Photo: E. Desnoyers, AESRD

Crown Fire Behaviour in Conifer Forests

by Marty Alexander, University of Alberta and

Miguel Cruz, CSIRO Land & Water Flagship

Wildland Fire Lessons Learned Center Monthly Webinar Series – May 7, 2015

Good day! Your presenters today:

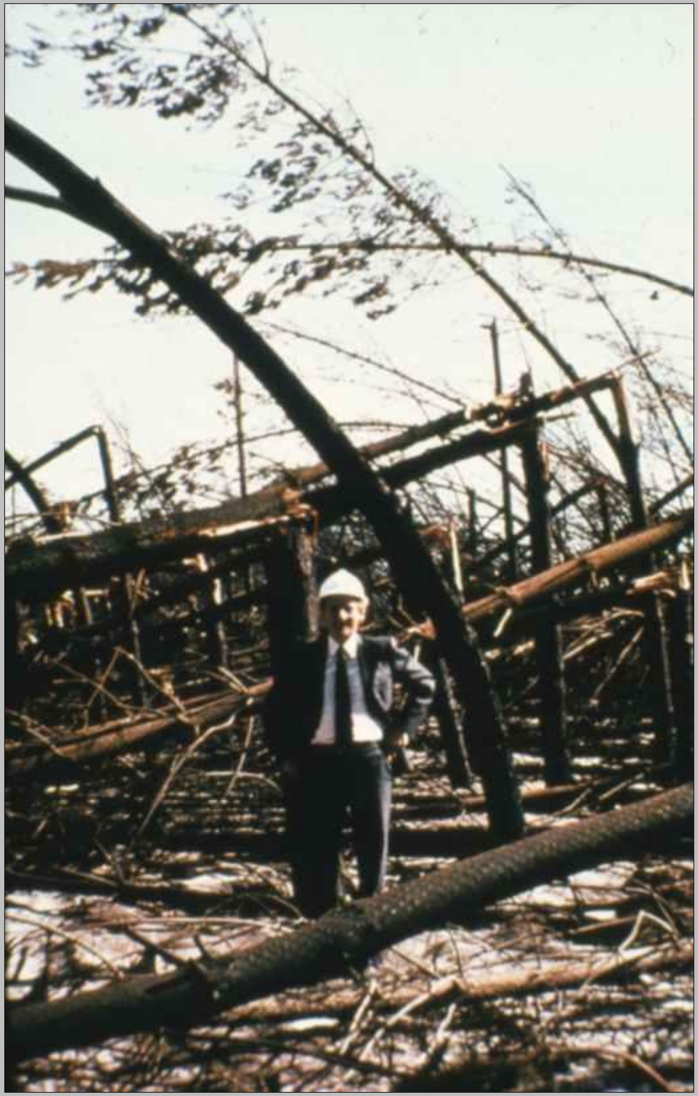
Marty Alexander

Miguel “Two Torch” Cruz

Implications of Crown Fires

Suppression Strategies/Tactics & Expenditures

Community Wildland Fire Protection

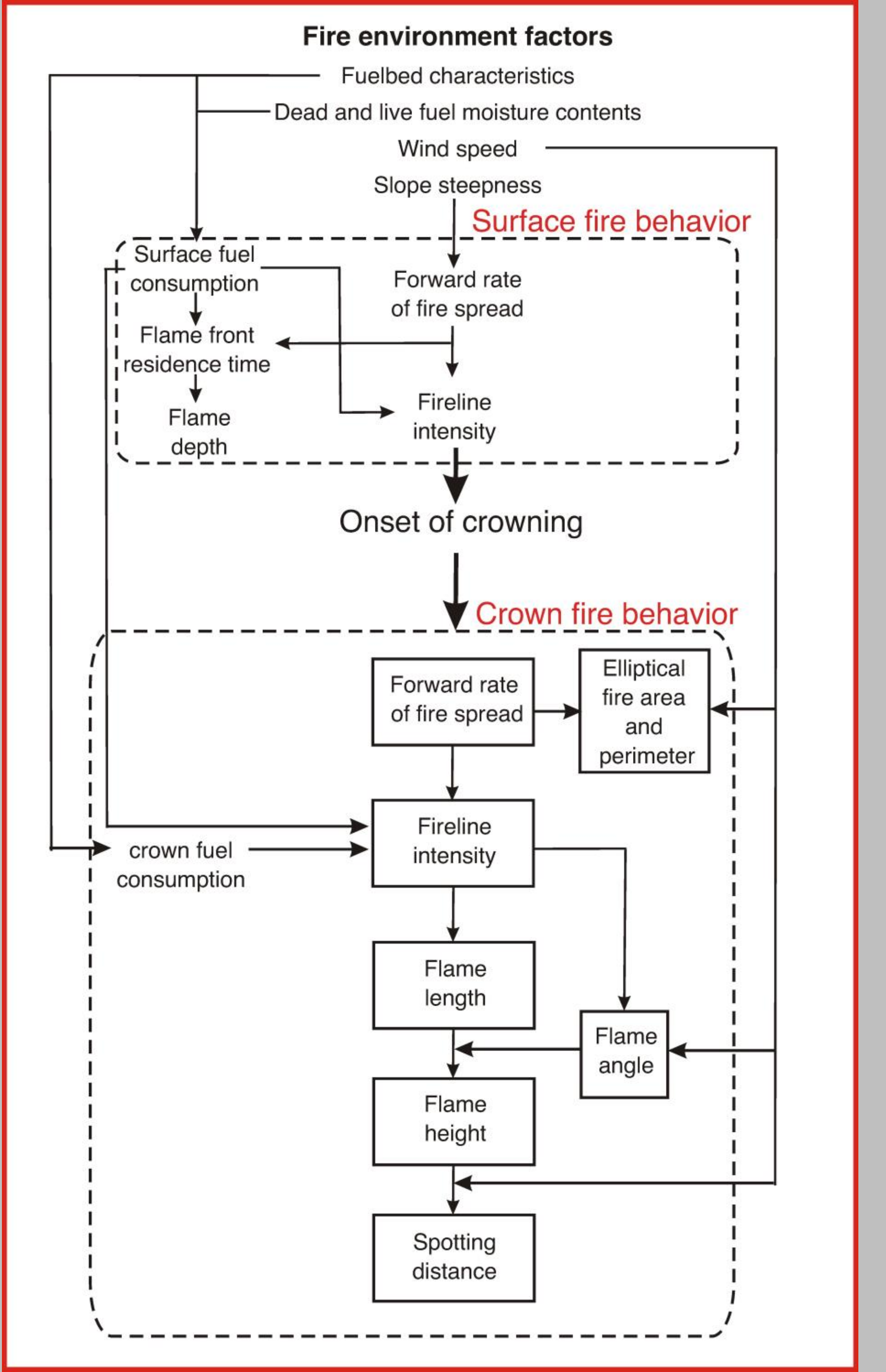


Resource Damages & Impacts

Firefighter Safety

Roles & Uses of Fire

Linkages involved in the basic features of surface and crown fire behaviour and the fire environment



Outline of Presentation

I. Introduction to Crown Fires

II. Types of Crown Fires

III. Understanding Crown Fire Behaviour based on Empirical Observations and Measurements in the Field

IV. Crown Fire Initiation

V. Crown Fire Propagation and Rate of Spread

VI. Crown Fire Flame Dimensions and Spotting Characteristics

VII. Some Salient Points Regarding Crown Fires

Introduction

to

Crown Fires

Basic Concepts

What is a "crown fire"?

A "crown fire" is defined as:

A fire that advances through the crown fuel layer, usually in conjunction with the surface fire. Crowning can be classified according to the degree of dependence on the surface fire phase.

What is "crowning"?

"Crowning" is defined as:

A fire ascending into the crowns of trees and spreading from crown to crown.

