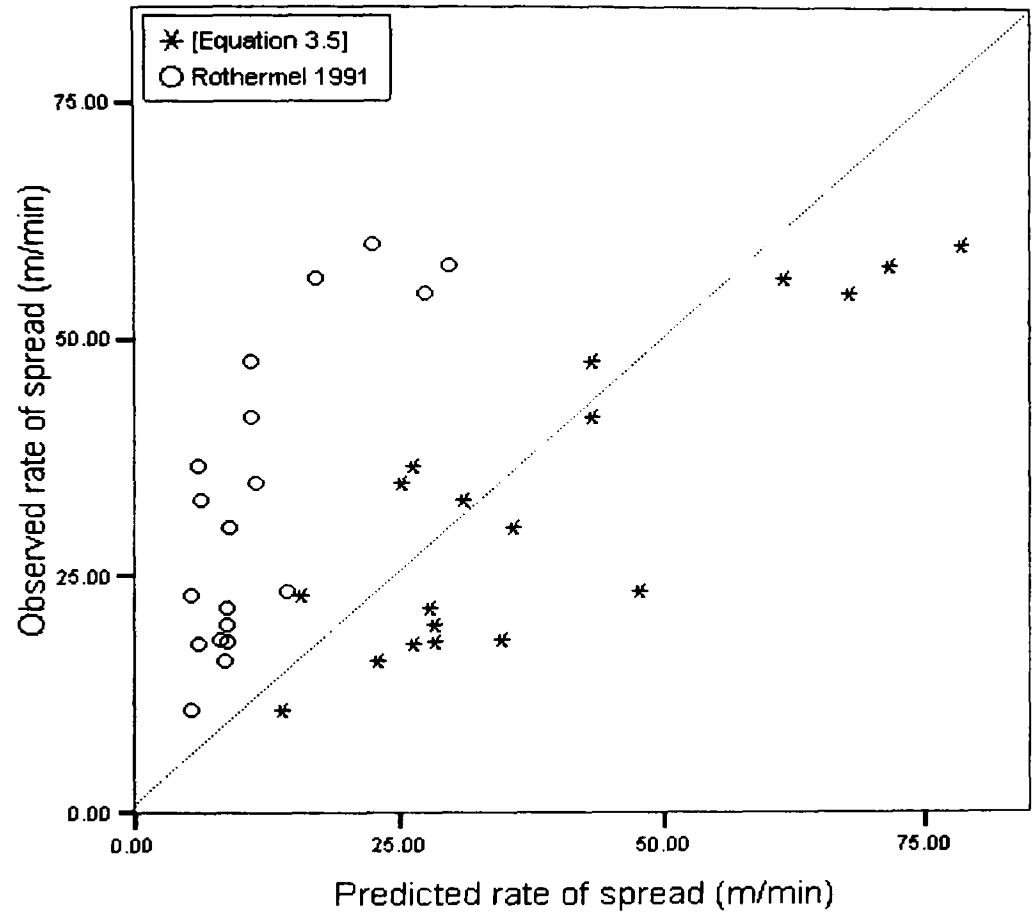


Figure 3.13. Plot of observed versus predicted rate of spread of crown fires by Equation 3.5 model and Rothermel (1991a) crown fire model; dashed line is line of perfect agreement.

The overall image of observed versus predicted crown fire spread rates (Figure 3.13) show an acceptable agreement of model predictions with the wildfire data. The model tends to over-predict the observed data as seen by the spread of the residuals in Figure 3.14. This fact should be expected for the following reasons:

- Some of the crown fire runs extent through various fuel types, encompassing broadleaf stands and shrublands. This will result in overall lower rates of spread than what would be expected if the fire path consisted by continuous crown fire prone fuel complexes, as assumed in the model run.
- Some of the crown fire runs extent through several hours, burning through a gradient of fine fuel moisture, whereas in the model validation runs worst case

scenarios are assumed. This worse case scenario uses the lower fine fuel moisture content computed for the fire run.

It is believed that the test of the model using detailed fire environment and behavior information from the case studies in order to compute various fire spread rates during a fire run would produce better fit. A final fire spread rate (result of the integration of the various fire spread rates verified during the fire run) would reduce or eliminate the over-prediction trend verified in Figure 3.13 and Table A.7.

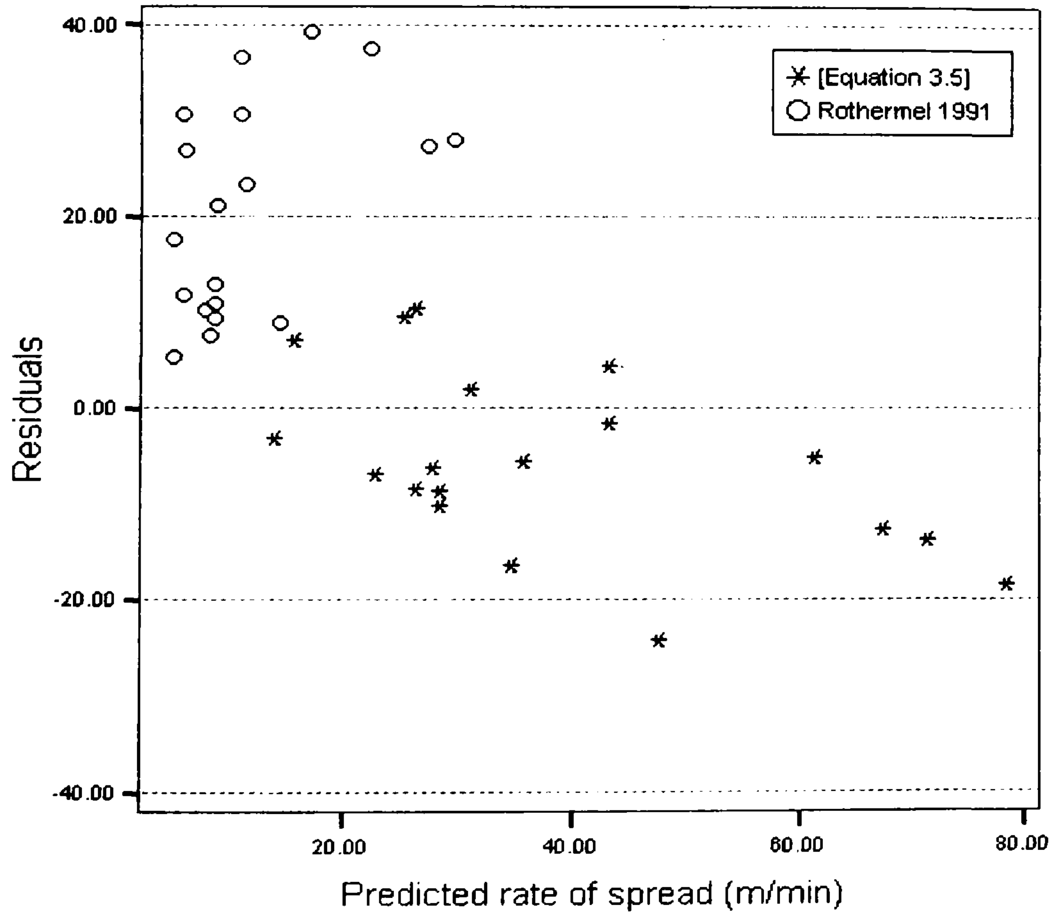


Figure 3.14. Plot of residuals versus predicted rate of spread of crown fires by Equation 3.5 model and Rothermel (1991a) crown fire model.

Considering the limiting effect of these two facts on the performance of the model on wildfire data, the results of the model can be considered very satisfactory.

Figures 3.13 and 3.14 also display the predictions of the Rothermel (1991a) crown fire spread model for the wildfires in Table A.7. The evaluation of this model against a wildfire crown fire rates of spread reinforces the conclusions from Section 1.4.2.4 that the Rothermel (1991a) model tends to greatly under-predict the spread rates of fast spreading crown fires. Results from figure 3.13 suggest a superior predictive power for the Equation 3.5 model relative to the Rothermel (1991a) model for the Table A.7 dataset.

Statistical validation

Statistical validation aims to quantitatively assess the performance of a model to predict real world situations. The tests performed here are the same as performed in Section 1.4.2.5. Table 3.7 indicates the results of the various tests. To the knowledge of the author, there are no defined acceptable levels of model deviance. Depending on the fire situation, namely rates of spread and values at risk, higher or lower model accuracy might be required. Under the wildfire data constraints previously discussed, the mean absolute error (MAE) value of 9.2 seems acceptable under the range of wildfire spread rates (10 to 60 m/min), and the 34 % mean absolute percent error (MA%E) seem acceptable for most of the fire situations faced by fire managers. The Rothermel crown fire model yielded a MAE of 20, and MA%E of 62 % when compared with the wildfire dataset of Table A.7. The modeling efficiency (EF) computed (Table 3.7) shows an improvement over the EF calculated for the Rothermel (1991a) crown fire spread model (Table 1.5) and an EF of – 0.14 computed for the comparison of the Rothermel model predictions with the wildfire dataset. As for all the results in Table 3.7, the significance of an EF of 0.68 is not easily measured, and is best used for comparison with other model performances. The linear regression parameters in Table 3.7 reflect the over prediction trend verified for the wildfire database.

The simultaneous F-test for slope = 1 and intercept = 0 rejects the null hypothesis $[H_0:(\beta_0, \beta_1) = (0,1)]$ at the 95 % probability level tested, since the calculated Q statistic (1087.3) exceeds the 277.5 value for $pS^2F(p,v,1-\alpha)$. Considering the uncertainty in the input conditions used to describe the wildfire runs and what should be an acceptable probability level for the phenomena under study, these results should be analyzed with caution.

Table 3.7. Validation parameters for the active crown fire spread model [Equation 3.5]

Deviance measures		EF	Linear regression		
MAE	MA%E		R^2	β_0 (lower / upper 95%)	β_1 (lower / upper 95%)
9.2	34	0.68	0.75	4.5 (-4.45 / 13.46)	0.74 (0.52 / 0.95)

A comprehensive evaluation of the active crown fire model (Equation [3.5]) should be based on more reliable data such as the experimental crown fire data used in Section 1.4.2.1. Only against such a dataset with those characteristics can a model be subject to a truthful and definitive evaluation.

3.5.2. Modeling passive crown fire spread rates

As described in Section 3.4.1, the passive crown fire dataset has a limited number of fires (n=14). The variability in fire phenomenology within this phase makes it extremely difficult to find trends in the effect of fire environment variables on fire spread. From theoretical reasoning on passive crown fire phenomena, such fires can be assumed to be the result of two distinct conditions function of the fuel complex structure:

- The requirements for crown fire initiation are meet, wind velocity is high and crown combustion occurs through the stand, but the low stand density, and consequently low canopy bulk density, limits the formation of a continuous flaming front through the vertical space of the fuel complex. Fires spreading under these conditions could attain fast spread rates although never achieving the criteria to be considered a active crown fire. As an example, a fire spreading at 35 m/min in a fuel complex with a characteristic canopy bulk density of 0.08 kg/m^3 would be classified as spreading as a passive crown fire.
- A fire spreading under low wind conditions in a stand characterized by a very small fuel strata gap and high canopy bulk density might partially consume the crown fuels, but never exceed a critical rate of spread for active fire spread. These fires would burn with moderate spread rates although attaining criteria for crown fire spread close to one.

This idea is supported by Figure 3.15 where passive crown fire spread rate is plotted against the criteria for active crown spread. Although the data is scarce, it can be noted that there exist two separate groups of data. One group (Group A) with criteria for active crowning close to one, and characterized by low spread rates, and a second group (Group B), showing a linear trend between spread rate and criteria for active crowning. Canopy bulk densities above 0.26 kg/m^3 characterize the first group, whereas the second group averages 0.11 kg/m^3.

In the U.S., the separation and analysis of crown fires by passive and active has not received much attention when considering crown fire behavior prediction (e.g. Rothermel 1991a, 1991b, NWCG 1993). Finney (1998) acknowledge this problem due to the non-existence of a model to predict passive crown fire spread in the U.S.. Conservatively, he approaches the problem of modeling passive crown fire spread as a surface fire. This approach might under-predict fire spread since passive crown fires exhibit a wide spectrum of fire behavior. Passive crown fires can be characterized by the torching of single trees to a fire spreading with an almost solid flame front occupying the canopy and sub-canopy space and very close to achieving the defined critical crown fire spread rate.

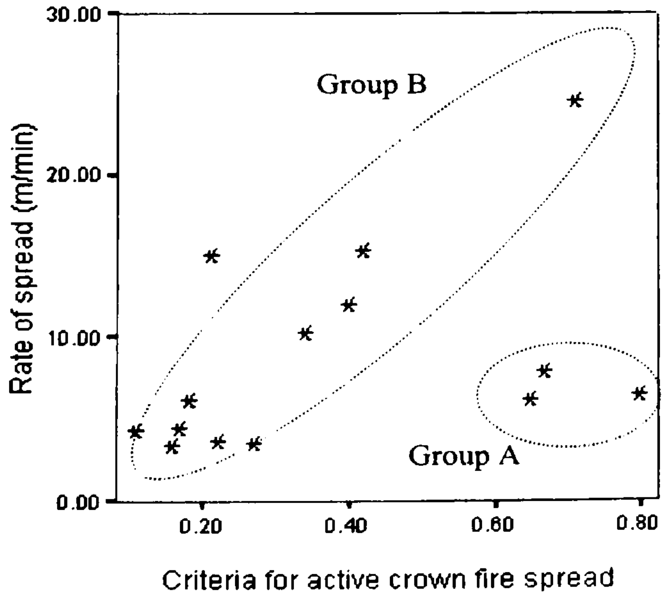


Figure 3.15. Scatterplot of passive crown fire rate of spread versus estimated criteria for active crowning.

Building an empirically based model to predict passive crown fire spread would not be viable with the dataset available, because of the variability in fire behavior characteristics of passive crown fires. Two approaches were considered to model passive crown fire spread in this study:

- Base passive crown fire spread prediction on the output of the active crown fire spread model (Equation [3.5]) with an adjusting term.
- Base passive crown fire spread prediction on the output of BEHAVE (Andrews 1986) system using NFFL fuel model 2, as this fuel model characterizes open fuel complexes, with low canopy bulk densities (Anderson 1982).

The modeling of passive crown fire spread based on the active crown fire spread model output is based on the assumption that a continuous gradient in spread rate exists between the passive and active crown fire phases. A passive crown fire burning under increasingly favorable conditions will cover that gradient and reach an active crown fire spreading phase. This idea is supported by the linear trend between passive crown fire spread rate and the criteria for active crowning (Figure 3.15). Based on these considerations, passive crown fire spread rate was modeled as:

$$CROS_P = CROS_A \cdot CAC \qquad [3.7]$$

where

$CROS_P$ is the passive crown fire rate of spread;

$CROS_A$ is the active crown fire rate of spread;

CAC is the criteria for active crowning.

In order to model passive crown fire spread as a function of predicted surface fire spread rate for NFFL fuel model 2, certain assumptions needed to be made concerning fuel moisture conditions in several types of fuel. Herbaceous fuel moisture was set to a minimum value of 50 %, and medium and large woody fuels were set to 12 and 13 percent. Variation of the moisture contents in these woody fuels has minimal effect on fire spread rate.

3.5.2.1. Modeling results

Figures 3.16.a and b present the scatterplot of predicted versus observed passive crown fire rate of spread using Equation [3.7] and BEHAVE output for NFFL fuel model 2 respectively. Both approaches yield coherent results, with the predicted fire spread rates following the 1:1 line. Regression analysis between predicted and observed rates of spread yield R^2 of 0.76 for both models.

The use of the passive crown fire model of Equation [3.7] over the BEHAVE output for NFFL fuel model 2 for predicting passive crown fire rates of spread is supported by several theoretical considerations:

- The relationship between passive crown fire spread rate and the BEHAVE output for fuel model 2 may be spurious, as there is no physical relationship between the spread rate of a fire in a surface fuelbed constituted mostly by herbaceous fuels and fire spread of a passive crown fire.
- The use of NFFL Fuel model 2 for predicting passive crown fire rate of spread could result in situations where the predicted passive crown fire spread rate could be higher than the predicted active crown fire spread rate.
- The use of the active crown fire spread rate model as a basis for predicting passive crown fire spread rate is more coherent in the transition area between the two phases.

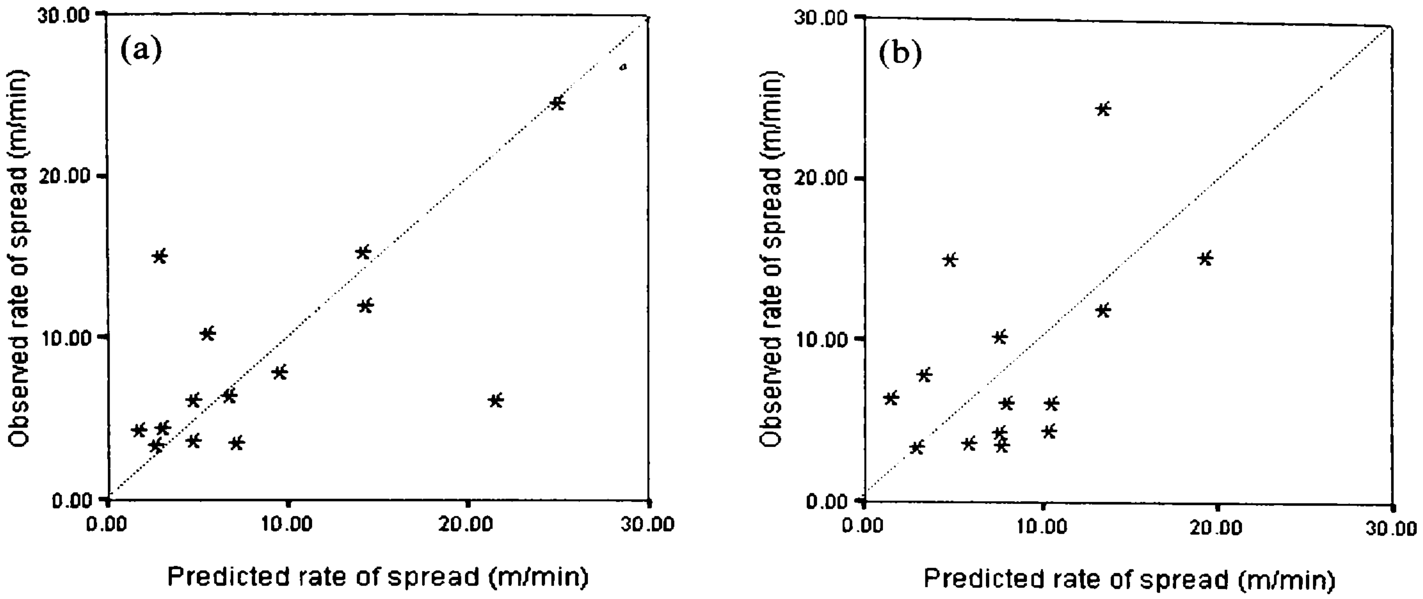


Figure 3.16. (a): Observed versus predicted passive crown fire spread rate by equation [3.7]; (b) Observed versus predicted fire spread rate by BEHAVE for fuel model NFFL 2. Dashed line is line of perfect agreement.

Based on these considerations, it was decided to accept Equation [3.7] for predicting the spread of passive crown fires. Although the scatter of figure 3.16.a seems acceptable under the data limitations, the author recognizes that this model gives just a rough approximation of passive crown fire spread rates. Given the limited fire behavior knowledge of passive crown fire spread, the reasoning behind the model is sound, and appears to be an improvement over predicting passive crown fire spread rates using direct output of a surface fire spread model. It should also be noted that this model should be applicable only to the passive crown fires burning stands with low canopy bulk densities, as a large percentage of the data in the passive crown fire dataset exhibit this condition.

3.5.2.2. *Model Behavior*

The form of the passive crown fire model of equation [3.7] makes it respond to changes in wind speed and fine fuel moisture content in the same way as the active crown fire model. The passive crown fire spread model reacts differently to changes in canopy bulk density when compared with active crown fire spread model. Figure 3.17 shows how the variation in canopy bulk density affects crown fire spread rate under different wind speeds (fine fuel moisture was set to 9 %). The abrupt change on slope in the 20 and 30 wind speed curves is due to the fact that the rate of fire spread reached the critical rate of spread for active crowning. After this change in slope the fire is spreading as an active crown fire. At low wind speeds, i.e. below 10 km/h, a fire might required higher canopy bulk densities to achieve an active crown fire phase.