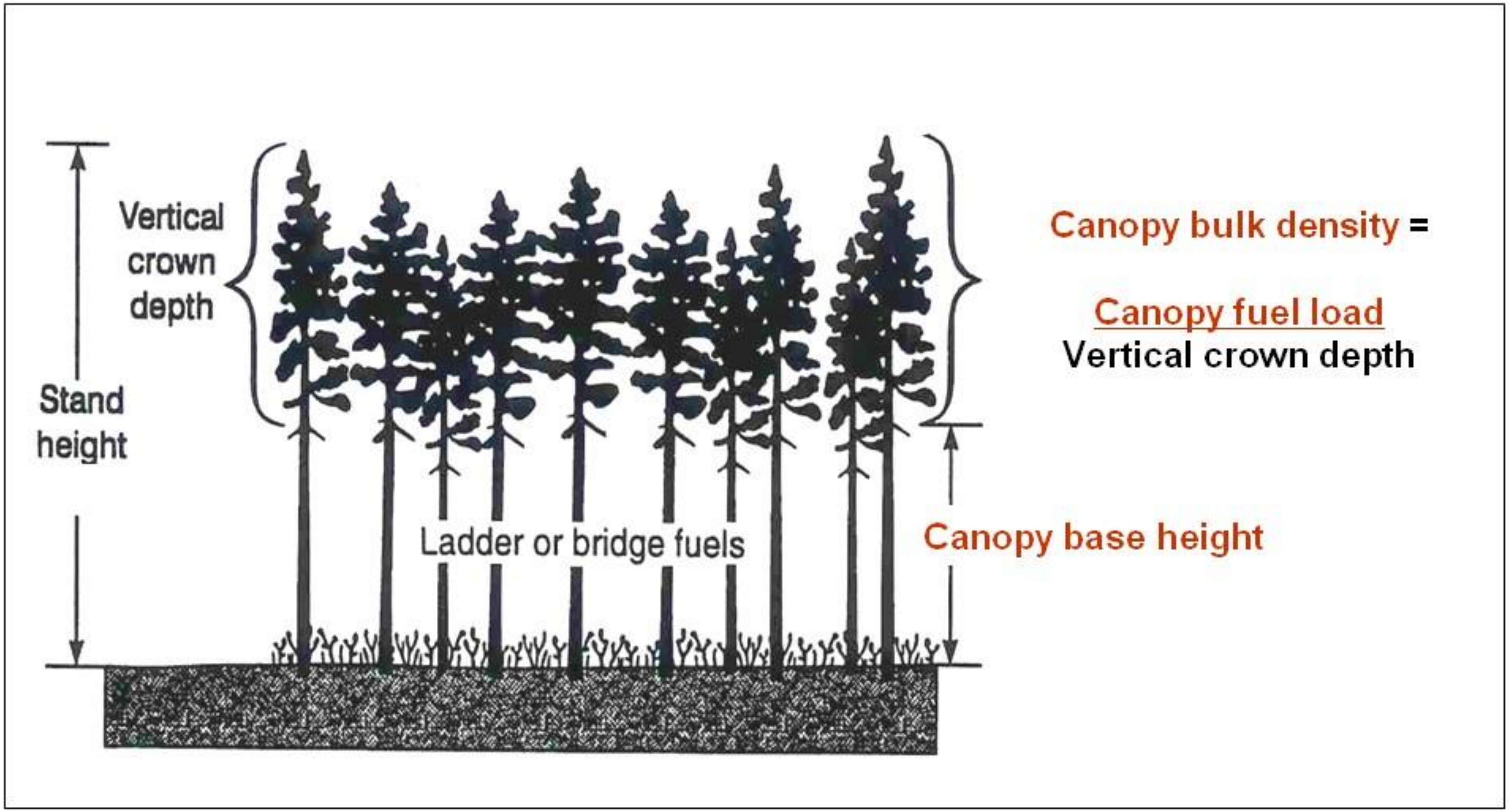
from Merrill and Alexander (1987) – Glossary of Forest Fire Management Terms

While crown fires do occur in other fuel complexes, the focus here is on conifer forests.

Crown fire in eucalypt forest

Crown fire in shrublands

Canopy Fuel Stratum & Stand Characteristics



Available Crown Fuel Load: needle foliage, lichens, small dead and live (a proportion) twigs < 1 cm in diameter

Ladder or bridge fuels: bark flakes, lichens, needle drape, boles branches (live & dead), understory conifers, tall shrubs

Fireline Intensity (Byram 1959)

$$I = H \times w \times r$$

I	H	w	r
Fireline Intensity (kW/m)	**Heat of Combustion** (18 000 kJ/kg)	**Fuel Consumed** (kg/m^2)	**Rate of Fire Spread** (m/sec)

Fireline intensity is the rate of energy or heat release per unit time per unit length of fire front

George M. Byram

Types of Crown Fires

Fires classified as “crown fires” also contain areas of ground or sub-surface fire plus low- to high-intensity surface fire activity.

Brief History

- The term “crown fire” has appeared in the forestry and ecological literature since at least the 1880s (e.g., Bell 2012).

- Eventually the terms “dependent crown fire” and “running crown fire” emerged in the late 1930s in order to distinguish the degree of dependence on the surface fire.

- Other terms have appeared in the literature – “fully developed crown fire”, “wind-driven crown fire”, “plume-dominated crown fire”, “intermittent crown fire” and “continuous crown fire”, in addition to those Van Wagner’s (1977) crown fire classification.

C.E. Van Wagner's (1977) three types of crown fires is the most widely recognized classification:

- **Passive crown fire**

- **Active crown fire**

- **Independent crown fire**

Passive Crown Fires can occur under two broad situations:

- Canopy base height and canopy bulk density are considered optimum but **fuel moisture and wind conditions are not quite severe** enough to induce full-fledged crowning

- **Canopy base height and canopy bulk density are, respectively, above and below** the thresholds generally considered necessary for crowning so that even under severe burning conditions full-fledged crowning is not possible, although vigorous, high-intensity fire behaviour can occur.

Torching does not constitute passive crowning as it generally does not generate any kind of forward fire spread.