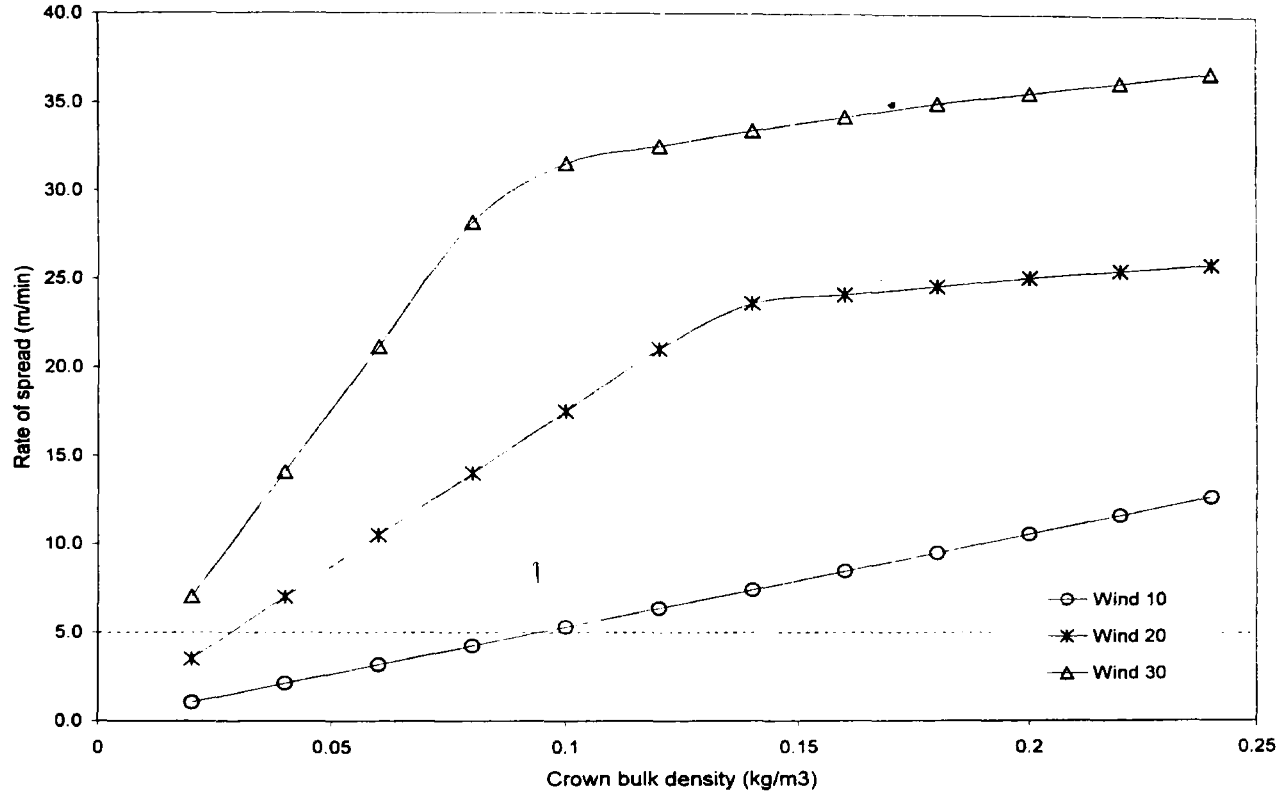


Figure 3.17. Rate of spread of a passive crown fire function of canopy bulk density as predicted by model of Equation [3.7].

It is difficult to evaluate this model using current wildfire data, as there are no descriptions of the crown fuel stratum characteristics in the wildfire case studies reviewed. The predictive capacity of the passive crown fire model is open to question, as it was built based on a limited dataset without a separate dataset to evaluate it. The reasoning behind the model might be considered valid, but the use of a critical mass flow rate for solid crown flame of 3 kg/m^2-min as estimated by Van Wagner (1977) might not fit in the wide variety of fuel arrangements found in forest stands.

3.6. CONCLUSIONS

Based on a relatively large and diverse crown fire spread dataset taken from high intensity experimental fires, an empirically based model was built to predict the spread rate of crown fires. The model was based on the fundamental fire spread equation incorporating the effect of wind, canopy bulk density and fine fuel moisture to predicted the spread of active crown fires. For fires defined as passive crown fires, an adjustment based on the criteria for active crown fire spread is applied for reducing the predicted active crown fire spread rate. This adjustment, based on Van Wagner (1977) theory for crown fire spread, fit the limited passive crown fire dataset reasonably well. Notice that this adjustment makes the prediction of passive crown fire spread very sensitive to errors in the estimation of canopy bulk density.

The model incorporates some of the main fire environment variables that theoretically influence crown fire spread. Other theoretically important variables identified as important controls on crown fire behavior, such as fuel strata gap, crown fuel weight, foliar moisture content and available fuel in the surface fuelbed, did not produce meaningful effects in the model due to the lack of variability in the data or incompleteness of the data set. The wind effect in the models is similar to the effect found in other experimental studies. The low fuel bulk densities encountered in forest canopies yield a relationship contrary to some theoretical reasoning, but is supported by results from laboratory experimental fires using very porous fuel beds.

The active crown fire model was evaluated against an independent dataset of wildfires burning in several distinct fuel complexes in North America. Model predictive performance was quite satisfactory. The model tended to over-predict the spread rates of the wildfires. This over-prediction can be explained by the use of a single low moisture content value to describe the fine fuel moisture content throughout a fire run period, and the fuel heterogeneity, namely deciduous and shrub patches, along the fire run. The passive crown fire adjustment was not tested against an independent dataset, since there were no data available to do so.

CHAPTER IV

ASSESSING CANOPY FUEL BULK DENSITIES FOR SOME WESTERN U.S. COMMON CONIFER FUEL COMPLEXES.

4.1. INTRODUCTION

The growing complexity of deterministic fire behavior models implemented in state-of-the-art fire management decision support systems requires descriptions of fuel complex characteristics that are as accurate as possible given the existing resource and knowledge constraints. In the Seventies and Eighties fuel complex characterization was limited in the U.S. to the surface fuelbeds due to the restricted applicability of fire behavior models, e.g. the BEHAVE system (Burgan and Rothermel 1984; Andrews 1986), to this fuel stratum. Several studies quantifying crown biomass at the individual tree basis were designed to predict logging slash quantity and structure for prescribed fire planing (e.g. Kill 1967; Wade 1969; Brown 1978). The development of fire behavior models designed to predict crown fire behavior (Albini 1985, 1996) indicated the need to describe this fuel stratum as accurately as possible, although model limitations could not justify detailed canopy fuels structure studies.

With the introduction by Finney (1998) of Van Wagner (1977) crown fire initiation and spread theories into the FARSITE fire growth simulator, information on canopy bulk density and height of crown base became required for fire management planning, although no method of quantifying these parameters were directly available to fire managers. Crown fuels structural properties are also required inputs for estimating important fire environment variables such as windspeed within a forest stand (Albini and Baughman 1979) and dead fuel moisture content (Rothermel et al. 1986). Maximum-spotting distance models from burning trees (Albini 1979) and running crown fires (Albini 1998) require the knowledge of several crown fuel structure properties.

As presented in chapter III, canopy bulk density is an important input variable for the Equation [3.5] and [3.7] crown fire spread models. Canopy bulk density has a strong effect on passive crown fire spread. It also determines the transition thresholds between passive and active crown fire spread.

Few studies have been designed to quantify canopy bulk density at the stand level. Alexander (1979) computed canopy bulk density for several lodgepole pine sapling and pole/sawtimber stands using stand inventory data and Brown (1978) equations. In Alexander (1979) estimated canopy bulk densities ranged from 0.336 to 0.72 kg/m^3 in the sapling stage stands, and from 0.064 to 0.224 kg/m^3 in the pole/sawtimber stage stands. Scott (1998) evaluate crown potential in four different ponderosa pine stands that had canopy bulk densities ranging from 0.045 to 0.082 kg/m^3. Apart from canopy bulk density quantification as part of pre-burn fuel sampling in experimental fires (Table A.4 in Appendix), no other published studies quantifying canopy bulk density in forest stands were found by the author.

4.2. OBJECTIVES

The objective of this study is to estimate canopy bulk density of some important fuel complexes that are subject to crowning. To achieve this objective the study will focus on linking crown fuel characteristics models published in the literature (e.g. Brown 1978; Stocks 1980) with stand inventory data taken from the Forest Inventory and Analysis (FIA) (Woudenberg and Farrenkopf 1998). This approach allows the quantification of the variability of canopy bulk density in forest stands and the development of statistical models created to predict canopy bulk density using commonly inventoried stand characteristics.

4.3. METHODS

4.3.1. Fuel complex selection

This study was designed to focus on forest fuel complexes that are subject to the occurrence of crown fires. The identification of the fuel complexes in this category was based on natural fire regime characteristics (Kilgore 1981) and published wildfire case studies (e.g. Anderson 1968; Rothermel 1983, NFPA 1992; 1993). The diversity of fuel complexes was reduced further to the available data in the FIA dataset, covering the following states: Arizona, Colorado, Idaho, Montana and New Mexico.

The fuel complexes selected to use in this study are indicated in Table 4.1.

Table 4.1. Fuel complexes selected for analysis and respective forest type

FUEL COMPLEX	FOREST TYPE
DOUGLAS-FIR	Douglas-fir
PONDEROSA PINE	Ponderosa pine
FIR-SPRUCE	White fir and grand fir Engelmann spruce Engelmann spruce – subalpine fir
HEMLOCK-SITKA SPRUCE	Western redcedar Mountain hemlock – subalpine fir Western hemlock
LARCH	Larch – Douglas-fir
LODGEPOLE PINE	Lodgepole pine

4.3.2. The Forest Inventory and Analysis data

The idea behind this study was to use a large forest stand-based database to assess the variability of canopy bulk density in forest stands, and develop equations to predict canopy bulk density. This was accomplished by using the FIA Westwide Forest Inventory database. The FIA plot data analyzed was a sample of the original FIA ground plots. Plot selection was restricted to forested coded areas of conifers. Data of each available state (referred above) was sorted by cover type and basal area, a systematic sample design was applied selecting each percentile of the population for a total of 100 plots by state.

FIA ground plots cover a 1-acre or larger sample area through various fixed and variable radius (prism) sample points. Various measurements and estimates are made for each sample tree. Of these species, tree diameter at breast height, tree height, crown ratio, crown class (crown position) and a tree expansion factor (TEF), were used in this study. TEF expressed the number of trees per acre that the sample tree represents and it is the inverse of the size of the plot within which the tree was sampled (Woudenberg and Farrenkopf 1998).

4.3.3. Selection of foliage load equations

The quantification of crown biomass is a valuable piece of information for several areas of study such as fire management, whole tree utilization, forest ecology, and nutrient cycling. Many authors have related crown biomass or foliage biomass with tree dendrometric characteristics through dimensional analysis. From the multitude of studies (e.g. Kittredge 1945; Weetman and Hartland 1964; Stiell 1966; Kiil 1967; Kiil 1968; Kiil 1971; Baskerville 1972; Brown 1978; Loomis and Roussopoulos 1978; Rencz and Auclair 1980; Stocks 1980; Mouer 1981; Snell and Anholt 1981; Agee 1983; Grigal and Kernik 1984; Johnson et al. 1990) quantifying crown load at the tree level from tree diameter at breast height and tree height for the species found in the forest types listed in Table 4.1, a criteria needed to be defined in order to select among the published equations. The approach used in equation selection restricted the number of studies considered, in order to avoid variability introduced by different sampling designs. A second criterion was to use equations that discriminate foliage weight, since some of the studies yield crown weight lumping together foliage and fine branch weight. The selected equations related with data and sources are in Tables A.8 and A.9, in the Appendix.

For some species found in the FIA plot data no published foliage equations were found. To calculate foliage weight of these trees, surrogate species were used. The decision as to which species should be used as a surrogate was based on tree crown architecture and structured similarities. Table 4.2 shows the correspondence of trees used.

Table 4.2. Correspondence between species with no foliage equations published and surrogate species.

Species	Surrogate species
White fir, *Abies concolor*	Grand fir
Corkbark fir, *Abies lasiocarpa var. arizonica*	
Blue spruce, *Picea pungens*	Engelmann spruce
Bristlecone pine, *Pinus aristata*	White bark pine
Twoneedle pinyon, *Pinus edulis*	
Limber pine, *Pinus flexilis*	
Southwestern white pine, *Pinus strobiformis*	Western white pine
Mountain hemlock, *Tsuga mertensiana*	Western hemlock
Western paper birch, *Betula papyrifera*	Aspen
Cottonwood and poplar, *Populus spp.*	
Quaking aspen, *Populus tremuloides*	

4.3.4. Procedure for calculating canopy bulk density at plot level

The estimation of canopy bulk density was made through the following procedure:

Canopy foliage load estimation procedure

Canopy foliage load was estimated through the following procedure:

$$CFL = \sum (FW_i * TEF_i), \qquad [4.1]$$

where CFL is canopy foliage load (kg/m^2) for the plot;

FW is foliage weight (kg) on per a tree basis computed from equations in Table A.8;

TEF is the tree expansion factor corrected to a per hectare basis.

Canopy bulk density estimation procedure

The average canopy bulk density expressed in kg/m^3, was estimated through:

$$CBD = \frac{CFW}{CL}, \qquad [4.2]$$

where, CL is the length of the canopy fuel stratum, estimated from:

$$CL = \frac{\sum (cl_i * TEF_i)}{\sum TEF_i}, \qquad [4.3]$$

where, cl_i is the crown length of the i sample tree in the plot

4.4. RESULTS

The objective of this chapter was not to do a intensive analysis of canopy bulk density, by discussing theoretical considerations of the dependency of canopy bulk density on site characteristics, stand structure, species crown architecture and physiological adaptations to competition. The sole purpose of this chapter is quantify the variability of canopy bulk density and develop a way to assess this stand characteristic.

An important consideration must be made before analyzing the results. It is expected that for forest stands with high densities and/or basal areas, the estimated canopy bulk density might be unrealistic, as the dimensional relationships for which the equations were build are dependent on age (Baskerville 1983), density and site quality (Long and Smith 1988). Table A.9 in Appendix gives the ranges of basal area and stand density of the original sample trees. It is in its lower range, i.e. below 0.10 kg/m^3, that canopy bulk density has a stronger effect on the predicted crown fire spread rates according to the models built in Section 3.5. From this stand point the limitation of the approach pursued in this study has low impact in the expected results, since for low density, low canopy bulk density stands, the foliage load models give acceptable predictions.

4.4.1. Canopy bulk density variability

One of the objectives of this study was to assess the variability of canopy bulk density within certain fuel complexes. From the fuel complexes listed in Table 4.1, the Fir – Spruce, Hemlock – Sitka Spruce and Larch fuel complexes were merged into a single fuel complex due to the limited number of plots in the database for each type. The new fuel complex was called Mixed Conifer.

Figure 4.1 displays the computed range of canopy bulk density for the four selected fuel complexes. Douglas-fir and ponderosa pine have very similar canopy bulk density distributions, with more than 50 % of their data below 0.15 kg/m^3. Higher bulk densities characterize lodgepole pine and mixed conifer, with a substantial number of plots with canopy bulk densities greater than 0.5 kg/m^3. It is very difficult to determine at what level of bulk densities the estimates began to over-predict this quantity. Very dense stands are expected to have lower live foliage quantities than predicted, but should have larger amounts of aerial dead fuels, which can counterbalance the model over-prediction for live foliage component. As referred to previously, there are few studies to which the estimated distributions could be compared. The interval generated for lodgepole pine agrees with the range estimated by Alexander (1979) for this species in the Colorado Front Range.

The boxplot and error bars in figure 4.2.a and b give further insight on the distribution of the canopy bulk density by fuel complex. For Douglas-fir and Ponderosa pine, the interval between the 0.25 and 0.75 quartiles is in a narrow band under 0.25 kg/m^3. Canopy bulk density in the Lodgepole pine and Mixed Conifer fuel complexes show a wider range between those two quartiles. Mixed conifer fuel complexes have the highest average canopy bulk density, followed by Lodgepole pine, Douglas-fir and Ponderosa pine respectively.

The differences in canopy bulk density between fuel complexes showed in this analysis have strong implications in terms of crown fire behavior, as it will condition the easy by which fire will spread as an active crown fire under certain fire weather conditions. The variability in canopy bulk density encountered within each fuel type reinforces the need of develop methods by which to estimate this crown stratum property.

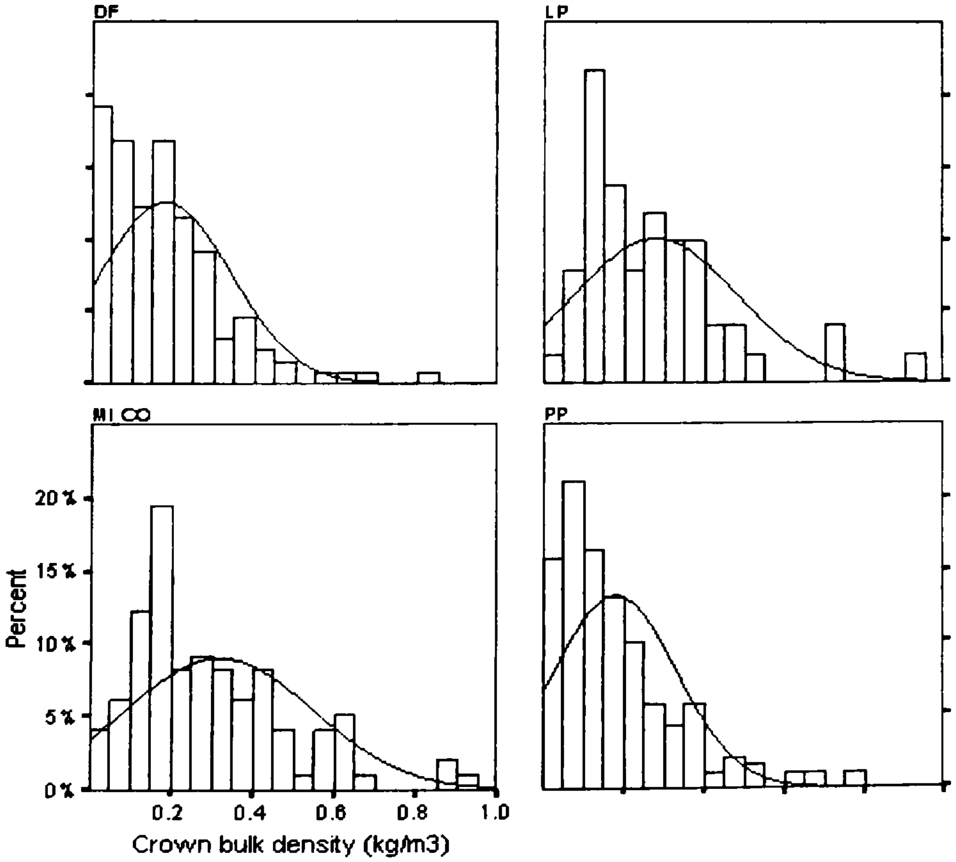


Figure 4.1. Canopy bulk density distribution for Douglas-fir (DF), n = 132; Lodgepole pine (LP), n = 52; Mixed conifer (MICO), n = 101; and Ponderosa pine (PP), n = 190.

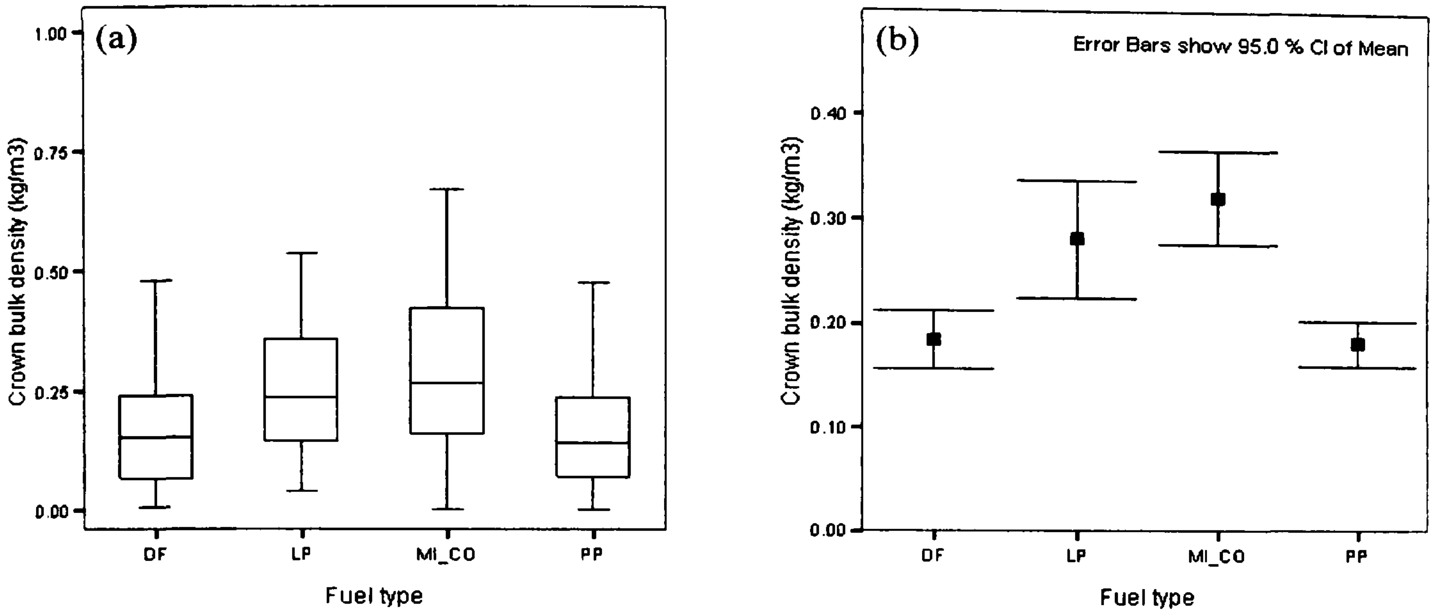


Figure 4.2. Boxplot and error bars for canopy bulk density of Douglas-fir (DF), Lodgepole pine (LP), Mixed conifer (MICO), and Ponderosa pine (PP).

4.4.2. Canopy bulk density modeling

The relationships between canopy bulk density and independent variables found in the dataset that are expected to influence crown fuel stratum structural characteristics were evaluated through the use of correlation coefficients and scatterplots. This was done in order to gather information relative to the power of the linear relation and the type of relationship existent between the variables. Table 4.3 through 4.6 gives the correlation matrix for the various fuel complexes considered in this study.

Table 4.3. Correlation matrix for Douglas-fir fuel complex (n = 132)

	CBD	TPH	CFL	BA	ST_H	SI	AGE
CBD	1.000	0.870**	0.833**	0.649**	-0.317**	-0.082	0.041
TPH	0.870**	1.000	0.641**	0.502**	-0.410**	-0.060	-0.047
CFL	0.833**	0.641**	1.000	0.913**	-0.017	0.075	0.156
BA	0.649**	0.502**	0.913**	1.000	0.150	0.238**	0.265**
ST_H	-0.317**	-0.410**	-0.017	0.150	1.000	0.560**	0.184*
SI	-0.082	-0.060	0.075	0.238**	0.560**	1.000	-0.044
AGE	0.041	-0.047	0.156	0.265**	0.184*	-0.044	1.000

SI – Site Index; **TPH** – Trees per hectare; **ST_H** – Mean stand height; **CFL** – Crown foliage load; **BA** – Basal area; **CBD** – Canopy bulk density;
* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level.

Table 4.4. Correlation matrix for Ponderosa pine fuel complex (n = 190)

	CBD	TPH	CFL	BA	ST_H	AGE	SI
CBD	1.000	0.796**	0.792**	0.724**	-0.431**	-0.088	-0.086
TPH	0.796**	1.000	0.594**	0.649**	-0.362**	-0.104	-0.049
CFL	0.792**	0.594**	1.000	0.930**	-0.075	-0.117	0.138
BA	0.724**	0.649**	0.930**	1.000	-0.019	-0.043	0.227**
ST_H	-0.431**	-0.362**	-0.075	-0.019	1.000	0.049	0.285**
AGE	-0.088	-0.104	-0.117	-0.043	0.049	1.000	-0.241**
SI	-0.086	-0.049	0.138	0.227**	0.285**	-0.241**	1.000

Table 4.5. Correlation matrix for Mixed conifers fuel complex (n = 101)

	CBD	TPH	CFL	BA	ST_H	SI	AGE
CBD	1.000	0.858**	0.804**	0.508**	-0.307**	-0.164	0.102
TPH	0.858**	1.000	0.648**	0.394**	-0.342**	-0.149	-0.016
CFL	0.804**	0.648**	1.000	0.840**	0.027	0.015	0.239*
BA	0.508**	0.394**	0.840**	1.000	0.350**	0.189	0.290**
ST_H	-0.307**	-0.342**	0.027	0.350**	1.000	0.589**	0.161
SI	-0.164	-0.149	0.015	0.189	0.589**	1.000	-0.096
AGE	0.102	-0.016	0.239*	0.290**	0.161	-0.096	1.000

Table 4.6. Correlation matrix for Lodgepole pine fuel complex (n = 52)

	CBD	CFL	TPH	BA	AGE	ST_H	SI
CBD	1.000	0.817**	0.806**	0.763**	0.098	-0.067	0.033
CFL	0.817**	1.000	0.688**	0.963	0.090	0.336*	0.292*
TPH	0.806**	0.688**	1.000	0.628**	-0.010	-0.143	0.119
BA	0.763**	0.963	0.628**	1.000	0.151	0.450**	0.356**
AGE	0.098	0.090	-0.010	0.151	1.000	0.182	-0.356**
ST_H	-0.067	0.336*	-0.143	0.450**	0.182	1.000	0.432**
SI	0.033	0.292*	0.119	0.356**	-0.356**	0.432**	1.000

From the correlation matrices for the various fuel complexes it is noted that canopy bulk density is significantly correlated (at the 0.01 level) with stand density (trees per hectare) and basal area. This would be expected, since these two variables are measures of stand occupancy. These two variables are also auto-correlated, which will pose some limitations in the regression analysis carried out on the dataset. Stand mean height is negatively significantly correlated with canopy bulk density for Douglas-fir, ponderosa pine and mixed conifer fuel complexes. Figure 4.3 and 4.4 illustrates the linear relationship that exists between canopy bulk density - stand density and canopy bulk density – basal area for the various fuel types under analysis. The fan shape of the scatterplots reveal heteroscedasticity.

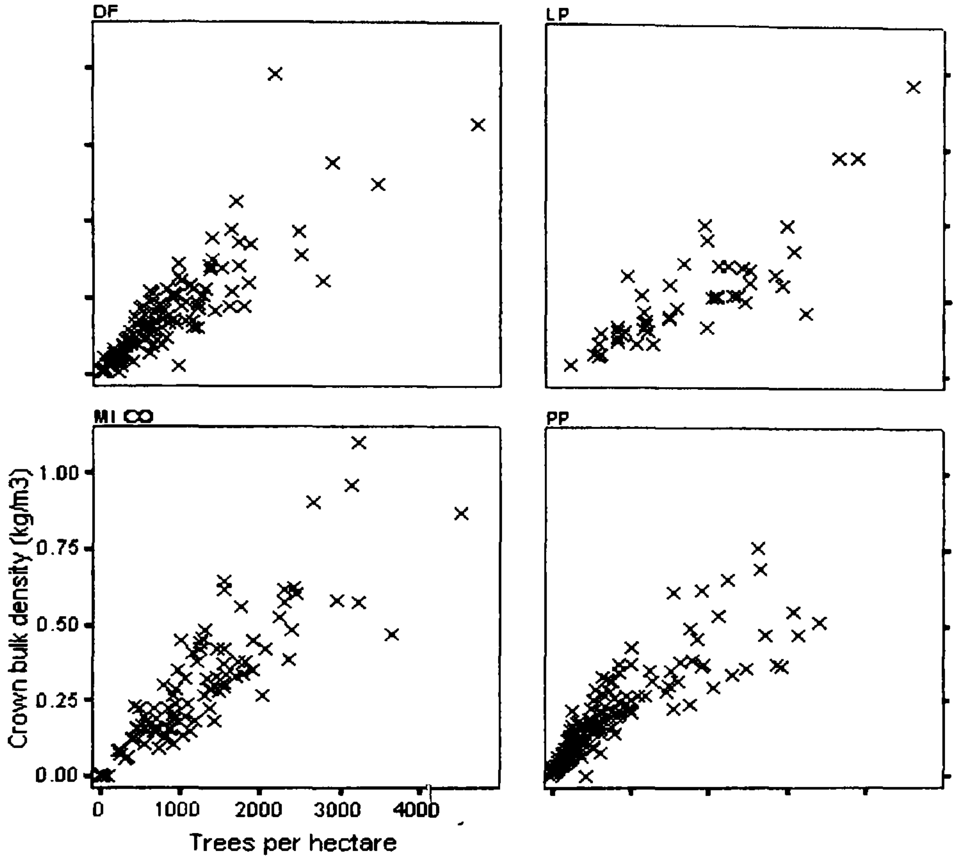


Figure 4.3. Scatterplot of canopy bulk density with stand density for Douglas-fir (DF), Lodgepole pine (LP), Mixed conifer (MICO) and Ponderosa pine (PP).

Figure 4.3 and 4.4 exhibit the existence of linear trends between canopy bulk density and variables trees per hectare and basal area. From these results, a linear regression analysis approach was used to model canopy bulk density as a function of stand density and basal area. Although stand mean height was significantly correlated with canopy bulk density for some of the fuel complexes, it was not used in the model building since it would increase the data requirements for predicting canopy bulk density. Table 4.7 gives the equations developed for the four fuel complexes under analysis. The four equations yield coefficients of determination between 0.88 and 0.92, revealing an acceptable fit of the model to the data. Standard errors of estimate ranged from 0.069 for Douglas-fir to 0.110 to mixed conifer. The minor effect that basal area has in the models, verified by the basal area coefficients, might be the consequence of the non-independence of the two independent variables.

The inclusion of stand mean height as an independent variable did not significantly improve the predictive power of the equations for Douglas-fir, ponderosa pine and mixed conifer fuel complexes. The inclusion of this parameter in the models would have increase the difficulty in applying the models due to the need for estimating this difficult to measure variable. For these reasons, the variable stand mean height was not included in the equations.

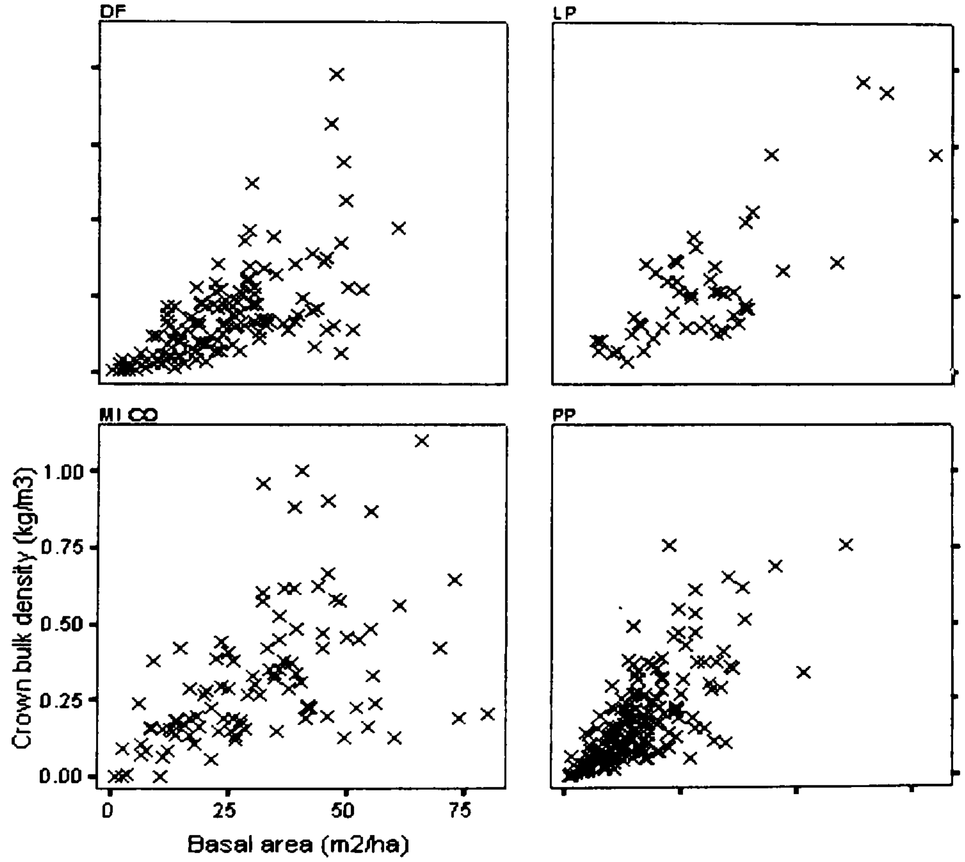


Figure 4.4. Scatterplot of canopy bulk density with basal area for Douglas-fir (DF), Lodgepole pine (LP), Mixed conifer (MICO) and Ponderosa pine (PP).

The regression models were forced through the origin because the computed intercepts would have given unrealistic canopy bulk density estimates for low density/low basal area stands. This is the region where the crown fire spread model outputs are more sensitive to changes in canopy bulk density. Tables 4.8 through 4.11 give canopy bulk densities as a function of stand density and basal area for the four fuel types considered. The results in these tables emphasize the models structure, with a strong dependence of canopy bulk density on tree density, and a minor effect of basal area. It is for low bulk density situations that the models estimate higher relative differences between them. For stands characterized by high densities and basal areas all the models, except for ponderosa pine, yield similar values. The equation developed for lodgepole pine yields lower canopy bulk densities, given similar stand characteristics, when compared to the others fuel complexes. This does not mean that it is expected to find the lower canopy bulk density in this fuel complex, as can be verified in Figure 4.1 and 4.2.

Table 4.7. Equations to predict canopy bulk density (kg/m^3)

Fuel complex	Equation	n	R^2	SEE
Douglas-fir	$CBD = 0.000157TPH + 0.00277BA$	132	0.92	0.069
Ponderosa pine	$CBD = 0.0000785TPH + 0.00734BA$	190	0.88	0.083
Mixed conifer	$CBD = 0.000164TPH + 0.00283BA$	101	0.92	0.110
Lodgepole pine	$CBD = 0.000072TPH + 0.00493BA$	52	0.92	0.102

CBD in kg/m^3; TPH in trees per hectare; BA in m^2/ha.

Table 4.8. Canopy bulk density (kg/m^3) for Douglas-fir fuel complex

Stand density	Basal area (m^2/ha)								
(Trees/ha)	5	10	15	20	25	30	35	40	45
250	0.05	0.07	0.08	0.09	0.11	0.12	0.14	0.15	0.16
500	0.09	0.11	0.12	0.13	0.15	0.16	0.18	0.19	0.20
750	0.13	0.15	0.16	0.17	0.19	0.20	0.21	0.23	0.24
1000	0.17	0.18	0.20	0.21	0.23	0.24	0.25	0.27	0.28
1250	0.21	0.22	0.24	0.25	0.27	0.28	0.29	0.31	0.32
1500	0.25	0.26	0.28	0.29	0.30	0.32	0.33	0.35	0.36
1750	0.29	0.30	0.32	0.33	0.34	0.36	0.37	0.39	0.40
2000	0.33	0.34	0.36	0.37	0.38	0.40	0.41	0.42	0.44
2250	0.37	0.38	0.39	0.41	0.42	0.44	0.45	0.46	0.48
2500	0.41	0.42	0.43	0.45	0.46	0.48	0.49	0.50	0.52
2750	0.45	0.46	0.47	0.49	0.50	0.51	0.53	0.54	0.56
3000	0.48	0.50	0.51	0.53	0.54	0.55	0.57	0.58	0.60
3250	0.52	0.54	0.55	0.57	0.58	0.59	0.61	0.62	0.63
3500	0.56	0.58	0.59	0.60	0.62	0.63	0.65	0.66	0.67

Table 4.9. Canopy bulk density (kg/m^3) for Ponderosa pine fuel complex

Stand density				Basal area (m^2/ha)					
(Trees/ha)	5	10	15	20	25	30	35	40	45
250	0.06	0.09	0.13	0.17	0.20	0.24	0.28	0.31	0.35
500	0.08	0.11	0.15	0.19	0.22	0.26	0.30	0.33	0.37
750	0.10	0.13	0.17	0.21	0.24	0.28	0.32	0.35	0.39
1000	0.12	0.15	0.19	0.23	0.26	0.30	0.34	0.37	0.41
1250	0.13	0.17	0.21	0.24	0.28	0.32	0.36	0.39	0.43
1500	0.15	0.19	0.23	0.26	0.30	0.34	0.37	0.41	0.45
1750	0.17	0.21	0.25	0.28	0.32	0.36	0.39	0.43	0.47
2000	0.19	0.23	0.27	0.30	0.34	0.38	0.41	0.45	0.49
2250	0.21	0.25	0.29	0.32	0.36	0.40	0.43	0.47	0.51
2500	0.23	0.27	0.31	0.34	0.38	0.42	0.45	0.49	0.53
2750	0.25	0.29	0.33	0.36	0.40	0.44	0.47	0.51	0.55
3000	0.27	0.31	0.35	0.38	0.42	0.46	0.49	0.53	0.57
3250	0.29	0.33	0.37	0.40	0.44	0.48	0.51	0.55	0.59
3500	0.31	0.35	0.38	0.42	0.46	0.49	0.53	0.57	0.61

Table 4.10. Canopy bulk density (kg/m^3) for mixed conifer fuel complex

Stand density				Basal area (m^2/ha)					
(Trees/ha)	5	10	15	20	25	30	35	40	45
250	0.06	0.07	0.08	0.10	0.11	0.13	0.14	0.15	0.17
500	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.21
750	0.14	0.15	0.17	0.18	0.19	0.21	0.22	0.24	0.25
1000	0.18	0.19	0.21	0.22	0.23	0.25	0.26	0.28	0.29
1250	0.22	0.23	0.25	0.26	0.28	0.29	0.30	0.32	0.33
1500	0.26	0.27	0.29	0.30	0.32	0.33	0.35	0.36	0.37
1750	0.30	0.32	0.33	0.34	0.36	0.37	0.39	0.40	0.41
2000	0.34	0.36	0.37	0.38	0.40	0.41	0.43	0.44	0.46
2250	0.38	0.40	0.41	0.43	0.44	0.45	0.47	0.48	0.50
2500	0.42	0.44	0.45	0.47	0.48	0.49	0.51	0.52	0.54
2750	0.47	0.48	0.49	0.51	0.52	0.54	0.55	0.56	0.58
3000	0.51	0.52	0.53	0.55	0.56	0.58	0.59	0.61	0.62
3250	0.55	0.56	0.58	0.59	0.60	0.62	0.63	0.65	0.66
3500	0.59	0.60	0.62	0.63	0.64	0.66	0.67	0.69	0.70

Table 4.11. Canopy bulk density (kg/m^3) for Lodgepole pine fuel complex

Stand density (Trees/ha)	Basal area (m^2/ha) 5	10	15	20	25	30	35	40	45
250	0.04	0.07	0.09	0.12	0.14	0.17	0.19	0.22	0.24
500	0.06	0.09	0.11	0.13	0.16	0.18	0.21	0.23	0.26
750	0.08	0.10	0.13	0.15	0.18	0.20	0.23	0.25	0.28
1000	0.10	0.12	0.15	0.17	0.20	0.22	0.24	0.27	0.29
1250	0.11	0.14	0.16	0.19	0.21	0.24	0.26	0.29	0.31
1500	0.13	0.16	0.18	0.21	0.23	0.26	0.28	0.31	0.33
1750	0.15	0.18	0.20	0.22	0.25	0.27	0.30	0.32	0.35
2000	0.17	0.19	0.22	0.24	0.27	0.29	0.32	0.34	0.37
2250	0.19	0.21	0.24	0.26	0.29	0.31	0.33	0.36	0.38
2500	0.20	0.23	0.25	0.28	0.30	0.33	0.35	0.38	0.40
2750	0.22	0.25	0.27	0.30	0.32	0.35	0.37	0.40	0.42
3000	0.24	0.27	0.29	0.31	0.34	0.36	0.39	0.41	0.44
3250	0.26	0.28	0.31	0.33	0.36	0.38	0.41	0.43	0.46
3500	0.28	0.30	0.33	0.35	0.38	0.40	0.42	0.45	0.47

The models and the tables constructed in this section are meant to help predict canopy bulk density when information relative to stand structure, namely diameter distribution and crown characteristics, does not exist. These models would allow the estimation of canopy bulk density from information of dominant species, stand density and basal area.