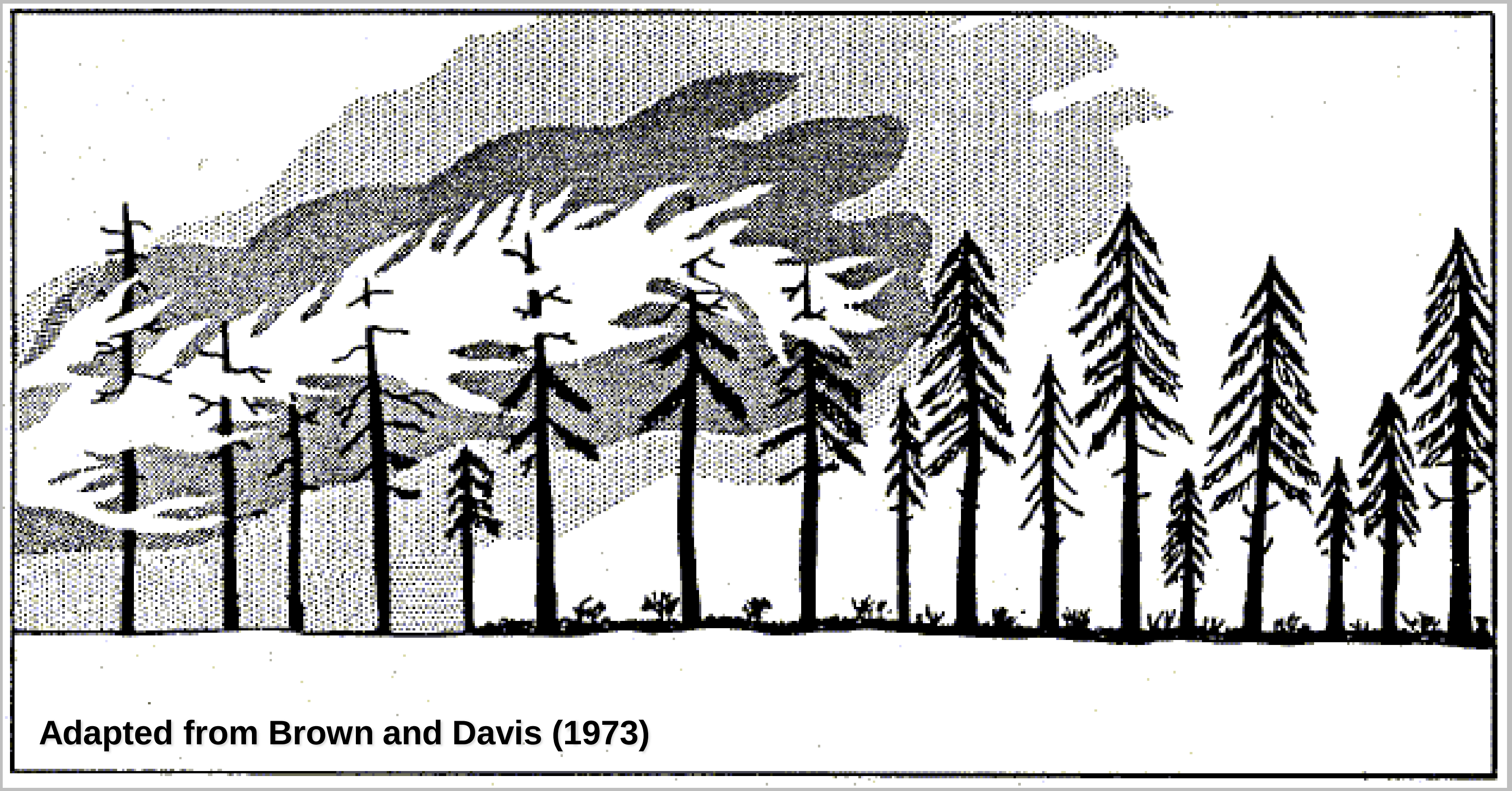
Active Crown Fires are most likely to occur in forests that have:

- Ground and surface fuels that permit development of a substantial surface fire
- A moderately high canopy or crown base height
- A fairly continuous crown layer of moderate to high bulk density and low to normal foliar moisture content

This mosaic pattern the result of short-term variations in wind speed/direction interacting with surface fuel characteristics, topography (including differences in fuel moisture).

Van Wagner (1977) termed this “intermittent active crowning”.

Independent Crown Fire



Adapted from Brown and Davis (1973)

"The crown phase will ... no longer depend in any way on the surface phase and can run ahead on its own."

Van Wagner (1977)

"The concept of independent crown fire remains dubious … true independent crown-fire spread ahead of the surface phase could only proceed if the flame front from crown base to flame tip were titled well forward, perhaps so much as to approach the horizontal.

In other words, the spread of crown fire independent of any surface fire is essentially ruled out as a stable phenomenon on level terrain.

The concept may still have value in rough or steep terrain and as a short-term fluctuation under the most extreme conditions …".

Van Wagner (1993)

Conditional Crown Fire: Myth or Fact?

Scott and Reinhardt (2001) claimed that the possibility exists for a stand to support an active crown fire that would otherwise not initiate a crown fire.