4.5. CONCLUSIONS

The present study linked an extensive stand database consisting in 476 plots distributed over the states of Montana, Idaho, Colorado, Arizona and New Mexico, with several regionally developed foliage weight equations. The use of a limited set of foliage equations has the advantage of limiting errors caused by differences in fuel sampling techniques. Stocks (1980) and Grigal and Kernik (1984) showed that foliage equations based on dimensional relationships develop in different studies produced different results. The foliage equations were applied without regard to the effect of stocking, age and site quality within the validity of the foliage equation. Nevertheless, it is believed that the present study satisfactorily describes the range of canopy bulk densities encountered in Douglas-fir, ponderosa pine, lodgepole pine and mixed conifer fuel complexes identified as in this study.

At the present state of knowledge the more accurate way to compute canopy bulk density for a stand is to apply foliage biomass equations to a determined stand structure (e.g. Alexander 1979, Agee 1996, Scott 1998). The canopy bulk density prediction equations developed in this study provide a very reasonable approximation of canopy bulk density in a stand. Since in fire management situations there is little or no information describing stand structure, the equations developed can help overcome this information gap and allow the use of crown fire models such as the ones developed in this study or others (e.g. Finney 1998).

The canopy bulk density models presented here show different trends for the various fuel complexes analyzed. The relatively high sensitivity of the canopy bulk density models in low density/low basal area stands reinforces the need of accurate stand information. Under these conditions, the "trash in – trash out" principle is magnified, compromising the expected (un)certainty of crown fire spread models outputs.

No evaluation of the developed canopy bulk density models was pursued. The relatively high standard errors of estimate produced by the models (Table 4.7) are indicative of the natural variability of the data. The variability one might expect to encounter on the lower range of canopy bulk density is unknown. It would be expected that an evaluation procedure based on an independent dataset drawn from the original FIA data could be used to quantify the performance of the models under the expected range of canopy bulk densities.

CHAPTER V

MANAGEMENT IMPLICATIONS AND CONCLUDING REMARKS

Management implications

The models built in Chapter II, III and IV were designed to support decision making relatively to crown fire problems in various fire management activities. Fire managers in crown fire prone environments need information relative to the crown fire potential of a given stand for evaluating various activities such as high intensity prescribed fire planning for ecosystem health purposes, effectiveness of fuel treatments aimed at reducing crown fire hazard, or site specific wildfire behavior prediction. As possible uses of the two fire behavior models developed, a fire manager in a wilderness area might use such models to forecast crown fire behavior in prescribed natural fires and assess the possibility that a given fire will cross wilderness boundaries and damage private property. The models will allow also a fire manager to assess the impact of various silvicultural treatments, such as thinning and pruning, on crown fire potential. The models will allow quantitative answers to questions relative to (i) the effect of the reduction in canopy cover, and consequently reduction on canopy bulk density, on the potential of the occurrence of active crown fires; (ii) the effect of leaving thinning or pruning residues within the stand on crown fire initiation; (iii) the effect of increasing vertical stratification through pruning within the stand on crown fire initiation potential.

Several studies evaluating the effect of thinning and pruning on fire behavior merely considered the effect of surface fuel modification on fire behavior (Alexander and Yancik 1977; Kalabokidis and Omi 1998). Their conclusions did not address the effect of the silvicultural treatment on crown fire potential. Scott (1998) analyzed the effect of silvicultural treatments on crown fire potential based on the link of BEHAVE outputs and Van Wagner (1977) crown fire initiation and spread theory. The main limitation of his approach was that the models used for crown fire initiation and spread are based in scant fire data and were never systematically evaluated. The under-prediction trend for the Rothermel (1991a) crown fire spread model, verified in the present study, might explain why Scott (1998) results show extreme difficulty in attaining fires spreading as active crown fires. The fact that the crown fire initiation model used by Scott is based on only one fire, and requires the knowledge of the output of other models, namely fireline intensity (estimated from predicted rate of spread and the *unknown* available fuel for flaming combustion), raises questions relative to the output results. The two crown fire behavior models in the present study do not depend on uncertain outputs from other models and reduce the uncertainty in the outputs.

The crown fire initiation and spread models developed in this study constitute a system to predict crown fire behavior in fuel complexes that sustain such phenomena. Figure 5.1 illustrate how the information flows between the models built in chapter II and III. The process can be summarized as follows:

i. Compute the probability of crown fire initiation from [Equation 2.5]. Required inputs are wind speed, fuel strata gap, estimated surface fuel consumption and estimated fine dead fuel moisture content;

ii. If the probability is < 0.5, the fire should spread as a surface fire, and (i) should be repeated after changes in fire environment characteristics;

iii. If probability is > 0.5, the fire should spread as a crown fire;

iv. Compute crown fire spread from [Equation 3.5]. Required inputs are wind speed, canopy bulk density, and estimated fine dead fuel moisture content;

v. Compute criteria for active crowning

vi. If the criteria for active crowning is > 1, fire is spreading as an active crown fire and fire spread rate is the one computed in (iv);

vii. If the criteria for active crowning is < 1, fire is spreading as a passive crown fire, and the fire spread rate should be adjusted by [Equation 3.7].

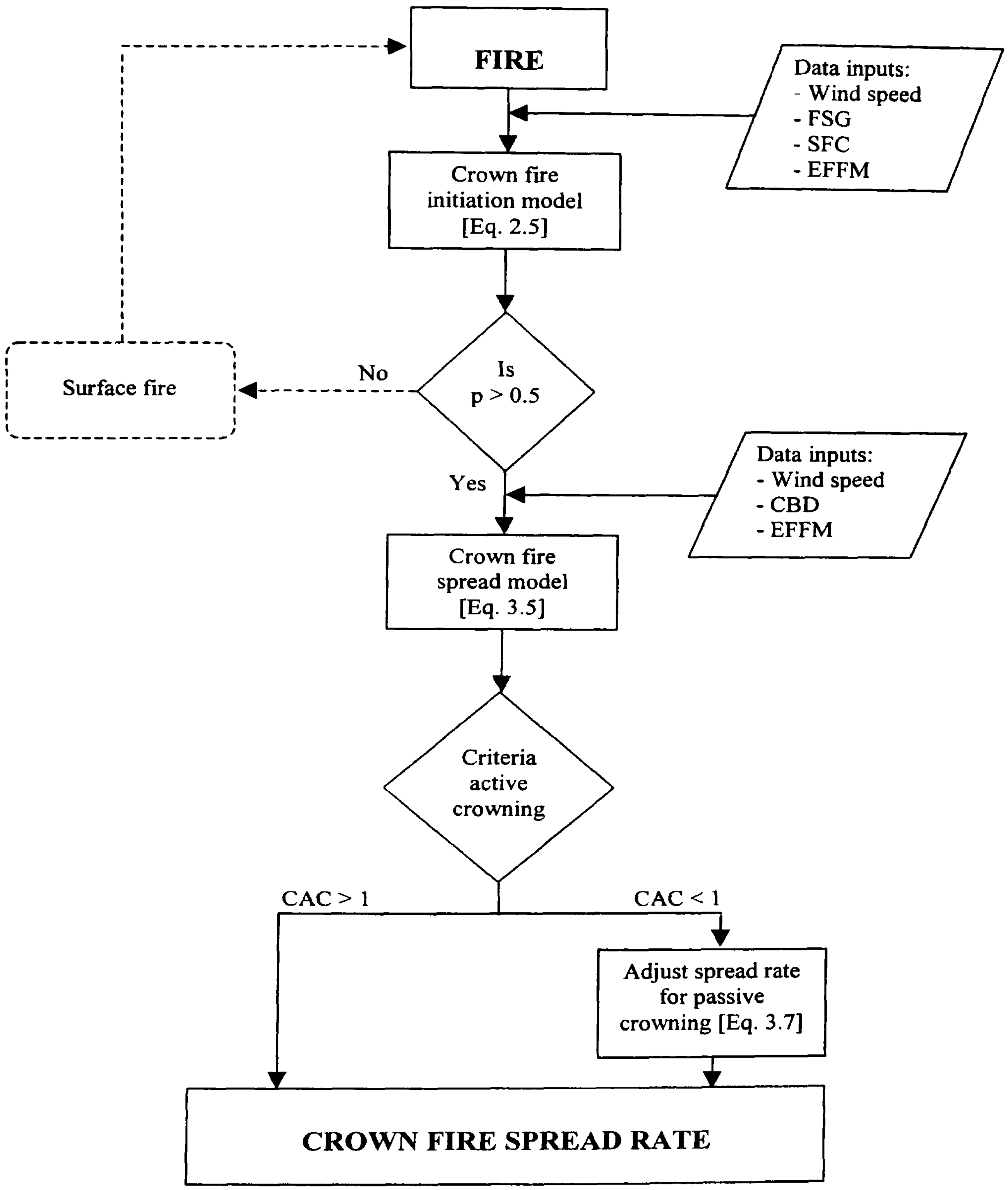


Figure 5.1: Diagram of information flow for the prediction of crown fire behavior.

The fact that the models developed in this study are based on data originating mainly from Canada may raise questions relatively to their applicability in the U.S.. The modeling approach followed in which the fuel complex was described through physical quantities, gives confidence that the model can be applied to fuel types characterized by a large spectrum of fuel complex structures regardless of geographical location. The variety of fuel complex structures used Section 2.4.1 and 3.4.1) and the results from the model evaluation support such a claim.

Concluding remarks

Within this study a set of models were developed to allow a user to predict the onset and spread of a crown fire. The empirical based modeling approach used in the development of the models makes the models a refection of the dataset. Limitations in the datasets led to inconclusive results relative to the effect of certain fire environment variables on crown fire behavior. In the crown initiation model the effect of foliar moisture content was not incorporated in the model. Surface fuel availability and vertical stratification of the fuel complex were not found to have a significant effect on crown fire spread rate. Nevertheless, the simplification carried out to build the crown fire behavior models in this study seemed to have not limited the coherence and applicability of the models.

One of the initial thought approaches to modeling crown fire spread rates was to use the current experimental crown fire database and relate these crown fire spread rates with predicted spread rates for surface fires as used by Rothermel (1991a) and previously discussed in Chapter I. The main attraction of this approach would be the ease of applicability of such a model, since as a user would just require knowledge of the same inputs as needed for the surface fire behavior prediction in order to forecast crown fire spread rates.

Nevertheless this approach offer some problems relative to the definition of fuel complex on which to base the modeling. Prior to modeling it would be necessary to define how to group the fire behavior data, i.e., group the fire behavior data by the fuel types of Table 3.2, or by physical characteristics of the fuel complex. The former approach would yield two problems: (i) the use of the models built in this way would be restricted to the fuel complexes used in the model building; (ii) the partitioning of the already limited crown fire spread data into three categories would further restrict the predictive power of the models.

The second approach would require the definition of a certain number of fuel complex structures characterized by certain distinct crown fuel structural characteristics, namely canopy bulk density and vertical stratification of the fuel complex. This approach would face the problem of what subjective criteria to be used in the partition of the data, as there is no clear physical separation of fuel complex characteristics between the fuel types in Table 3.2. The division of the crown fire behavior data into several groups would create the same problem as already discussed in the previous paragraph.

Apart from the problems above, this approach would also have a conceptual validity problem. Crown fire spread rates from empirical relations derived in experimental laboratory fires, are very sensitive to wind and dead fuel moisture changes as discussed in Section 1.4.1.

Given these considerations, the approach of modeling crown fire spread based on the correlation of experimental crown fire spread data and predicted surface fire spread rates was not followed. Nevertheless, for those who believe that such approach is appropriate and more desirable than the one followed in this study, the data in Table A.4, A.5 and A.6 is given in easily usable format and ready for such pursuit.

The crown fire initiation and spread models developed in this study do not incorporate the effect of slope. The effect of slope in fire spread rate has been difficult to quantify. Within physically based models the slope effect has been accounted for through changes in the radiation angle (e.g. Pagni and Peterson 1973). In operational models, slope is accounted for through a slope function, based on laboratory experiments (Rothermel 1972) or field observations (McArthur 1967; Noble et al. 1980). Van Wagner (1977) compared several empirically derived slope functions and established an average function that is used in the Canadian FBP (Fire Danger Group 1992). These functions raise some questions relatively to their validity. The laboratory experimental setups used were characterized by small fuelbeds, normally around 1 meter long, and the experimental fire may not have reached steady state behavior. Functions based on field observations might not be independent of wind speed and wind changes in slopes.

As for the crown fire initiation and spread models built in this study, a possible approximation for slope usage would be the calculation of a wind equivalency based on the slope as approached by Rothermel (1972) and Fire Danger Group (1992). The slope function to use is open to personal interpretation by the user.

The increase in the understanding of fire phenomenology through time has led to an increase in the discrimination between fire environment inputs. The use of the crown initiation and spread models will require the knowledge of fuel complex characteristics that might not be available. The crown fire spread models in this study require an estimate of the bulk density of the crown fuel stratum. How accurate and easy to use the canopy bulk density models build in Chapter IV is not known. Their use will require a knowledge of stand characteristics, namely stand density and basal area, that might not be available in certain areas. The crown fire initiation model requires an estimate of the fuel complex vertical continuity for which a visual assessment is required. The use of the crown fire initiation and spread models will require estimates of variables that were not necessary until now, thus increasing the complexity of the fire behavior input information collection process.

The fire behavior models built in this study are simplifications of the fire phenomena they pretend to describe. The objective of the model construction was to build models that could be used operationally to support decision making in fire management related issues. They do not pretended to explain cause-effect relationships between fire environment and behavior variables or enlighten our understanding of some non-comprehended fire behavior phenomena. In crown fire initiation modeling more physically based approaches, as done by Alexander (1998), are inherently more powerful, although the applicability of his reasoning is hampered by the use of fire behavior variables that are difficult to estimate and of questionable adequacy.

Until now, physically based fire behavior research has not produced crown fire initiation and spread models that could be applied to field situations. Apart from their large computational time requirements, physically based crown fire behavior models have not been subject to testing, and so their performance has never been evaluated. Normally the acceptance of a physical model has been based mainly on the credibility of the author. It is not known when a physical based model will be available to explain the processes modeled in this study. The applicability of physically based models to predict crown fire initiation and spread might not be a sole function of the increase in computational power of computers, but mainly in the capability of modelers to address the unknowns in fire phenomena with more realistic assumptions.

BIBLIOGRAPHIC REFERENCES

Agee, J.K. 1983. Fuel weights of understory-grown conifers in southern Oregon. Can. J. For. Res. 13:648-656.

Agee, J.K. 1996. The influence of forest structure on fire behavior. 17th Annual forest vegetation management conference. Redding, CA, January 16-18, 1996.

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

Albini, F.A. 1979. Spot fire distance from burning trees - a predictive model. USDA For. Serv. Gen. Tec. Rep. INT-56, Intermountain For. and Range Exp. Stn., Ogden Utah, 31p.

Albini, F.A. 1980. Thermochemical properties of flame gases from fine wildland fuels. Intermoumtain Forest and Range Experimental station, USDA For. Ser. Res. Pap. INT-243 Odgen,UT. 42 p.

Albini, F.A. 1981. A model for wind-blown flame from a line fire. Combustion and Flame: 155-174.

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

Albini, F.A. 1985b. Wildland fire spread by radiation – a model including fuel cooling by natural convection. Combust. Sci. and Tech. 45:101-113.

Albini, F.A. 1993. Dynamics and modeling of vegetation fires: Observations. Pages 39-52 In Crutzen, P.J., Goldammer, J.G. (eds.) Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires. John Wiliey & Sons, Chichester, England.

Albini, F.A. 1996. Iterative solution of the radiation transport equations governing spread of fire in wildland fuel. Fizika Goreniya I Zvryva 32(5):71-82.

Albini, F.A. 1998. Maximum spotting distance from an active crown fire. In the Proceedings of the National Interagency Fire Behavior Workshop. May 1999, Phoenix. 22 p.

Albini, F.A., Baughman, R.G. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA For. Serv. Res. Pap. INT-221, Intermountain For. and Range Exp. Stn., Ogden Utah, 12p.

Albini, F.A., Reinhardt, E.D. 1995. Modeling ignition and burning rate of large woody natural fuels. Int. J. of Wildland Fire 5(2):81-91.

Albini, F.A., Stocks, B.J. 1986. Predicted and observed rates of spread of crown fires in immature Jack pine. Comb. Sci. and Tech. 48:65-76.

Alexander, M.E. 1979. Fuels description in lodgepole pine stands of the colorado front range. MSc. Thesis Colorado State University. Fort Collins, Colorado.

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

Alexander, M.E. 1991. The 1985 Butte fire in central Idaho; a Canadian perspective on the associated burning conditions. Pages 334-343 in Fire and the Environment; Ecological and Cultural Perspectives. Proceedings of an International Symposium. USDA For. Serv. Gen. Tec. Rep. SE-69, Southeast For. Exp. Stn., Asheville, North Carolina.

Alexander, M.E. 1998. Crown fire thresholds in exotic pine plantations of Australasia. Ph.D. Thesis, Australian National University, Canberra, Australia. 228 p.

Alexander, M.E. 1999. Fire Researcher, Northern Forestry Center, Edmonton. Canadian Forestry Service. FBP data base.

Alexander, M.E., Cole F.V. 1994. Predicting and interpreting fire intensities in Alaska black spruce forests using the Canadian system of fire danger rating. Pages 185-192 in Managing forests to meet peoples needs, Proceedings of the 1994 Society of American Foresters/Canadian institute of forestry Convention, Society of American Foresters, Bethesda, Maryland. SAF publication 95-02.

Alexander, M.E., Lanoville, R.A. 1987. Wildfires as a source of fire behavior data: a case study from Northwest Territories, Canada. Pages 86-93 in Postprint Volume Ninth Conference on Fire and Forest Meteorology. Am. Meteo. Soc., San Diego, California.

Alexander, M.E., Pearce, H.G. 1992. Guidelines for investigation and documentation of wildfires in exotic pine plantations. RWG N°6 meeting, Creswick, Victoria.

Alexander, M.E., Quintilio, D. 1990. Perspectives on experimental fires in Canadian forestry research. Math. Comput. Modelling 13(12):17-26.

Alexander, M.E., Stocks, B.J., Lawson, B.D., 1991, Fire behavior in black spruce-lichen woodland: the Porter Lake project. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-310. 44 p.

Alexander, M.E., Yancik, R.F. 1977. The effect of precommercial thinning on fire potential in a lodgepole pine stand. Fire Management Notes 38 (3):7-9.

Anderson, H.E. 1968. Sundance fire: an analysis of fire phenomena. USDA Forest Service Research Paper INT-56, Intermountain For. and Range Exp. Station, Ogden, Utah, 39 p.

Anderson, H.E. 1969. Heat transfer and fire spread. USDA Forest Service Research Paper INT-69, Intermountain For. and Range Exp. Station, Ogden, Utah, 20 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv. Res. Pap. INT-122, Intermountain For. and Range Exp. Stn., Ogden Utah, 22 p.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system - BURN subsystem, part 1. USDA For. Serv. Gen. Tech. Rep. INT-260, Intermountain For. and Range Exp. Stn., Ogden Utah.

Andrews, P.L. 1996 Fire behavior research news. Intermountain Fire Sciences Laboratory. 5 p.

Andrews, P.L. Chase, C.H. 1989. BEHAVE: fire behavior prediction and fuel modeling system - BURN subsystem, part 2. USDA For. Serv. Gen. Tech. Rep. INT-194, Intermountain For. and Range Exp. Stn., Ogden Utah.

Arno, S.F. 1996. The seminal importance of fire in ecosystem management – impetus for this publication. Pages 3-5 in The use of fire in forest restoration. USDA For. Serv. Intermountain Forest and Range Experimental Station. GTR-INT-341. Ogden, Utah.

Bacsi, Z., Zemankovics, F. 1995. Validation: and objective or a tool? Results on a winter wheat simulation model application. Ecological Modelling 81:251-263.

Baines, P.G. 1990. Physical mechanisms for the propagation of forest fires. Mathl. Comput. Modelling 13(12):83-94.

Bartlink, H.H. 1998. A model of dry matter partitioning in trees. Tree physiology 18:91-101.

Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Can. J. For. Res. 2:49-53.

Baskerville, G.L. 1983. Balsam fir foliage regressions are age dependent. Can. J. For. Res. 13:1248-1251.

Beck, J.A. 1995. Equations for the forest fire behaviour tables for western Australia. CALM Science 1(3):325-348.

Beer, T. 1995. Fire propagation in vertical stick arrays: the effect of wind. Int. J. Wildland Fire 5(1):43-49.

Beggs, B.J. 1973. Forest fire danger tables. For. Dept., Western Australia, 27 p.

Benedict, G.W., Swan, L.R., Belnap, R.A. 1989. Evolution and implementation of a fire management program which deals with high intensity fires on the payette national forest in Central Idaho. Pages 339-352 in High intensity fire in wildlands: management challenges and options. Proceedings of the 17th Tall timbers fire ecology conference. May 18-21, Tallahassee, Florida.

Bevins, C.D., Martin, R.E. 1978. An evaluation of the slash (I) fuel model of the 1972 National Fire Danger Rating System. USDA Forest Service Res. Pap. PNW-115, Pacific Northwest For. and Range Exp. Station, Portland, Or. 17 p.

Brown, J.K. 1972. Field test of rate of fire spread in slash fuels. Intermountain Research Station, USDA For. Ser. Gen. Tech. Rep.,INT-116 Ogden, UT.

Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. USDA For. Serv. Res. Pap. INT-197, Intermountain For. and Range Exp. Stn., Ogden Utah, 56 p.

Brown, J.K., Booth, G.D., Simmerman, D.G. 1989. Seasonal change in live fuel moisture of understory plants in Western U.S. Aspen. Pages 406-412 in Proceedings of 10th Conference on Fire and Forest Meteorology. Ottawa, Canada.

Brown, J.K., Oberheu, R.D., Johnston, C.M. 1982. Handbook for inventorying surface fuels and biomass in the interior west. USDA For. Serv. Res. Pap. INT-129, Intermountain For. and Range Exp. Stn., Ogden Utah, 48 p.

Buckley, A.J. 1992. Fire behaviour and fuel reduction burning: Bemm river wildfire, October 1988. Aust. For. 55:135-147.

Burgan, R.E. 1987. A comparison of procedures to estimate fine dead fuel moisture for fire behavior predictions. South African Forestry Journal 142:34-40.

Burgan, R.E., 1988. 1988 revisions to the 1978 National Fire-Danger Rating System. Res. Pap. SE-273. Asheville, NC: USDA For. Serv., Southeastern Forest Exp. Stn., 39 p.

Burgan, R.E., Rothermel, R.C. 1984. BEHAVE: Fire behavior prediction and fuel modeling system -- FUEL subsystem. USDA For. Serv. Res. Pap. INT-167, Intermountain For. and Range Exp. Stn., Ogden Utah, 126 p.

Burrows, N.D., Sneeuwjagt, R.J. 1988. McArthur's forest fire danger meter and the forest fire behaviour tables for western Australia: derivation, application and limitations. Pages 25-77 in Proc. of Conference on Bushfire Modeling and Fire Danger Rating Systems. 11-12 July, Canberra. CSIRO.

Butler, B.W. 1993. Experimental measurements of radiant heat fluxes from simulated wildfire flames. Proceedings of 12th Conference on Fire and Forest Meteorology, Jekyll Island, Georgia.

Byram, G.M. 1957. Some principles of combustion and their significance in forest fire behavior. Fire Control Notes 18(2):47-57.

Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P., Ed. *Forest Fire Control and Use*. New-York: McGraw-Hill Book Co.

Call, P.T., Albini, F.A. 1997. Aerial and surface fuel consumption in crown fires. International journal of Wildland Fire 7(3):259-264.

Catchpole, E.A., Catchpole, W.R., Rothermel, R.C., 1993. Fire behavior experiments in mixed fuel Complexes. Int. J. Wildland Fire 3(1):45-57.

Catchpole, T., de Mestre, N. 1986. Physical models for a spreading line fire. Aust. For. 49(2):102-111.

Catchpole, W.R., Catchpole, E.A., Butler, B.W., Rothermel, R.C., Morris, G.A., Latham, D.J. 1998. Rate of spread of free-burning fires in woody fuels in a wind tunnel. Comb. Sci. and Tech. 131:1-37.

Cheney, N.P. 1981. Fire behaviour. In Fire and the Australian Biota, edited by Gill, A.M., Groves, R.H., Noble, I.R., Australian Academy of Sciences, Canberra.

Cheney, N.P. 1988. Models used for fire danger rating in Australia. Pages 19-28 in Proc. of Conference on Bushfire Modeling and Fire Danger Rating Systems. 11-12 July, Canberra. CSIRO.

Cheney, N.P. 1989. Predicting forest fire behaviour - The Australian experience. In Proceedings of the Workshop Integrating research on hazards in fire-prone environments. The U.S. Man and the Biosphere Program.

Cheney, N.P. 1990. Quantifying bushfires. Mathl. Comput. Modelling 13(12):9-15.

Cheney, N.P., Gould, J.S., Catchpole, W.R. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. Int. J. Wildland Fire 3(1):31-44.

Cheney, N.P., Gould, J.S., Catchpole, W.R. 1998. Prediction of fire spread in grasslands. Int. J. Wildland Fire 8(1):1-13.

Christensen, N.L. 1989. Wilderness and high intensity fire: how much is enough. Pages 9-24 in High intensity fire in wildlands: management challenges and options. Proceedings of the 17th Tall timbers fire ecology conference. May 18-21, Tallahassee, Florida.

Chrosciewicz, Z. 1986. Foliar heat content variations in four coniferous tree species of central Alberta. Can. J. For. Res. 16:152-157.

Chrosciewicz, Z. 1986. Foliar heat content variations in four coniferous tree species of central Alberta. Can. J. For. Res. 16:152-157.

Cohen, W.B., Omi, P.N. 1991. Water-stress effects on heating-related water transport in woody plants. Can. J. For. Res. 21:199-206.

Cohen, W.B., Omi, P.N., Rothermel, R.C. 1989. Heating related water transport in woddy plants: Summary of experimental results. Proceedings of 10th Conference on Fire and Forest Meteorology. Ottawa, Canada.

Cuinas, P., Vega, J.A., Fonturbel, T., Fernandez, C. 1996. Field testing of BEHAVE system predictions in Galicia (NW Spain) shrublands. In Workshop on Forest Fire Behavior: modeling and testing, Luso 6-7 May 1996.

Custer, G., Thorsen, J. 1996. Stand replacement burn in the Ocala National Forest – a success. Fire Management Notes 56(2):7-12.

Davis, K.M., Mutch, R.W. 1994. Applying ecological principles to manage wildland fire, in Fire in Ecosystem Management, Training course, National Advanced Resource Technology Center.

De Groot, W.J.; Alexander, M.E. 1986. Wildfire behavior on the Canadian shield: a case study of the 1980 Chachukew fire, east central Alberta. Pages 23-45 in Proceedings of the Third Central Region Fire Weather Committee scientific and Technical Seminar, Can. For. Ser., Northern For. Centre, Edmonton, Alberta.

De Groot, W.J.; Schisler, J.M. 1989. Fire behavior on the 1987 Elan fire, Saskatchewan. Pages 26-40 in Proceedings of the Fifth Central Region Fire Weather Committee scientific and Technical Seminar, For. Can., Sask. Dist. Off., prince Albert, Saskatchewan.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire-Danger System-1978. USDA For. Serv. Gen. Tech. Rep. INT-39. Intermountain For. and Range Exp. Stn., Ogden, Utah 84401. 63 p.

Dimitrakopoulos, A.P. 1987. Sensitivity analysis of the national management system's fire behavior and supression input parameters. Pages 31-33 in Postprint Volume Ninth Conference on Fire and Forest Meteorology. Am. Meteo. Soc., San Diego, California.

Dimitrakopoulos, A.P., Mateevam V. 1998. Effect of fuel moisture on the ignitability of mediterranean species. Pages 456-466 in the Proceedings of 3rd International Conference on Forest Fire Research – 14th Conference on Fire and Forest Meteorology, Luso - Coimbra, Portugal - 16/20 November 1998.

Dorrer, G.A. 1984. A model of the spreading of a forest fire. Heat transfer - Soviet research, 16(6):39-52.

Draper, N.R., Smith, H. 1981. *Applied Regression Analysis*. John Wiley and Sons, Inc. New York. 407 pp.

Fahnestock, G.R. 1970. Two keys for appraising forest fire fuels. USDA Forest Service Research Paper PNW-99, Pacific Northwest For. and Range Exp. Station, Portland, OR.

Fendell, F.E., Carrier, G.F., Wolff, M.F. 1990. Wind-aided fire spread across arrays of discrete fuel elements. U.S. Dep. Defence, Defence Nuclear Agency, Alexandria, Virginia. Tech. Rep. DNA-TR-89-193. 113 p.

Fernandes, P.M. 1998. Fire spread modeling in Portuguese shrubland. Pages 611-628 in the Proceedings of 3rd International Conference on Forest Fire Research – 14th Conference on Fire and Forest Meteorology, Luso - Coimbra, Portugal - 16/20 November 1998.

Fernandes, P.M., Rego, F.C. 1998. Equations for fuel loading estimation in shrub communities dominated by Chamaespartium tridentatum and Erica umbelata. In the Proceedings of 3rd International Conference on Forest Fire Research – 14th Conference on Fire and Forest Meteorology, Luso - Coimbra, Portugal - 16/20 November 1998.

Finney, M.A. 1998. FARSITE: Fire area simulator – model development and evaluation. USDA, For. Serv., Res. Pap. RMRS-RP-4, Rocky Mountain Research Station. Ogden, Utah. 47 p.

Fire Danger Group, 1992, Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep. ST-X-3, Forestry Canada, Science and Sustainable Development Directorate, Ottawa. 65 p.

Fleeter, R.D.,Fendell, F.E., Cohen, L.M., Gat, N., Luitte, A.B. 1984. Laboratory facility for wind-aided firespread along a fuel matrix. Combustion and flame 57:289-311.

Fleming, R.A., Shoemaker, C.A. 1992. Evaluating models for spruce budworm-forest management: Comparing output with regional field data. Ecological Applications 2(4):460-477.

Fosberg, M.A., Demming, J.E. 1971. Derivation of the 1-hr and 10-hr timelag fuel moisture calculations for fire danger rating. USDA For. Serv. Res. Not. RM-207, Rocky Mountain Forest and Range Experimental Station. Fort Collins, CO, 8 p.

Frandsen, W.H. 1973. Effective heating of fuel ahead of spreading fire. Intermountain Research Station, USDA For. Ser. Res. Pap. INT-140 Odgen,UT. 16 p.

Frandsen, W.H. 1991. Burning rate of smoldering peat. Northwest Science, 65(4):166-172.

Fuglem, P.L. 1979. Foliar moisture content of central Alberta conifers and its implications in crown fire occurrence. Master thesis, University of Alberta, Edmonton.

Gill, M.A., Moore, P.H.R. 1990. Fire intensities in eucalyptus forests of Southeastern Australia. In "International. Conf. For. Fire Research", Coimbra, 19-22 November, Pages B24:1-12.

Gould, J.S. 1988. Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In Proc. of Conf. on Bushfire Modeling and Fire Danger Rating Systems. 11-12 July, Canberra.

Gould, J.S., Knight, I, Sullivan, A.L. 1997. Physical modelling of leaf scorch height from prescribed fires in young Eucalyptus sieberi regrowth forests in South-eastern Australia. Int. J. Wildland Fire 7(1):7-20.

Grigal, D.F., kernik, L.K. 1984. Generality of black spruce biomass estimation equations. Can. J. For. Res. 14:486-470.

Grishin, A.M. 1997. Mathematical modeling of forest fires and new methods of fighting them. Tomsk State University, Tomsk, Russia. 390 p.

Grishin, A.M., Perminov, V.A. 1990. Transition of the forest ground fire to crown fire. In Combustion Explosions and Shock Waves. Plenum Publishing Corporation.

Hartford, R., Rothermel, R.C. 1991. Moisture measurements in the Yellowstone fires, in 1988. Intermountain Research Station, USDA For. Ser., Res. Not. INT- 396, Ogden, UT.

Hatch, A.B. 1969. The estimation of fire hazard in Western Australia. For. Dept. WA, Bull. 77.

Hirsch, K.G. 1989a. Analysis of the fire behavior associated with three 1988 spring wildfires in Central Canada. Pages 416-425 in Proceedings of the 10th Conference on Fire and Forest Meteorology. For. Can. and Environ. Can., Ottawa, Canada.

Hirsch, K.G. 1989b. Documenting wildfire behavior: The 1988 Brereton Lake Fire, Manitoba. Fire Management Notes 50(1):45-48.

Hirsch, K.G. 1996. Canadian Forest Fire Behavior Prediction (FBP) system: user's guide. Nat, resour. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Spec. Rep.7, 122 p.

Hosmer, D.W., Lemeshow, S. 1989. *Applied Logistic Regression*. John Wiley & Sons. 307 p.

Hough, W.A. 1969. Caloric value of some forest fuels of the Southern United States. USDA For. Serv. Res. Not. SE-120, Southeastern Forest Experiment Station, Forest Service, USDA, 6 p.

Hough, W.A. 1973. Fuel and Weather influence wildfires in sand pine forests. USDA For. Serv. Res. Paper SE-106, Southeastern Forest and Range Exp. Station, Asheville, North Carolina.11 p.

Johnson, A.F., Woodard, P.M., Titus, S.J. 1990. Lodgepole pine and white spruce crown fuel weights predicted from diameter at breast height. The Forestry Chronicle 66:596-599.

Johnson, E.A. 1992. Fire and vegetation dynamics. Studies from the North American boreal forest. Cambridge Studies in Ecology. Cambridge University Press.129 p.

Johnson, V.J. 1966. Seasonal fluctuation in moisture content of pine foliage. North Central Forest Experiment Station, USDA For. Serv. Res. Not. NC-11. 4 p.

Kalabokidis, K.D., Omi, P.N. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. Int. J. Wildland Fire 8(1):29-35.

Kiil, A.D. 1967. Fuel weight tables for White Spruce and Lodgepole Pine crowns in Alberta. Forestry Branch, Dep. Publication N°1196, Dep. of Forestry and Rural Development, Canada.

Kiil, A.D. 1968. Weight of the fuel complex in 70-year old lodgepole pine stands of different densities. Forestry Branch, Department Publication N° 1228. 9 p.

Kiil, A.D., Miyagawa, R.S., Quintilio, D. 1977. Calibration and perfomance of the Canadian Fire Weather Index in Alberta. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-173.

Kilgore, B.M. 1978. Fire in ecosystem distribution and structure: western forests and scrublands. Pages 58 – 89 in Proceeding of the Conference Fire Regimes and ecosystem properties. USDA Forest Service, GTR-WO-26.

Kilgore, B.M., Heinselman, M.L. 1990. Fire in wilderness ecosystems. Pages 297-335, in Hendee, R., Stankey, J.H., Lucas, R.C. Wilderness management. North American press, Golden, CO.

Kilgore, B.M., Sando, R.W. 1975. Crown-fire potential in a sequoia forest after prescribed burning. Forest Sci. 21:83-87.

Kiil, A.D. 1971. Estimating weights of tree components of lodgepole pine from -scale aerial photographs. Can. J. Forest Res. 1:193-134.

Kittredge, J., 1944. Estimation of the amount of foliage of trees and stands. J. Forestry 42:905-912.

Konev, E.V. 1993. The semiempirical model of crown forest fire. In Dorrer, G., editor, Forest fires, modeling and simulation. Scientific Siberian, International Association of Wildland Fire.

Kurbatskiy, N.P., Telitsin, G.P. 1977. Theoretical and experimental analysis of the radiation mechanisms for the spread of forest fires. in Characteristics of the processes of combustion in forests. USSR Academy of Sciences, Siberian Branch, Krasnoyarsk.

Latham, D.J., Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. Intermountain Research Station, USDA For. Ser. Res. Pap. INT-411 Odgen,UT. 16 p.

Law, A.M., Kelton, W.D. 1991. *Simulation Modeling and Analysis*. McGraw-Hill, New York, 759 p.

Lawson, B.D., Armitage, O.B., Dalrymple, G.N., 1994. Ignition probabilities for simulated people-caused fires in British Columbia's Lodgepole pine and white spruce-subalpine fir forests. Proceedings of 12th Conference on Fire and Forest Meteorology, Jekyll Island, Georgia.

Lawson, B.D., Armitage, O.B., Hoskins, W.D. 1996. Diurnal variation in the Fine Fuel Moisture Code: Tables and computer source code. FRDA report 245. 20 pp.

Lawson, B.D., Frandsen, W.H., Hawkes, B.C., Dalrymple, G.N 1997. Probability of sustained smoldering ignition for some boreal forest duff types. Nat. resour. Can., Can. For. Serv. North. For. Cent., Edmonton, Alberta. For. Management Note 63.

Leemans, R. 1991. Sensitivity analysis of a forest succession model. Ecological Modelling 53:247-262.

Lindenmuth, A.W., Davis, J.R. 1973. Predicting fire spread in Arizona's oak chaparral. USDA Forest Service, Res. Pap. RM-101, Rocky Mountain For. and Range Exp. Station, Fort Collins, Co.

Long, J.N., Smith, F.W. 1988. Leaf area – sapwood area relations of lodgepole pine as influenced by stand density and site index. Can. J. For. Res. 18:247-250.

Loomis, R.M., Roussopoulos, P.J. 1978. Estimating aspen crown fuels in northern Minnesota. USDA For. Serv. Res. Pap. NC-156, North Central Forest Experiment Station St. Paul, Minnesota. 6 p.

Luke, R.H., McArthur, A.G. 1978. Bushfires in Australia. Aust. Goverm. Publishing Serv. Canberra, ACT. 359 p.

Mahamah, D.S. 1988. Simplified sensitivity analysis applied to a nutrient-biomass model. Ecological modelling, 42:103-109.

Marsden-Smedley, J., Catchpole, W.R. 1995. Fire behaviour modelling in Tasmanian Buttongrass Moorlands. II. Fire Behaviour. Int. J. Wildland Fire 5(4):215-228.

Mayer, D.G., Butler, D.G. 1993. Statistical validation. Ecological Modelling 68:21-32.

Mayer, D.G., Stuart, M.A., Swain, A.J. 1994 Regression of real world data on model output: an appropriate overall test of validity. Agricultural systems 45:93-104.

McAlpine, R.S. Hobbs, M.W. 1994. Predicting the height to live crown base in plantations of four boreal forest species. Int. J. Wildland Fire 4(2):103-106.

McArthur, A.G. 1958. The preparation and use of fire danger tables. In Proceedings Fire Weather Conference, Bureau of Meteorology, Melbourne.

McArthur, A.G. 1967. Fire Behaviour in Eucalyptus forests. Commonw. Aust., Dep. Nat. Devel., Forest and Timber Bureau, Camberra, Leaflet n°107, 36 p.

McArthur, A.G., 1973, Forest Fire Danger Meter, Tasmania Forestry Commission.

McCarl, B.A. 1984. Model validation: an overview with some emphasis on risk models. Rev. Market Agric. Econ., 52:153-173.

McCaw, L., Simpson, G., Mair, G. 1992. Extreme wildfire behaviour in 3-year-old fuels in a western Australian mixed Eucalyptus forest. Aust. For. 55:107-117.

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

Merrill, D.F., Alexander, M.E. 1987. Glossary of fire management terms. Canadian Committee on Forest Fire Management, NRCC N°26516, Ottawa, Canada.

Moeur, M. 1981. Crown width and foliage weight of northern Rocky Mountains conifers. Intermountain Forest and Range Experimental station, USDA For. Ser. Res. Pap. INT-283 Odgen,UT. 14 p.

Molchanov, V.P. 1957. Conditions for the spread of crown fire in pine forest. Translated from Lesnoe Khozydystvo 10:50-63

Moreno, J.M, Oechel, W.E. 1989. A simple method for estimating fire intensity after a burn in California chaparral. Acta OEcologica 10(1):57-68.