To our knowledge, no empirical proof has been produced to date to substantiate the possible existence of such a situation, at least not as a steady-state phenomenon.

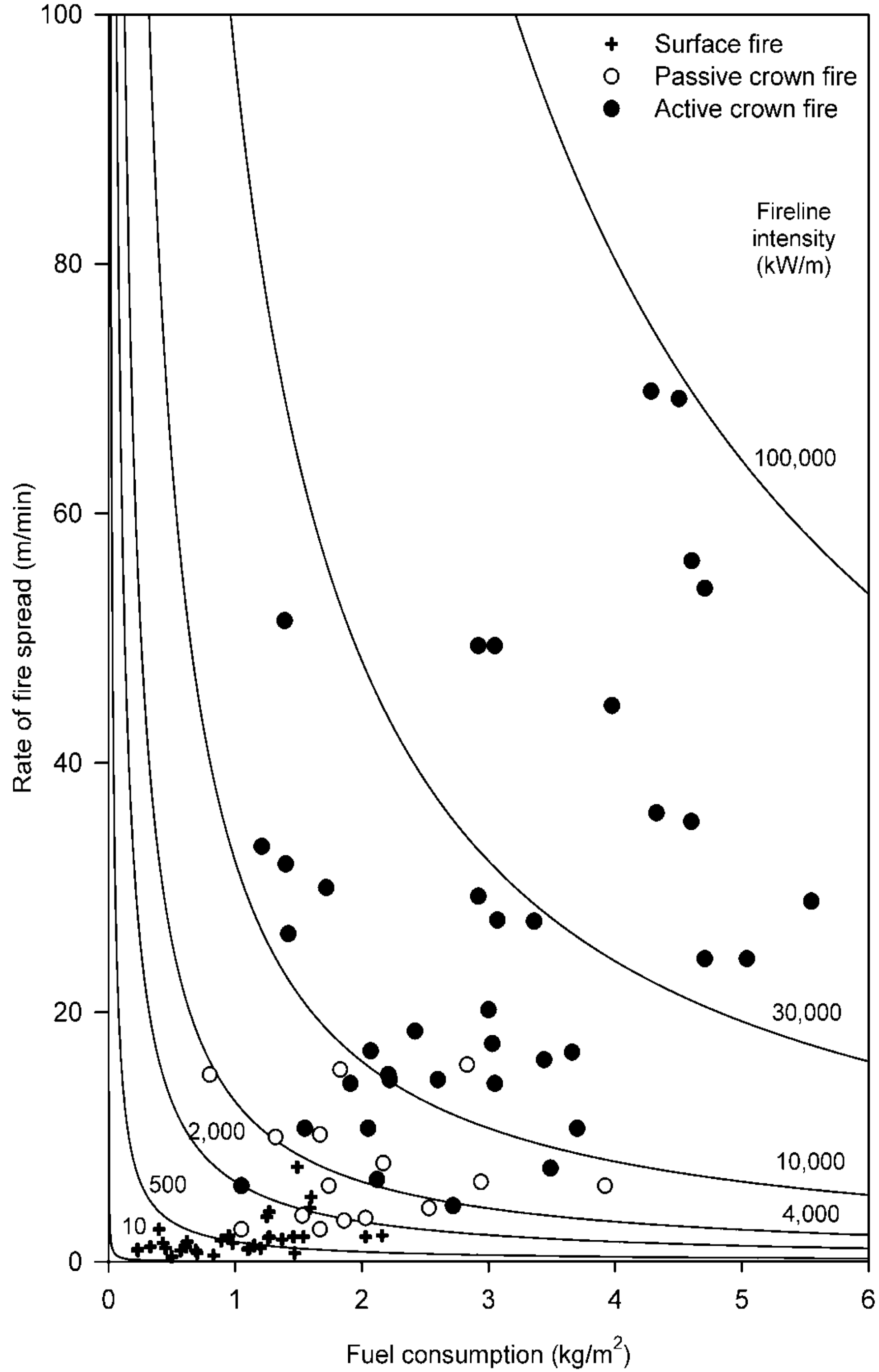
Understanding Crown Fire Behaviour Based on Empirical Observations and Measurements in the Field

Observations and measurements of crown fire activity

- **Key to our understanding of crown fire dynamics**
- **Provides benchmark data for empirical-based model development and performance evaluation**
- **Serves as reality-checks for simulation studies**

Experimental fire, Ontario, Canada

Wildfire, Victoria, Australia



Fire behaviour characteristics chart

- **Rate of fire spread and fuel consumption vs. six levels of fireline intensity**
- **Experimental surface and crown fires plotted**

from Alexander and Cruz (2014)

Experimental surface and crown fires carried out at Petawawa Forest Experiment Station, Chalk River, Ontario, Canada – beginning in 1961 by Charlie Van Wagner

Red Pine Plantations

C.E. Van Wagner

Semimature Jack pine
NE Alberta – 1974

Mature Jack Pine
Ontario – 1970s

Immature Jack Pine
NE Ontario – 1970s

Spruce Budworm-killed
Balsam Fir – NE Ontario
late 1970s/early 1980s

Black Spruce Lichen
Woodland – Northwest Territories
1982

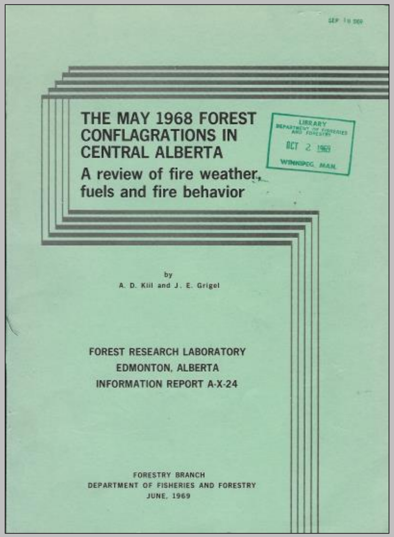
Black Spruce Lowland
North-central Alberta
mid to late 1980s

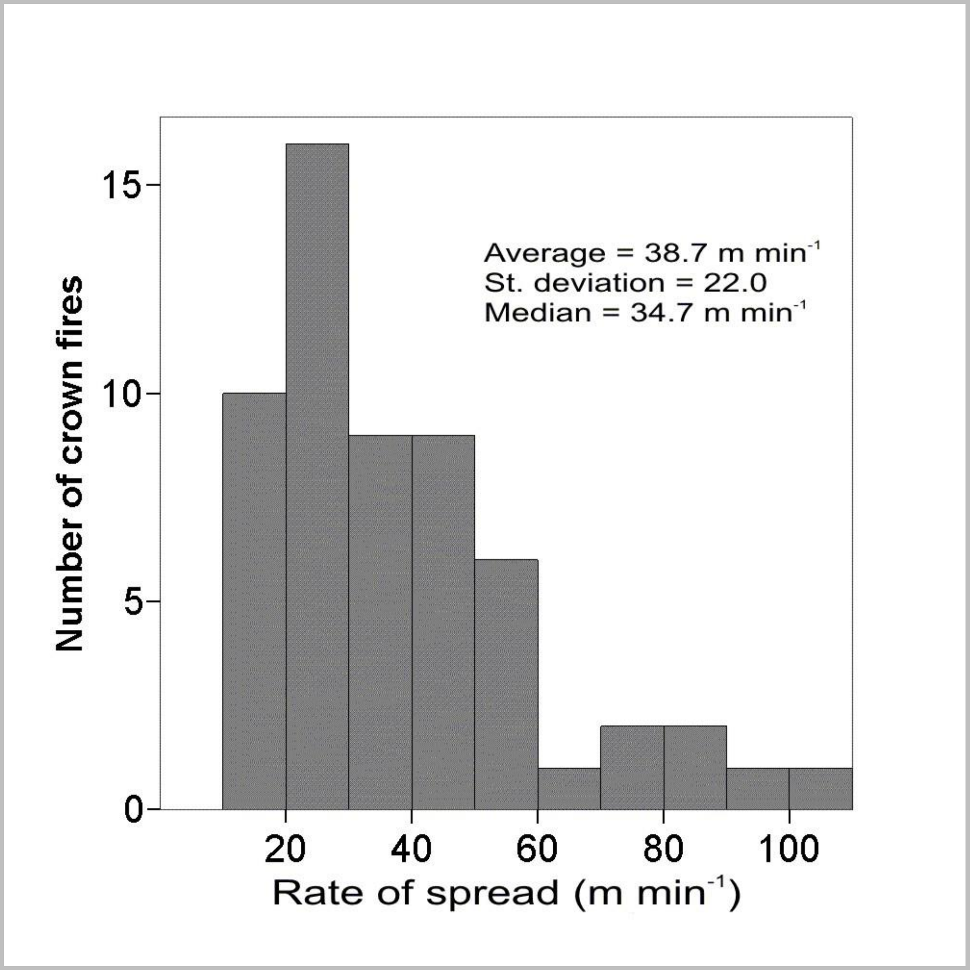
Jack Pine-Black Spruce

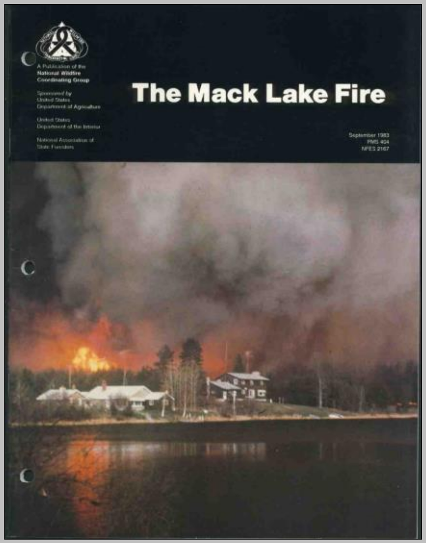
International Crown Fire Modelling Experiment (ICFME), Northwest Territories – 1995-2002