Nelson, R.M. 1993. Byram's energy criterion for wildland fires: units and equations. Intermountain Research Station, USDA For. Serv. Res. Note INT-415, Intermountain Research Stn., Ogden Utah, 5 p.

Newstead, R.G., Alexander, M.E. 1983. Short-term fire retardant effectiveness in a lowland black spruce fuel complex. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. For. Rep. 28:3-4.

NFPA. 1992. Black Tiger fire case study. National Wildland/Urban Interface Fire Protection Initiative.

NFPA. 1993. Stephan Bridge Road fire case study. National Wildland/Urban Interface Fire Protection Initiative.

Noble, I.R., Bary, G.A.V., Gill, A.M., 1980. McArthur's fire-danger meters expressed as equations. Australian Journal of Ecology 5:201-203.

Norusis, M.J. 1997. *SPSS Professional Statistics*. SPSS Inc., Chicago. 376 p.

NWCG 1993. S-490 Advanced wildland fire behavior calculations, National Wildfire Coordination Group.

Oderwald, R.G., Hans, R.P. 1993. Corroborating models with model properties. Forest Ecology and Management 62:271-283.

Olson, C.M. 1980. An evaluation of the Keetch-Byram drought index as a predictor of foliar moisture content in chaparral community. In Proceedings Sixth Conference on Fire and Forest Meteorology, April 22-24, 1980. Society of American Foresters, 241-245.

Ottmar, R.D., Vihnanek, R.E., Wright, C.S. 1998. Stereo photoseries for quantifying natural fuels. Vol. I: Mixed-conifer with mortality, Western Juniper, Sagebrush, and Grassland types in the Interior Pacific Northwest. 73 p.

Packham, D. 1989. Background to fire behavior models. pages 23-25 in proceedings of the 3rd fire Weather conference, may 18-20, Bureau of Meteorology.

Pagni, P.J., Peterson, T.G. 1973. Flame spread through porous fuels. Pages 1099-1106 in 14th Symposium in Combustion. Pittsburgh, Pa. The combustion Institute.

Peet, G.B. 1965. A fire danger rating and controled burning guide for the northern jarrah (euc. Marginata Sm) forest, of Western Australia. For. Dept. WA, Bull. 74. 37 p.

Philpot, C.W. 1963. The moisture content of ponderosa pine and whiteleaf manzanita foliage in the central Sierra Nevada. U.S.D.A. Forest Service Research Note PSW-39, Pacific Southwest For. and Range Exp. Station, Berkeley, CA.

Philpot, C.W. 1969. Seasonal changes in heat content and ether extractive content of chamois. Res. Pap. INT-61, Intermountain Forest and Range Experiment Station, Forest Service, USDA, 10 p.

Philpot, C.W., Mutch, R.W. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. Intermountain Forest and Range Experimental station, USDA For. Ser. Res. Pap. INT-102 Odgen,UT. 21 p.

Pompe, A., Vines., R.G., 1966. The influence of moisture on the combustion of leaves. Australian Forestry 30(3):231-241.

Pyne, S.J., 1984 - *Introduction to Wildland Fire*. John Wiley & Sons, New York, 456 p.

Quintilio, D., Fahnestock, G.R., Dubé, D.E. 1977. Fire behavior in upland jack pine: the Darwing Lake Project. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-174.

Ramachandran, G. 1988. Probabilistic approach to fire risk evaluation. Fire Technology, August, 204-225.

Rencz, A.N., Auclair, A.N. 1980. Dimension analysis of various components of black spruce in subarctic lichen woodlands. Can. J. For. Res. 10:491-497.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, Intermountain For. and Range Exp. Stn., Ogden Utah, 40 p.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143, USDA For. Serv. Intermountain For. and Range Exp. Stn., Ogden, Utah 84401, 161 p.

Rothermel, R.C. 1991a. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Gen. Tech. Rep. INT-438, USDA For. Serv. Intermountain. For. and Range Exp. Stn., Ogden, Utah 46 p.

Rothermel, R.C. 1991b. Crown fire analysis and interpretation. Pages 253 – 263 in the Proceedings of 11th Conference on Fire and Forest Meteorology. Missoula, MT.

Rothermel, R.C. 1993. Some fire behavior modeling concepts for fire management systems. Proceedings of 12th Conference on Fire and Forest Meteorology, Jekyll Island, Georgia.

Rothermel, R.C., Wilson, R.A., Morris, G.A., Sackett, S.S. 1986. Modeling moisture content of fine dead fuels: input to the BEHAVE fire prediction system. Intermountain Research Station, USDA For. Ser., Res. Pap. INT- 359, Ogden, UT.

Rothermel, R.C.; Mutch, R.W. 1986. Behavior of the live-threatening Butte fire: August 27-29, 1985. Fire Management Notes 47(2):14-24.

Rykiel, E.J. 1996. Testing ecological models: the meaning of validation. Ecological Modelling 90:229-244.

Sandberg, D.V., Ward, F.R. 1981. Predictions of fire behavior and resistance to control for use with photo series for the Douglas-Fir - Hemlock type and the Coastal Douglas-fir

- Hardwood type. USDA Forest Service General Technical Report PNW-116, Pacific Northwest For. and Range Exp. Station, Portland, Or.

Sando, R.W., Wick, C.H. 1972. A method for evaluating crown fuels in forest stands. USDA For. Serv. Research Paper NC-84, North Central For. and Range Exp. Station, St. Paul, MN.

Scott, J.H. 1998. Fuel reduction in residential and scenic forests: a comparison of three treatments in a western Montana ponderosa pine stand. Res. Pap. RMRS-RP-5, Ogden, Utah: USDA, Forest Service, Rocky Mountain Research Station. 19 p.

Shafizadeh, F. 1968. Pyrolysis and combustion of cellulosic materials. Advan. Carbohyd. Chem. 23:419-474.

Shafizadeh, F.; Chin, P.P.S.; De Groot, W.F. 1977. Effective heat content of green forest fuels. Forest Sci. 23:81-89.

Simard, A.J. 1968. The moisture content of forest fuels - 1. A review of the basic concepts. Canadian Department of Forest and Rural Development, Forest Fire Research Institute, Information Report FF-X-14, Ottawa, Ontario. 47 p.

Simard, A.J.; Haines, D.A.; Blank, R.W.; Frost, J.S. 1983. The Mack lake fire. USDA For. Serv. Gen. Tec. Rep. NC-83, North Central Forest Experiment Station St. Paul, Minnesota. 36 p.

Smith, C.A.B. 1969. Biometrics. Vol. II. 4th Edition. Charles Griffin & Co. , London.

Sneeuwjagt, R.J., Frandsen, W.H. 1977. Behavior of experimental grass fires vs. predictions based on Rothermel's fire model. Can. J. For. Res. 7:357-367.

Sneeuwjagt, R.J., Peet, G.B., 1979. Forest fire behaviour tables for western Australia. For. Dept. WA 47 p.

Sneeuwjagt, R.J., Peet, G.B., 1985. Forest fire behaviour tables for western Australia. Department of Conservation and Land Management. 59 p.

Snell, J.A.K., Anholt, B.F. 1981. Predicting crown weight of coast douglas-fir and western hemlock. U.S.D.A. Forest Service Research Paper PNW-281, Pacific Northwest For. and Range Exp. Station, Portland, Or. 13 p.

Stiell, W.M. 1966. Red pine crown development in relation to spacing. Department of Forestry. Publication N° 1145. 44 p.

Stiell, W.M. 1969. Crown development in white spruce plantations. Forestry Branch, Department of Fisheries and Forestry, Publication N° 1249. 11 p.

Stocks, B.J. 1980. Black spruce crown fuel weights in Northern Ontario. Can. J. For. Res. 10:498-501.

Stocks, B.J. 1987. Fire behavior in immature jack pine. Can. Jour. Forest. Res. 17:80-86.

Stocks, B.J. 1989. Fire behavior in mature Jack pine. Can. J. For. Res. 19:783-790.

Stocks, B.J., Flannigan, M.D. 1987. Analysis of the behavior and associated weather for a 1986 northwestern Ontario wildfire: Red Lake Number 7. Pages 94-100 in Postprint volume, ninth conference on fire and forest meteorology. Am. Meteorological. Soc., Boston, MA.

Stocks, B.J., McRae, D.J., Lynham, T.J., Hartley, G.R. 1990. A photo-series for assessing fuels in natural forest stands in northern Ontario. Canada-Ontario Forest Resource Development Agreement Report N° 3304.

Sussot, R.A. 1980a. Thermal behavior of conifer needle extractives. Forest Sci. 26(3):347-360.

Sussot, R.A. 1980b. Effect of heating rate on char yield from forest fuels. USDA For. Serv. Res. Note INT-295, Intermountain For. and Range Exp. Stn., Ogden Utah. 9 p.

Sussot, R.A. 1982a. Characterization of the thermal properties of forest fuels by combustible gas analysis. Forest Sci. 28(2):404-420.

Sussot, R.A. 1982b. Differential scanning calorimetry of forest fuels. Forest Sci. 28(4):839-851.

Sussot, R.A. 1998. Researcher, USDA Forest Service, Intermountain Fire Sciences Laboratory, Missoula, Montana. Personal oral comunication.

Sussot, R.A., DeGroot, W.F., Shafizadeh, F. 1975. Heat content of natural fuels. J. Fire & Flammability 6:311-325.

Taylor, G.I. 1961. Fire under the influence of natural convection. Pages 10-31 in Proceedings of the use of models in fire research. Natl. Acad. Sci.-Natl. Res. Counc. , Washigton, D.C.

Telitsin, H.P. 1992. Propagation mechanisms of intense forest fires and their influence on atmosphere processes. In. Proc. of Research on the Processes of Combustion, Explosions and Modeling of Fires. Khabarousk, Russia.

Telitsyn, G.P. 1968. A study of the process of spreading in wind forest fires in far eastern forests. Krasnoyarsk, Akedemiia Nauk CCCP, Special dissertation N° 562. P1-21.

Thomas, P.H. 1963. The size of flames from natural fires. In: Proceedings ninth symposium on combustion. Pages 844-859. Ithaca, NY.

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. Orgn., Fire Res. Stn., England. Fire Res. Note N° 576. 36 p.

Thomas, P.H. 1967. Some aspects of the growth and spread of fire in the open. Forestry, 40(2):139-164.

Thomas, P.H. 1970. The rate of spread pf head fires in the New Forest, Hampshire. Report on Forest Research 1970, 190-194.

Thomas, P.H. 1971. Rates of spread of some wind-driven fires. Forestry 44:155-175.

Thomas, P.H., Simms, D.L. 1963. A study of fire spread in forest fires. Report on Forest Research 1963, 108-112.

Trevitt, A.C.F. 1988. Weather parameters and fuel moisture content: standards for fire model inputs. Pages 157-166 in Proc. of Conference on Bushfire Modeling and Fire Danger Rating Systems. 11-12 July, Canberra. CSIRO.

Tunstall, B. 1988. Live fuel water content. . Pages 127-136 in Proc. of Conference on Bushfire Modeling and Fire Danger Rating Systems. 11-12 July, Canberra. CSIRO.

USDI/USDA. 1995. Federal Wildland Fire management: Policy and Program review. National Interagency Fire Center. 45 p.

Valette, J.C., 1990. Flammabilities of mediterranean species: INRA's methodology. Ministère de l'Agriculture, Recherches Forestières Station de Sylviculture Méditerranéenne, Avignon. PIF9328. 14 p.

Van Wagner, C.E. 1965. Story of an Intense Crown fire at Petawawa. Pulp Pa. Mag. of Canada, Woodlands Rev. June, p. 2-4.

Van Wagner, C.E. 1967a. Flammability of Christmas trees. Revised edition. Can. Dep. For. Rural Develop., For. Branch, Ottawa, Ontario. Dep. Publ. N°1034. 27 p.

Van Wagner, C.E. 1967b. Seasonal variation in moisture content of eastern Canadian tree foliage and possible effect on crown fires. Forestry Branch, Dep. Publication N°1204, Dep. of Forestry and Rural Development, Canada.

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 solitude's in forest fire research. Canadian Forestry Service. Inf. Rep. PS-X-29, Ottawa, Canada.

Van Wagner, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. Forest Res. 2:34-39.

Van Wagner, C.E. 1973. Height of crown scorch in forest fires. Can. J. For. Res. 3:373-378.

Van Wagner, C.E. 1974. A spread index for crown fires in the spring. Can. For. Serv. Inf. Rep. PS-X-55.

Van Wagner, C.E. 1975. Convection temperatures above low intensity forest fires. Bimonthly. Res. Notes, Canadian For. Serv. 31:21.

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. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, Ontario. For. Tech. Rep. 35. 34 p.

Van Wagner, C.E. 1989. Prediction of crown fire behavior in conifer stands, Proceedings of 10th Conference on Fire and Forest Meteorology. Ottawa, 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 Wagner, C.E. 1998. Modelling logic and the Canadian Forest Fire Behavior Prediction system. Forestry Chronicle 74(1):50-52.

Van Wagtendonk, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. Pages 1155-1165. Sierra Nevada Ecosystem Project: Final report to congress. Davis, University of California, Centers for water and wildland resources..

Van Wagtendonk, J.W., Sydoriak, W.M., Benedict, J.M. 1998. Heat content variation of Sierra Nevada Conifers. . Int. J. Wildland Fire 8(3):147-158.

Van Wilgen, B.W., Le Maitre, D.C., Kruger, F.J. 1985. Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. J. Appl. Ecol. 22:207-216.

Van Wilgen, B.W., Wills, A.J. 1988. Fire behaviour prediction in savanna vegetation. S. Afr. J. Wildl. Res. 18(2):41-46.

Vanclay, J.K., Skovsgaard, J.P. 1997. Evaluating forest growth models. Ecological Modelling 98:1-12.

Vega, J.A., Cuinas, P., Fonturbel, T., Fernandez, C. 1996. Fire behavior modelling in Galician (NW Spain) shrublands. In Workshop on Forest Fire Behavior: modeling and testing, Luso 6-7 May 1996.

Viegas, D.X., Pinol, J. Viegas, M.T., Ogaya, R. 1998. Moisture content of living forest fuels and their relationship with meteorological indices in the Iberian peninsula. Pages 1029-1046 in the Proceedings of 3rd International Conference on Forest Fire Research – 14th Conference on Fire and Forest Meteorology, Luso - Coimbra, Portugal - 16/20 November 1998.

Wade, D.D. 1969. Estimating slash quantity from standing loblolly pine. USDA For Serv. Southeast For. Range Exp. Stn., Asheville, North Carolina. Res. Note SE-125. 4 p.

Wade, D.D., Ward, D.E. 1973. An analysis of the Air Force Bomb Range Fire. USDA For Serv. Southeast For. Range Exp. Stn., Asheville, North Carolina. Res. Pap. SE-105.38 p.

Weber, M.G., Hummel, M, Van Wagner, C.E. 1987. Selected parameters of fire behavior and Pinus banksiana Lamb. regeneration in Ontario. The For. Chron. 63:340-346.

Weber, R.O., Gill, A.M., Lyons, P.R.A., Mercer, G.N. 1995. Time dependence of temperature above wildland fires. CALMScience Supplement 4:17-22.

Weetman, G.F., Harland, R. 1964. Foliage and wood production in unthinned black spruce in Northern Quebec. Forest Sci. 10(1):80-88.

Wilson, A.A.G., Ferguson, I.S. 1986. Predicting the probability of house survival during bushfires. Jour. Envir. Management 23:259-270.

Wilson, A.A:G. 1988. Width of firebreak that is necessary to stop grass fires: some field experiments. Can. J. For. Res. 18:682-687.

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

Wilson, R.A. 1990. Reexamination of Rothermel's fire spread equations in No-wind and no-sole conditions. Intermountain Research Station, USDA For. Ser. Gen. Tech. Rep. INT-434 Odgen,UT.

Woudenberg, S.W., Farrenkopf, T.M. 1998. The Westwide Forest Inventory data base: user's manual. USDA For. Serv. 67 p.

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

APPENDIX

Table A.1. Fire behavior database used in the evaluation of Rothermel (1991a) crown fire spread model

Fire name	Fuel Type	Date (dd/mm/yy)	T_a (ºC)	RH (%)	U_{10} (km/h)	M_{ffe} (%)	ROS (m/min)	I_B. (kW/m)	Predicted ROS (m/min)	Source:
Sharpsand #2	IMJP	June 26, 1975	25.5	40	11	11	10.74	4717	3.67	Stocks, 1987
Sharpsand #3	IMJP	June 26, 1975	25.5	40	16	11	16.88	9900	5.68	Stocks, 1987
Sharpsand #4	IMJP	June 27, 1975	27	52	14	15	14.28	7728	4.34	Stocks, 1987
Sharpsand #5	IMJP	June 30, 1975	30.5	33	10	9	14.64	10785	3.67	Stocks, 1987
Sharpsand #6	IMJP	July 1, 1975	29.5	48	11	9	14.58	9171	4.01	Stocks, 1987
Sharpsand #11a	IMJP	July 6, 1976	29	35	13	10.9	29.34	24274	4.68	Stocks, 1987
Sharpsand #11b	IMJP	July 6, 1975	29	35	21	10.9	49.44	40903	8.02	Stocks, 1987
Sharpsand #12	IMJP	July 9, 1976	25	40	14	12.5	20.16	17136	4.68	Stocks, 1987
Sharpsand #13	IMJP	July 9, 1976	25	40	15	12.5	16.2	15790	5.01	Stocks, 1987
Sharpsand #14	IMJP	July 13, 1976	22	36	16	14.4	27.3	25990	5.34	Stocks, 1987
Sharpsand #17	IMJP	July 13, 1981	27	42	10	9	7.86	4833	3.67	Stocks, 1987
Kenshoe #5	MJP	May 17, 1975	23	39	29	8	15.36	7964	13.69	Stocks, 1989
Kenshoe #9	MJP	July 8, 1979	27	45	18	10	4.26	3054	7.01	Stocks, 1989
Kenshoe #12	MJP	June 21, 1983	29.2	48	18	10	10.2	4826	7.01	Stocks, 1989
Darwin lake #4b	MJP	August 4, 1974	31	26	8.5	8	3.35	1900	3.01	Quintilio et al. 1977
Darwin lake #6	MJP	August 5, 1974	30.5	33	16.9	9	6.1	7460	6.68	Quintilio et al. 1977
Porter lake #1	BS	June 30, 1982	26.5	30	20.4	5	6.1	3184	9.69	Alexander et al. 1991
Porter lake #2	BS	July 1, 1982	20.5	50	24	6	26.3	13650	11.36	Alexander et al. 1991
Porter lake #3	BS	July 5, 1982	20	28	17	8.1	3.5	2131	6.68	Alexander et al. 1991
Porter lake #4	BS	July 6, 1982	21.5	36	14.5	7.7	3.7	1698	5.68	Alexander et al. 1991
Porter lake #5	BS	July 7, 1982	27.5	31	28	7.1	33.3	18082	13.36	Alexander et al. 1991
Porter lake #5a	BS	July 7, 1982	27.5	31	34.6	7.1	51.4	33153	17.70	Alexander et al. 1991
Porter lake -CR-6	BS	July 7, 1982	27	32	26	7.1	31.9	19332	12.02	Alexander et al. 1991
VW C6	RP	May 31, 1967		25	19	12	27.6	22500	7.01	Van Wagner, 1968
VW C4	RP	July 14, 1966		32	23	12	16.8	21100	9.02	Van Wagner, 1968
VW R1	RP	June 8, 1962			14.9	10	10.8	7300	5.34	Van Wagner, 1968
VW GL-A	MJP	May 7, 1964	27.2	25	23	8	12	4800	10.02	Van Wagner, 1965
VW GL-B	MJP	May 7, 1964	27.2	25	23	8	24.6	18300	10.02	Van Wagner, 1965

Fuel Types: IMJP – immature jack pine, MJP – mature jack pine, BS – black spruce, RP – red pine; Ta – air temperature; RH – relative humidity; U_{10} – wind speed at 10 meters; Mffe – estimated fine fuel moisture content; ROS – Observed rate of spread; I_B – Fireline intensity.