Wildfire Opportunities

Distribution of active crown fire rates of spread based on Canadian and U.S. wildfires





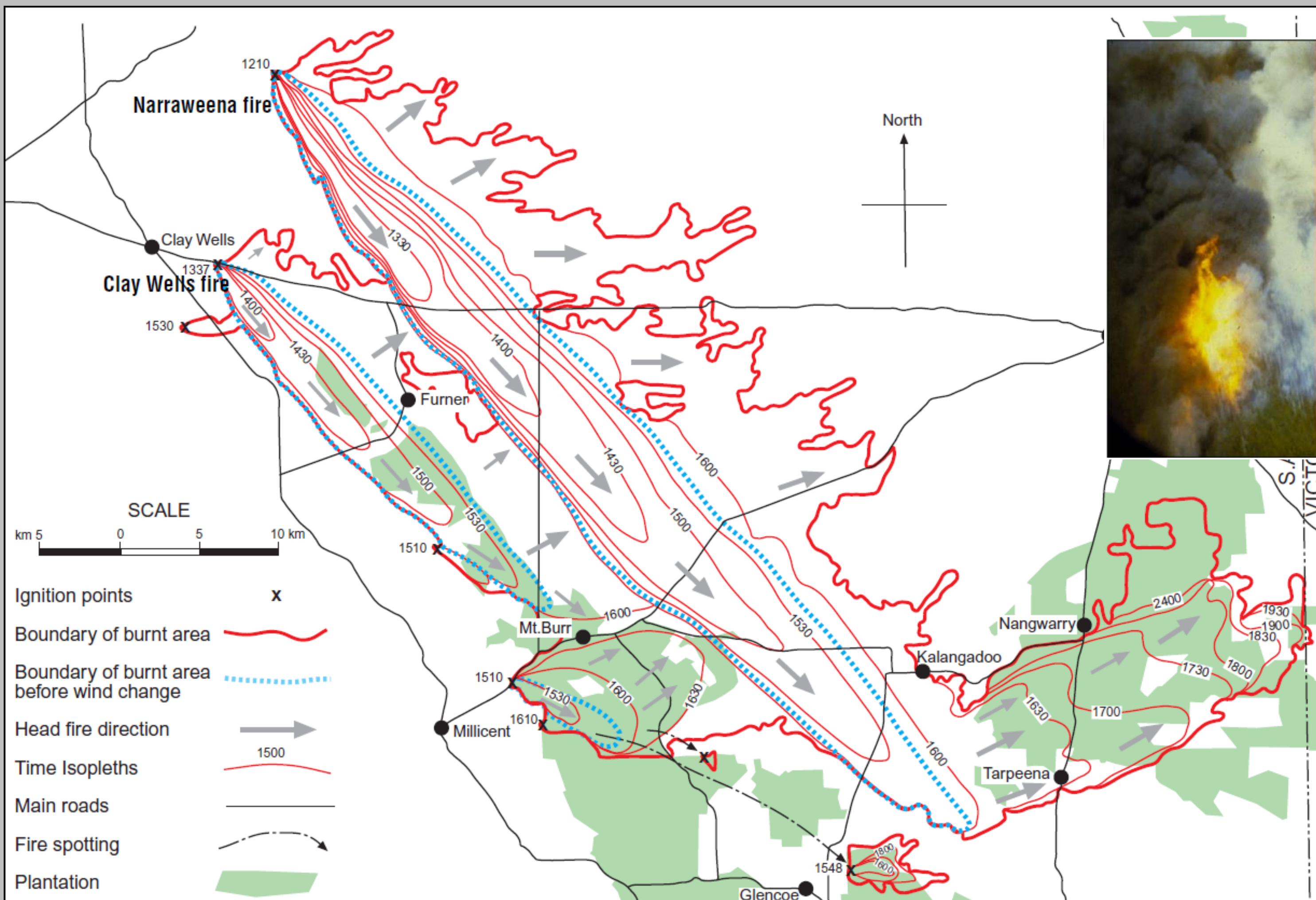


from Alexander and Cruz (2006)

Mount Muirhead Fire, South Australia - 16 February 1983

Temp: 40-44 ºC; RH 10-12%; Winds >80 km/h.