Table A.2. Fire behavior database used in the probabilistic crown fire initiation model building – Fire environment variables

Fire name	Fuel Type	Date	T_a (°C)	RH (%)	U_{10} (km/h)	FMC (%)	FSG (m)	M_{ffm} (%)	M_{ffe} (2) (%)
Kenshoe #1	MJP	730528	10.5	41	8	103 (1)	2	-	9
Kenshoe #2	MJP	730529	12	35	11	103 (1)	2	-	9
Kenshoe #3	MJP	730529	12	35	11	103 (1)	2	-	9
Kenshoe #4	MJP	740605	26	48	12	105 (1)	2	-	10
Kenshoe #5	MJP	750517	23	39	29	102 (1)	2	-	8
Kenshoe #6	MJP	750519	25	47	3	102 (1)	2	-	10
Kenshoe #7	MJP	760525	17	30	7	104 (1)	2	-	8
Kenshoe #8	MJP	760526	20	33	11	104 (1)	2	-	8
Kenshoe #9	MJP	790708	27	45	18	118 (1)	2	-	10
Kenshoe #10	MJP	830619	28.8	33	8	112 (1)	2	-	8
Kenshoe #11	MJP	830620	29	36	12	112 (1)	2	-	8
Kenshoe #12	MJP	830621	29.2	48	18	113 (1)	2	-	10
PNFI 602 #1	MJP	620614	24.4	44	5	103	8.5	-	9
PNFI 602 #2	MJP	620810	22.2	45	10	115	8.5	-	10
PNFI 602 #3	MJP	630624	28.3	28	8	105	8.5	-	7
PNFI 602 #4	MJP	630703	14.4	56	23	110	8.5	-	11
PNFI 602 #5	MJP	630731	25	34	6	118	8.5	-	8
SC corner	MJP	640611	21.1	44	13	100	6	-	9
Sharpsand thinned #1	MJP	740627	27	32	11	85 (1)	-	-	8
Sharpsand thinned #8	MJP	760628	22	39	14	85 (1)	-	-	8
Sharpsand thinned #9	MJP	760705	30.5	23	8	107 (1)	-	-	6
Sharpsand thinned #10	MJP	760706	29	35	15	107 (1)	-	-	8
Sharpsand thinned #15	MJP	810711	29	37	14	112 (1)	-	-	8
Sharpsand thinned #16	MJP	810712	26	65	9	113 (1)	-	-	11
Prince George #124	LP	700617	25.6	14	8.1	110 (1)	9.6	10.9	5
Prince George #123	LP	700618	22.8	14	12.9	110	9.6	7.1	5
Prince George #119	LP	700619	26.1	21	9.7	110	9.6	8.8	6
Prince George #120	LP	700620	27.8	15	6.4	110	9.6	10.3	5
Prince George #430	LP	700705	22.2	22	6.4	110	6.6	6.6	6
Prince George #433	LP	700712	22.2	16	6.4	110	6.6	9.3	5

Table A.2. Continued

Fire name	Fuel Type	Date	T_a (°C)	RH (%)	U_{10} (km/h)	FMC (%)	FSG (m)	M_{ffm} (%)	M_{ffe} (2) (%)
Prince George #431	LP	700713	23.3	18	9.7	110	6.6	9.1	5
Prince George #432	LP	700714	24.4	26	6.4	110	6.6	15.6	7
Sharpsand #2	IMJP	750626	25.5	40	11	109 (1)	4	11	9
Sharpsand #3	IMJP	750626	25.5	40	16	109 (1)	4	11	9
Sharpsand #4	IMJP	750627	27	52	14	109 (1)	4	15	10
Sharpsand #5	IMJP	750630	30.5	33	10	110 (1)	4	9	8
Sharpsand #6	IMJP	750701	29.5	48	11	113 (1)	4	9	10
Sharpsand #7	IMJP	760604	27	30	6	102 (1)	4		8
Sharpsand #11A	IMJP	760706	29	35	13	112 (1)	4	10.9	8
Sharpsand #11B	IMJP	760706	29	35	21	112 (1)	4	10.9	8
Sharpsand #12	IMJP	760709	25	40	14	113 (1)	4	12.5	9
Sharpsand #13	IMJP	760709	25	40	15	114 (1)	4	12.5	9
Sharpsand #14	IMJP	760713	22	36	16	115 (1)	4	14.4	8
Sharpsand #17	IMJP	810713	27	42	10	114 (1)	4	9	9
Sharpsand #18	IMJP	810715	25	46	7	115 (1)	4	-	10
Sharpsand #3/91	IMJP	910619	29.4	26	19	107 (1)	4	8	7
PNFI R1	RP	620608	-	-	14.9	95	7	10	10
PNFI R3	RP	630625	-	-	13	92	7	9	9
PNFI R4	RP	630723	-	-	11	100	7	13	13
PNFI R5	RP	630827	-	-	6	108	7	4	9
PNFI C4	RP	660714	-	-	23	135	7	12	12
PNFI C6	RP	670531	-	-	19.2	95	7	12	12
Big Fish P12	BS	850711	20.5	35	14	105	0.4	-	8
Big Fish P1 A	BS	850712	18.5	36	12	105	0.4	-	9
Big Fish P9 A	BS	850720	21.5	38	10	110	0.4	-	8
Big Fish P11	BS	850810	19	38	14	110	0.4	-	9
Big Fish P21	BS	850817	23.5	37	16	110	0.4	-	8
Big Fish P4 A	BS	860717	20	56	13	105	0.4	-	11
Big Fish P18	BS	860721	22.5	58	14	110	0.4	-	11
Big Fish P17	BS	860803	27.5	36	5	110	0.4	-	8

Table A.2. Continued

Fire name	Fuel Type	Date	T_a (°C)	RH (%)	U_{10} (km/h)	FMC (%)	FSG (m)	M_{ffm} (%)	M_{ffe} (2) (%)
Hondo #1	BS	780726	26.5	42	5	109	1.9	10.8	9
Hondo #2	BS	780726	26.5	42	5	109	1.4	11.3	9
ADK	BS	720713	22.8	38	18.7	80	1.5	10	8
Darwin Lake #4a	MJP	740803	29	40	8.5	117	2.8	-	9
Darwin Lake #4b	MJP	740804	31	26	8.5	117	2.8	-	7
Darwin Lake #6	MJP	740805	31.5	33	16.9	117	5.6	-	7
Darwin Lake #7	MJP	740806	23	46	8.5	117	5.6	-	10
GL-A	MJP	640507	27.2	25	23	100	12	8	7
GL-B	MJP	640507	27.2	25	23	100	6	8	7
BWR88#1	MP	-	21	27	20	120	3.9	-	7
BWR88#2	MP	-	23	22	22	120	4.2	-	6
BWR88#3	MP	-	25	30	24	120	3.6	-	8
VLL73#A2	MP	-	30.6	50	15	109	2.44	-	10

Fuel Types: IMJP – immature jack pine, MJP – mature jack pine, BS – black spruce, RP – red pine; LP – Lodgepole pine; MP – Maritime pine; Ta – air temperature; RH – relative humidity; U_{10} – wind speed at 10 meters; FMC – foliar moisture content; FSG – height of crown base; Mff_m – measured fine fuel moisture content; Mff_e – estimated fine fuel moisture content.

(1) - estimated from Fire Danger Group (1992);

(2) - estimated from Rothermel (1983).

Table A.3. Fire database used in the probabilistic crown fire initiation model building – Fire behavior

Fire name	ROS (m/min)	DMC	DC	BUI	SFC (kg/m^2)	I_B (kW/m)	Fire type	I_{prob}	Source
Kenshoe #1	0.9	33	79	33	0.69	186	Surface	0.13	Stocks, 1989
Kenshoe #2	1.9	35	84	35	1.19	718	Surface	0.86	Stocks, 1989
Kenshoe #3	1.8	35	84	35	1.16	740	Surface	0.86	Stocks, 1989
Kenshoe #4	0.7	30	117	36	0.7	147	Surface	0.33	Stocks, 1989
Kenshoe #5	15.4	28	65	28	0.88	8455	Crown	1.00	Stocks, 1989
Kenshoe #6	0.5	35	78	35	0.83	125	Surface	0.02	Stocks, 1989
Kenshoe #7	1.5	19	86	25	0.43	194	Surface	0.12	Stocks, 1989
Kenshoe #8	1.6	23	92	28	0.62	298	Surface	0.38	Stocks, 1989
Kenshoe #9	4.3	42	145	49	1.54	3264	Crown	0.98	Stocks, 1989
Kenshoe #10	1.7	29	160	40	0.68	454	Surface	0.17	Stocks, 1989
Kenshoe #11	3.6	34	169	46	0.8	1350	Surface	0.47	Stocks, 1989
Kenshoe #12	10.2	39	178	50	1.07	5110	Crown	0.98	Stocks, 1989
PNFI 602 #1	1.1	51	225	65	1.1	377	Surface	0.01	Weber et al. 1987
PNFI 602 #2	0.4	28	308	45	0.49	66	Surface	0.00	Weber et al. 1987
PNFI 602 #3	2.6	37	222	52	0.4	318	Surface	0.00	Weber et al. 1987
PNFI 602 #4	4.5	76	299	93	2.73	3834	Crown	0.96	Weber et al. 1987
PNFI 602 #5	2.1	66	423	95	2.16	1429	Surface	0.09	Weber et al. 1987
SC corner	15	77	195	77	2.56		Crown	0.84	Van Wagner 1977; Weber et al. 1987
Sharpsand thinned #1	10	29	60	29	0.93	3960	Crown		Alexander 1999
Sharpsand thinned #8	3.6	41	210	55	1.53	1652	Surface		Alexander 1999
Sharpsand thinned #9	1.3	38	213	53	1.15	449	Surface		Alexander 1999
Sharpsand thinned #10	2.6	43	222	58	1.18	1303	Crown		Alexander 1999
Sharpsand thinned #15	2.6	45	170	54	0.83	819	Crown		Alexander 1999
Sharpsand thinned #16	1	47	179	57	1.02	330	Surface		Alexander 1999
Prince George #124	0.9	64	161	64	0.53	154	Surface	0.00	Lawson 1972
Prince George #123	1.2	68	168	68	0.28	119	Surface	0.02	Lawson 1972
Prince George #119	2	72	175	72	1.24	762	Surface	0.05	Lawson 1972
Prince George #120	1	77	183	77	0.19	69	Surface	0.00	Lawson 1972
Prince George #430	0.9	33	215	47	0.19	62	Surface	0.01	Lawson 1972
Prince George #433	1.1	54	264	72	0.41	149	Surface	0.01	Lawson 1

Table A.3. Continued

Fire name	ROS (m/min)	DMC	DC	BUI	SFC (kg/m^2)	I_B (kW/m)	Fire type	I_{prob}	Source
Prince George #431	1.2	58	271	76	0.56	220	Surface	0.04	Lawson 1972
Prince George #432	1.1	62	279	79	1.15	396	Surface	0.08	Lawson 1972
Sharpsand #2	10.7	25	73	27	0.66	4976	Crown	0.31	Stocks, 1987
Sharpsand #3	16.9	25	73	27	0.91	10495	Crown	0.74	Stocks, 1987
Sharpsand #4	14.3	28	82	30	0.92	8194	Crown	0.51	Stocks, 1987
Sharpsand #5	14.6	44	108	44	1.33	11388	Crown	0.85	Stocks, 1987
Sharpsand #6	14.6	48	117	48	1.16	9724	Crown	0.82	Stocks, 1987
Sharpsand #7	2.1	39	100	40	0.95	599	Surface	0.09	Stocks, 1987
Sharpsand #11A	29.3	43	222	58	1.52	25667	Crown	0.94	Stocks, 1987
Sharpsand #11B	49.4	43	222	58	1.52	43274	Crown	1.00	Stocks, 1987
Sharpsand #12	20.2	50	245	67	1.96	18180	Crown	0.95	Stocks, 1987
Sharpsand #13	16.2	50	245	67	2.41	16718	Crown	0.99	Stocks, 1987
Sharpsand #14	27.3	52	272	70	2.25	27518	Crown	1.00	Stocks, 1987
Sharpsand #17	7.9	51	187	61	1.71	5143	Crown	0.80	Stocks, 1987
Sharpsand #18	0.7	57	203	67	1.47	309	Surface	0.50	Stocks, 1987
Sharpsand #3/91	49.4	57	231	70		45200	Crown	1.00	Stocks, 1987
PNFI R1	10.7	64	190	70	2.2	11877	Crown	0.80	Van Wagner 1968
PNFI R3	6.1	48	240	64	1.05	1921	Crown	0.31	Van Wagner 1968; 1977
PNFI R4	1.5	39	362	61	0.98	441	Surface	0.01	Van Wagner 1968; 1977
PNFI R5	2	21	400	38	1.46	876	Surface	0.03	Van Wagner 1968; 1977
PNFI C4	16.8	89	352	109	1.91	18446	Crown	0.89	Van Wagner 1968; 1977
PNFI C6	27.4	41	86	41	1.32	25235	Crown	0.65	Van Wagner 1968; 1977
Big Fish P12	18.5	22	251	36	1.73	13431	Crown	0.99	FBP database; Alexander, 1999
Big Fish P1 A	14.3	16	224	27	1.86	13085	Crown	0.96	FBP database; Alexander, 1999
Big Fish P9 A	30	15	260	26	0.78	15480	Crown	0.55	FBP database; Alexander, 1999
Big Fish P11	17.5	16	292	28	2.34	15907	Crown	1.00	FBP database; Alexander, 1999
Big Fish P21	15	11	257	20	1.07	9945	Crown	0.99	FBP database; Alexander, 1999
Big Fish P4 A	4	9	69	13	0.93	1524	Surface	0.61	FBP database; Alexander, 1999
Big Fish P18	5.2	12	96	18	0.94	2496	Surface	0.69	FBP database; Alexander, 1999
Big Fish P17	10.7	16	103	24	1.51	6581	Crown	0.71	FBP database; Alexander, 19

Table A.3. Continued

Fire name	ROS (m/min)	DMC	DC	BUI	SFC (kg/m^2)	I_B (kW/m)	Fire type	I_{prob}	Source
Hondo #1	6.4	44	306	65	1.67	5645	Crown	0.41	Newstead and Alexander 1983
Hondo #2	7.5	44	306	65	2.29	7853	Crown	0.85	Newstead and Alexander 1983
ADK	6.6	27	250	43	1.88	4198	Crown	0.99	Kiil 1975
Darwin Lake #4a	2	31	222	46	1.54	924	Surface	0.58	Quintilio et al. 1977
Darwin Lake #4b	3.3	36	231	52	1.86	1841	Crown	0.71	Quintilio et al. 1977
Darwin Lake #6	6.1	41	239	57	3.23	7174	Crown	0.98	Quintilio et al. 1977
Darwin Lake #7	2	43	246	60	2.03	1218	Surface	0.49	Quintilio et al. 1977
GL-A	12	54	102	54	1.22	4800	Surface	0.54	Van Wagner 1965
GL-B	24.6	54	102	54	1.22	18300	Crown	0.98	Van Wagner 1965
BWR88#1	3				1.2	1104	Crown	0.99	Burrows et al. 1988 in Alexander 1999
BWR88#2	3.336				1.21	1237	Crown	0.99	Burrows et al. 1988 in Alexander 1999
BWR88#3	2.634				1.18	953	Crown	1.00	Burrows et al. 1988 in Alexander 1999
VLL73#A2	3.828				0.91	2100	Crown	0.53	Van Lonn and love 1973 in Alexander 1999

ROS – Fire spread rate; DMC- Duff moisture code (Van Wagner 1987), DC Drought code (Van Wagner 1987), BUI – Buildup index (Van Wagner 1987); SFC – Surface fuel consumption; I_B – Byram's fireline intensity; Iprob – Probability of crown fire initiation [Eq. 2.5].

Table A.4. Crown fire database used in crown fire spread model building – Fire environment characteristics

Fire name	Fuel Type	Date (dd/mm/yy)	T_a (°C)	RH (%)	U_{10} (km/h)	FMC (%)	HCB (m)	SH (m)	M_{ffm} (%)	M_{ffe} (3) (%)
Sharpsand #2	IMJP	June 26, 75	25.5	40	11	109(1)	4	10	11	9
Sharpsand #3	IMJP	June 26, 75	25.5	40	16	109(1)	4	10	11	9
Sharpsand #4	IMJP	June 27, 75	27	52	14	109(1)	4	10	15	10
Sharpsand #5	IMJP	June 30, 75	30.5	33	10	110(1)	4	10	9	8
Sharpsand #6	IMJP	July 1, 75	29.5	48	11	113(1)	4	10	9	10
Sharpsand #11a	IMJP	July 6, 76	29	35	13	112(1)	4	10	10.9	8
Sharpsand #11b	IMJP	July 6, 75	29	35	21	112(1)	4	10	10.9	8
Sharpsand #12	IMJP	July 9, 76	25	40	14	113(1)	4	10	12.5	9
Sharpsand #13	IMJP	July 9, 76	25	40	15	114(1)	4	10	12.5	9
Sharpsand #14	IMJP	July 13, 76	22	36	16	115(1)	4	10	14.4	8
Sharpsand #17	IMJP	July 13, 81	27	42	10	114(1)	4	10	9	9
Sharpsand #3/91	IMJP	June 19, 91	29.4	26	19	110(1)	4	10	8	7
Kenshoe #5	MJP	May 17, 75	23	39	29	102(1)	2	19	8	8
Kenshoe #9	MJP	July 8, 79	27	45	18	118(1)	2	19	10	10
Kenshoe #12	MJP	June 21, 83	29.2	48	18	113(1)	2	19	10	10
Darwin lake #4b	MJP	August 4, 74	31	26	8.5	117(1)	2.8	10	8	7
Darwin lake #6	MJP	August 5, 74	30.5	33	16.9	117(1)	5.6	15	9	7
Porter lake #1	BS	June 30, 82	26.5	30	20.4	91.4	0.9	4.1	5	8
Porter lake #2	BS	July 1, 82	20.5	50	24	108.3	0.8	4.3	6	7
Porter lake #3	BS	July 5, 82	20	28	17	80.8	1	5.2	8.1	8
Porter lake #4	BS	July 6, 82	21.5	36	14.5	75	0.8	4.1	7.7	8
Porter lake #5	BS	July 7, 82	27.5	31	28	78	1.1	5.6	7.1	8
Porter lake #5a	BS	July 7, 82	27.5	31	34.6	78	1.1	5.6	7.1	8
Porter lake -CR-6	BS	July 7, 82	27	32	26	78	1	4.8	7.1	8
VW C6	RP	May 31, 67		25	19	95	7	14	12	12
VW C4	RP	July 14, 66		32	23	135	7	14	12	12
VW R1	RP	June 8, 62			14.9	95	7	14	10	10

Table A.4. Continued

Fire name	Fuel Type	Date (dd/mm/yy)	T_a (°C)	RH (%)	U_{10} (km/h)	FMC (%)	HCB (m)	SH (m)	M_{ffm} (%)	M_{ffe} (3) (%)
VW GL-A	MJP	May 7, 64	27.2	25	23	100(2)	12	20	8	7
VW GL-B	MJP	May 7, 64	27.2	25	23	100(2)	4	18	8	7
PFNI SC	MJP	June 11, 64	21	44	13	102(2)	6	18		9
HONDO #1	BS	July 26, 78	26.5	42	5	109	1.9	5.3	10.8	9
HONDO #2	BS	July 26, 78	26.5	42	5	109	1.4	4.2	11.3	9
PNFI 602#4	MJP.	July 3, 63	14.4	56	23	110(2)	12	19		11
Sharp Thin #1	MJP.	June 27, 74	27	32	11	110(1)				8
Sharp Thin #10	MJP.	July 6, 76	29	35	15	110(1)				8
Sharp Thin #15	MJP	July 11, 81	29	37	14	110(1)				8
ADK	BS	July 13, 72	22.8	38	18.7	80	1.5	4.4	10	8
Big Fish Lake P12	BS	July 11, 85	20.5	35	14	105	0.4	3.1		8
Big Fish Lake P1 A	BS	July 12, 85	18.5	36	12	105	0.4	3.1		9
Big Fish Lake P9 A	BS	July 20, 85	21.5	38	10	110	0.4	3.4		8
Big Fish Lake P11	BS	August 10, 85	19	38	14	110	0.4	2.9		9
Big Fish Lake P21	BS	August 17, 85	23.5	37	16	110	0.4	3		8
Big Fish Lake P17	BS	August 3, 86	27.5	36	5	110	0.4	3.2		8

Fuel Types: IMJP – immature jack pine, MJP – mature jack pine, BS – black spruce, RP – red pine; Ta – air temperature; RH – relative humidity; U10 – wind speed at 10 meters; FMC – foliar moisture content; HCB – height of crown base; SH – stand height; Mffm – measured fine fuel moisture content; Mffe – estimated fine fuel moisture content.

(1) - estimated from Fire Danger Group (1992);

(2) - estimated from Van Wagner (1967);

(3) - estimated from Rothermel (1983).

TableA.5. Crown fire database used in crown fire spread model building – Fire environment characteristics II

Fire name	DMC	DC	BUI	SFC (km/m2)	W_l (kg/m2)	W_{cn} (kg/m2)	W_{cd} (kg/m2)	W_{ct} (kg/m2)	CBD (kg/m3)	Source:
Sharpsand #2	25	73	27	0.66	0.119	0.939	0.654	1.593	0.266	Stocks, 1987
Sharpsand #3	25	73	27	0.91	0.189	0.622	0.412	1.034	0.172	Stocks, 1987
Sharpsand #4	28	82	30	0.92	0.228	0.718	0.727	1.445	0.241	Stocks, 1987
Sharpsand #5	44	108	44	1.33	0.214	0.782	0.649	1.431	0.239	Stocks, 1987
Sharpsand #6	48	117	48	1.16	0.203	0.836	0.563	1.399	0.233	Stocks, 1987
Sharpsand #11a	43	222	58	1.52	0.124	0.888	0.568	1.456	0.243	Stocks, 1987
Sharpsand #11b	43	222	58	1.52	0.124	0.888	0.568	1.456	0.243	Stocks, 1987
Sharpsand #12	50	245	67	1.96	0.248	0.646	0.565	1.211	0.202	Stocks, 1987
Sharpsand #13	50	245	67	2.41	0.292	0.977	0.754	1.731	0.289	Stocks, 1987
Sharpsand #14	52	272	70	2.25	0.369	0.682	0.549	1.231	0.205	Stocks, 1987
Sharpsand #17	51	187	61	1.71	0.382	0.853	0.689	1.542	0.257	Stocks, 1987
Sharpsand #3/91	57	231	70		0.227	0.803	0.609	1.412	0.235	Stocks and Hartley, 1995
Kenshoe #5	28	65	28	0.88	0.12	0.715	0.695	1.41	0.083	Stocks, 1989
Kenshoe #9	42	145	49	1.54	0.12	0.535	0.744	1.279	0.075	Stocks, 1989
Kenshoe #12	39	178	50	1.07	0.04	0.591	1.128	1.719	0.101	Stocks, 1989
Darwin lake #4b	36	231	52	1.86	0.37	0.832	0.198	1.03	0.143	Quintilio et al. 1977
Darwin lake #6	41	239	61	3.23	0.56	0.687	0.144	0.831	0.088	Quintilio et al. 1977
Porter lake #1	62	204	71	1.12	1.12	1.02		1.02	0.319	Alexander et al. 1991
Porter lake #2	66	212	74	1.42	1.42	0.41		0.41	0.117	Alexander et al. 1991
Porter lake #3	51	240	67	1.55	1.55	0.96		0.96	0.229	Alexander et al. 1991
Porter lake #4	55	247	71	1.18	1.18	0.58		0.58	0.176	Alexander et al. 1991
Porter lake #5	59	256	75	1.21	1.21	0.81		0.81	0.180	Alexander et al. 1991
Porter lake #5a	59	256	75	1.39	1.39	0.81		0.81	0.180	Alexander et al. 1991
Porter lake -CR-6	59	256	75	1.39	1.31	0.77		0.765	0.201	Alexander et al. 1991
VW C6	41	86	41	1.32	0.3	1.8		1.8	0.257	Van Wagner, 1968; 1977
VW C4	89	352	109	1.91	0.3	1.8		1.8	0.257	Van Wagner, 1968; 1977
VW R1	64	190	70	2.2	0.3	1.8		1.8	0.257	Van Wagner, 1968; 1977

Table A.5. Continued

Fire name	DMC	DC	BUI	SFC (km/m2)	W_l (kg/m2)	W_{cn} (kg/m2)	W_{cd} (kg/m2)	W_{ct} (kg/m2)	CBD (kg/m3)	Source:
VW GL-A	54	102	54	1.22	0.3	0.8		0.8	0.100	Van Wagner, 1965; 1977
VW GL-B	54	102	54	1.22	0.3	1.22		1.22	0.087	Van Wagner, 1965; 1977
PFNI SC	77	195	77	2.56	0.3	0.5		0.5	0.042	Van Wagner, 1977
HONDO #1	44	306	65	1.67		1.27		1.27	0.374	Newstead and Alexander 1983
HONDO #2	44	306	65	2.29		1.2		1.2	0.429	Newstead and Alexander 1983
PNFI 602#4	75	304	95	2.73		0.8		0.8	0.114	Weber et al. 1987
Sharp Thin #1	29	60	29	0.93						FBP database
Sharp Thin #10	43	222	58	1.18						FBP database
Sharp Thin #15	45	170	54	0.83						FBP database
ADK	27	250	43	1.88		0.13		0.13	0.045	Kill, 1975
Big Fish Lake P12	22	251	36	1.73		1.01		1.01	0.374	FBP database; Alexander, 1999
Big Fish Lake P1 A	16	224	27	1.86		1.3		1.3	0.481	FBP database; Alexander, 1999
Big Fish Lake P9 A	15	260	26	0.78		1.09		1.09	0.363	FBP database; Alexander, 1999
Big Fish Lake P11	16	292	28	2.34		0.82		0.82	0.328	FBP database; Alexander, 1999
Big Fish Lake P21	11	257	20	1.07		1.23		1.23	0.473	FBP database; Alexander, 1999
Big Fish Lake P17	16	103	24	1.51		0.74		0.74	0.264	FBP database; Alexander, 1999

DMC, DC and BUI are codes from the FWI (Van Wagner 1987), respectively, duff moisture code, drought code and buildup index; SFC – Surface fuel consumption; Wl – litter fuel load; Wcn – crown needles fuel load; Wco – other corwn fuels load; Wct – total crown fuel load; CBD – canopy bulk density;

Table A.6. Crown fire database used in crown fire spread model building – Fire behavior

Fire name	ROS (m/min)	h (kJ/kg)	S (kg/m2*min)	E (kW/m2)	I_B (kW/m)	CFI	CSR	IC	SRC
Sharpsand #2	10.74	3277.7	2.85	155.8	4717	1512	11	3	0.95
Sharpsand #3	16.88	3277.7	2.91	158.9	9900	1512	17	7	0.97
Sharpsand #4	14.28	3277.7	3.44	187.9	7728	1512	12	5	1.15
Sharpsand #5	14.64	3303.5	3.49	192.2	10785	1530	13	7	1.16
Sharpsand #6	14.58	3381.1	3.40	191.6	9171	1585	13	6	1.13
Sharpsand #11a	29.34	3355.2	7.12	398.1	24274	1566	12	15	2.37
Sharpsand #11b	49.44	3355.2	12.00	670.9	40903	1566	12	26	4.00
Sharpsand #12	20.16	3381.1	4.07	229.3	17136	1585	15	11	1.36
Sharpsand #13	16.2	3406.9	4.67	265.4	15790	1603	10	10	1.56
Sharpsand #14	27.3	3432.8	5.60	320.5	25990	1621	15	16	1.87
Sharpsand #17	7.86	3406.9	2.02	114.7	4833	1603	12	3	0.67
Sharpsand #3/91	49.4	3303.5	11.62	640.0	45200	1530	13	30	3.87
Kenshoe #5	15.36	3096.7	1.27	65.8	7964	491	36	16	0.42
Kenshoe #9	4.26	3510.3	0.32	18.8	3054	593	40	5	0.11
Kenshoe #12	10.2	3381.1	1.03	58.1	4826	560	30	9	0.34
Darwin lake #4b	3.35	3484.5	0.48	27.8	1900	971	21	2	0.16
Darwin lake #6	6.1	3484.5	0.54	31.3	7460	2746	34	3	0.18
Porter lake #1	6.1	2822.7	1.94	91.5	3184	129	9	25	0.65
Porter lake #2	26.3	3259.6	3.08	167.4	13650	134	26	102	1.03
Porter lake #3	3.5	2548.7	0.80	34.0	2131	130	13	16	0.27
Porter lake #4	3.7	2398.8	0.65	26.0	1698	85	17	20	0.22
Porter lake #5	33.3	2476.3	5.99	247.4	18082	143	17	126	2.00
Porter lake #5a	51.4	2476.3	9.25	381.8	33153	143	17	232	3.08
Porter lake -CR-6	31.9	2476.3	6.42	265.0	19332	124	15	156	2.14
VW C6	27.6	2915.8	7.10	344.9	22500	2937	12	8	2.37
VW C4	16.8	3949.8	4.32	284.4	21100	4633	12	5	1.44
VW R1	10.8	2915.8	2.78	135.0	7300	2937	12	2	0.93

Table A.6. Continued

Fire name	ROS (m/min)	h (kJ/kg)	S (kg/m2*min)	E (kW/m2)	I_B (kW/m)	CFI	CSR	IC	SRC
VW GL-A	12	3045.0	1.20	60.9	4800	7036	30	1	0.40
VW GL-B	24.6	3045.0	2.14	108.8	18300	1354	34	14	0.71
PFNI SC	15	3096.7	0.63	32.3	17000	2551	72	7	0.21
HONDO #1	6.4	3277.7	2.39	130.6	3680	495	8	7	0.80
HONDO #2	7.5	3277.7	3.21	175.6	4230	313	7	13.51	1.07
PNFI 602#4	4.5	3303.5	0.51	28.3	3800	7952	26	0.48	0.17
Sharp Thin #1	10	3303.5			3960				
Sharp Thin #10	2.6	3303.5			1303				
Sharp Thin #15	2.6	3303.5			819				
ADK	6.6	2528.0	0.30	12.5	4198	235	67	18	0.10
Big Fish Lake P12	18.5	3174.3	6.92	366.1	13431	46	8	295	2.31
Big Fish Lake P1 A	14.3	3174.3	6.89	364.3	13085	46	6	287	2.30
Big Fish Lake P9 A	30	3303.5	10.90	600.1	15480	48	8	320	3.63
Big Fish Lake P11	17.5	3303.5	5.74	316.0	15907	48	9	329	1.91
Big Fish Lake P21	15	3303.5	7.10	390.7	9945	48	6	205	2.37
Big Fish Lake P17	10.7	3303.5	2.83	155.7	6581	48	11	136	0.94

ROS – fire spread rate; h fuel heat of ignition (from equation [1.4]); S – mass flow rate of fuel; E – net horizontal heat flux; IB – frontal fire intensity; CFI – critical fire intensity; CSR – critical spread rate; IC – intensity criterion; SRC – spread rate criterion.

Table A.7. Wildfire database used in crown fire spread model evaluation

FNUM	Date	T_a (°C)	RH (%)	M_{ffe} (%)	U_{10} (km/h)	BUI	ROS (m/min)	SFC (kg/m^2)	I_{prob}	ROS_p (m/min)	ROS_{91} (m/min)	Fire Name	Source
WFDB#1	800502	28.3	16	5	36	76	60	2.34	1.00	78.4	22.4	DND-4-80	Alexander et al. 1983
WFDB#2	800505	26.7	24	6	33	35	56.3	0.78	1.00	61.3	17.0	Mack Lake	Simard et al. 1983
WFDB#3	800709	27	35	8	20	77	19.7	2.37	1.00	28.3	8.7	Chachukew #116	De Groot and Alexander 1986
WFDB#4	810703	19.8	50	10	13	151	10.7	4.12	0.99	13.9	5.3	Hay River 36-81 A	Alexander and Lanoville 1987
WFDB#5	810703	20	48	10	15	151	22.8	4.12	1.00	15.7	5.3	Hay River 36-81 B	Alexander and Lanoville 1987
WFDB#6	810703	19.8	52	10	26	151	34.8	4.12	1.00	25.2	11.4	Hay River 36-81 C	Alexander and Lanoville 1987
WFDB#7	830707	23.1	31	8	20	66	18	2.66	1.00	28.3	8.7	Ft. Simpson 40-83 A	Lanoville and Sbhmidt 1984
WFDB#8	830708	21.2	41	9	19	66	16	2.66	1.00	22.8	8.4	Ft. Simpson 40-83 B	Lanoville and Sbhmidt 1984
WFDB#9	850829	22.2	19	6	17	29	18.2	4.7	1.00	34.6	8.0	Butte	Rothermel and Mutch
WFDB#10	860528	33	23	6	15	79	33.1	2.44	1.00	31.0	6.3	Red Lake7-86 A	Stocks and Flannigan 1987
WFDB#11	860528	33	23	6	22	47	41.7	1.24	1.00	43.2	11.0	Red Lake 14-86	Stocks 1987
WFDB#12	860528	33	23	6	22	47	47.7	1.24	1.00	43.2	11.0	Red Lake 5-86	Stocks 1987
WFDB#13	860529	34	28	7	15	86	36.7	2.67	1.00	26.2	6.0	Red Lake 7-86	Stocks 1987
WFDB#14	880501	20.4	24	7	48	34	57.7	0.74	1.00	71.4	29.7	Gull Lake A	Hirsch 1989
WFDB#15	880501	20.4	24	7	45	34	54.8	0.74	1.00	67.5	27.4	Gull Lake B	Hirsch 1989
WFDB#16	880501	22.5	27.5	7	30	58	23.3	1.68	1.00	47.6	14.4	Breteron Lake	Hirsch 1989
WFDB#17	880430	22.3	31	8	19.6	32	21.6	0.67	0.96	27.8	8.7	Kenora #14/88 A	Hirsch 1989
WFDB#18	880502	22.3	22	7	21.5	36	30.2	0.82	0.99	35.7	9.0	Kenora #14/88 B	Hirsch 1989
WFDB#19	880502	22.3	22	7	15	40	17.7	0.97	0.86	26.2	6.0	Kenora #14/88 C	Hirsch 1989

T_a. – Air temperature; RH – Relative humidity; M_{ffe} – Estimated fine fuel moisture content; U_{10} – Windspeed at 10 meters; BUI – Buildup index (FWI code); ROS – Observed rate of spread; SFC – Surface fuel consumption (Estimated from equation in Fire Danger Group 1992); I_{prob} – Probability of crown fire occurrence (Eq. 2.5); ROS_p – Predicted ROS by Eq. 3.5.; ROS_{91} – Predicted ROS by Rothermel (1991a) crown fire spread model.

Table A.8. Equations used to estimate foliage load

Species	Code	Equation	Observations	Units	Author
Black spruce *Picea mariana*	BS	$W = 0.93372 + 0.00457 dbh^{2.67088}$	Do/Co In/Su	W in Kg Dbh in cm	Stocks 1980
Douglas fir *Pseudotsuga menziesii*	DF	$W = \exp(1.1368 + 1.5819 * \ln dbh)$ $W = -20.74 + 1.0237 dbh^2$ $W = \exp(0.1508 + 1.862 * \ln dbh)$ $\% foliage = 0.484 * \exp(-0.021 dbh)$	Do/Co Ø<42.8cm Do/Co Ø<42.8cm In/Su	W in lb. Dbh in in.	Brown 1978
Lodgepole pine *Pinus contorta*	LP	$W = \exp(0.1224 + 1.882 * \ln dbh)$ $\% foliage = 0.493 - 0.0117 dbh$	Do/Co	W in lb. Dbh in in.	Brown 1978
Ponderosa pine *Pinus ponderosa*	PP	$W = \exp(0.268 + 2.074 * \ln dbh)$ $W = \exp(-0.7572 + 2.216 * \ln dbh)$ $\% foliage = 0.558 * \exp(-0.0475 dbh)$	Do/Co In/Su	W in lb. Dbh in in	Brown 1978
Subalpine fir *Abies lasiocarpa*	SAF	$W = 7.345 + 1.255 dbh^2$ $\% foliage = 0.597 * \exp(-0.0425 * dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978
Western hemlock *Tsuga heterophylla*	WH	$W = \exp(0.7218 + 1.7502 dbh)$ $\% foliage = 0.597 * \exp(-0.037 dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978
Western larch *Larix occidentallis*	WL	$W = \exp(0.4373 + 1.6786 * \ln dbh)$ $\% foliage = 0.347 * \exp(-0.0434 dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978
Western redcedar *Thuja plicata*	WRD	$W = \exp(0.8815 + 1.6389 * \ln dbh)$ $W = \exp(0.5743 + 1.796 * \ln dbh)$ $\% foliage = 0.617 * \exp(-0.0233 dbh)$	Do/Co In/Su	W in lb. Dbh in in	Brown 1978
Western white pine *Pinus monticola*	WWP	$W = \exp(0.7276 + 1.5497 dbh)$ $\% foliage = 0.55 * \exp(-0.0345 dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978
Whitebark pine *Pinus albicaulis*	WBP	$W = -1 + 0.8371 dbh$ $\% foliage = 0.512 * \exp(-0.0374 dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978

Table A.8. Continued

Species	Code	Equation	Observations	Units	Author
Aspen *Populus Tremuloides*	A	$W = 0.0079 dbh^{2.101}$	Do/Co	W in Kg Dbh in cm	Loomis and Roussopoulos 1978
Engelmann spruce *Picea engelmanni*	ES	$W = \exp(1.0404 + 1.7096 \ln dbh)$ $\% foliage = 0.578 * \exp(-0.0325 dbh)$	Do/Co	W in lb. Dbh in in	Brown 1978
Grand fir *Abies grandis*	GF	$W = \exp(1.3094 + 1.676 \ln dbh)$ $W = \exp(1.0144 + 1.6156 \ln dbh)$ $\% foliage = \frac{1}{1.592 + 0.0539 dbh}$	Do/Co In/Su	W in lb. Dbh in in	Brown 1978
White spruce *Picea glauca*	WS	$W = 2.91325 - 2.09655 dbh + 0.44974 dbh^2$	Do/Co In/Su	W in kg. Dbh in in	Stiell 1969

Do – Dominant; Co – Codominant; In – Intermediate, Su – Suppressed. W – is foliage weight; Dbh is diameter at breast height

Table A.9. Data origin, sample size and coefficient of determination of equations listed in Table A.8

Species	Data origin	n	Observ.	R2	Author	Basal area range (m^2/ha)	Stand density range (n/ha)
Black spruce	Ontario, Canada	62	Do/Co In/Su	0.75	Stocks 1980	10 - 29	1150 – 4650
Douglas-fir	Montana / Idaho	41	Do/Co	0.95	Brown 1978	0.5 – 55	52 – 17790
	Montana / Idaho	15	In/Su	0.96	Brown 1978		
Lodgepole pine	Montana / Idaho	45	Do/Co	0.88	Brown 1978	0.2 – 62	741 – 19718
Ponderosa pine	Montana / Idaho	40	Do/Co	0.95	Brown 1978	0.2 – 75	12 – 17790
	Montana / Idaho	15	In/Su	0.90	Brown 1978		
Subalpine fir	Montana / Idaho	16	Do/Co	0.84	Brown 1978	0.2 – 60	214 – 37363
Western hemlock	Montana / Idaho	27	Do/Co	0.98	Brown 1978	0.2 – 34	2095 - 17790
Western larch	Montana / Idaho	45	Do/Co	0.96	Brown 1978	0.2 – 20	1482 – 19273
Western redcedar	Montana / Idaho	34	Do/Co	0.96	Brown 1978	10 – 77	417 – 8922
	Montana / Idaho	13	In/Su	0.94	Brown 1978		
Western white pine	Montana / Idaho	44	Do/Co	0.95	Brown 1978	0.2 – 32	741 – 19273
Whitebark pine	Montana / Idaho	10	Do/Co	0.98	Brown 1978	0.2 – 42	1139 – 15626
Aspen	Minnesota	15	Do/Co	0.97	Loomis and Roussopoulos 1978		
Engelmann spruce	Montana / Idaho	29	Do/Co	0.96	Brown 1978	0.2 – 42	1482 – 31455
Grand fir	Montana / Idaho	35	Do/Co	0.95	Brown 1978	9 - 68	887 – 14341
	Montana / Idaho	15	In/Su	0.92	Brown 1978		
White spruce	Ontario, Canada	43	Do/Co In/Su	0.89	Stiell 1969		