Radiata Pine Plantation Fuel Types; Head Fire ROS ≅200 m/min (12 km/h)



Crown Fire Initiation

Van Wagner's (1977) Theory on the Initiation of Crowning

$$I_o = (0.010 \times CBH \times (460 + 25.9 \times FMC))^{3/2}$$

where:

I_o – critical surface intensity (kW/m) needed to initiate crowning

CBH – canopy base height (m)

FMC – foliar moisture content (%)

Vertical fire spread into the overstory canopy will occur when the surface fireline intensity (I_s) attains the critical value I_o as determined by ***CBH*** and ***FMC***.

Van Wagner's (1977) Crown Fire Initiation Model

$I_s < I_o$:

Surface Fire

$I_s \sim I_o$:

Surface Fire - Crown Fire Transition

$I_s > I_o$:

Crown Fire!

Van Wagner's (1977) Crown Fire Initiation Model: Strengths and Weaknesses

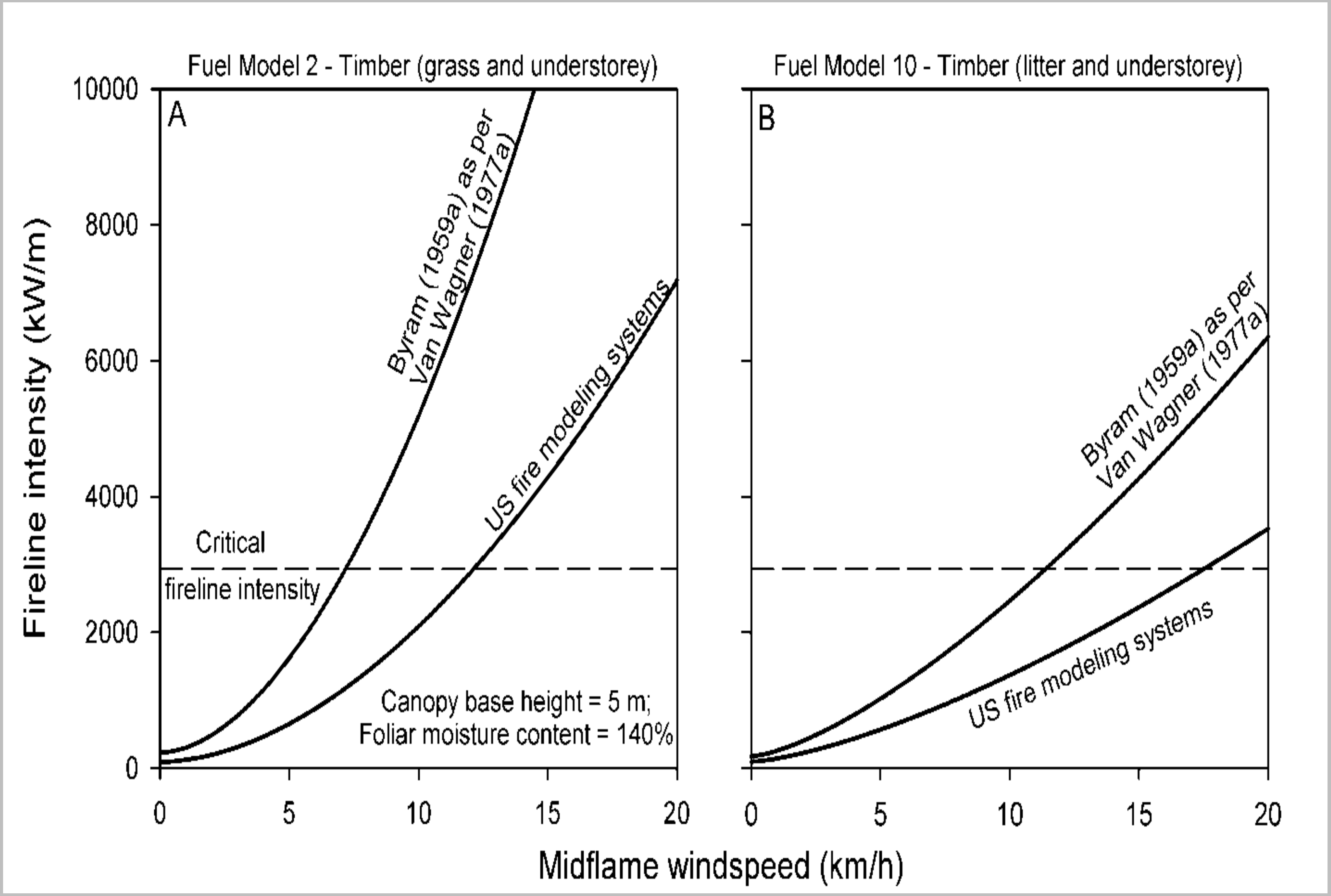
Simplicity:

Only two crown fuel properties (***CBH*** and ***FMC***) and an estimate of potential surface fire intensity required as inputs

Limitations:

• The 0.010 constant in his equation undoubtedly varied according to fuel structure characteristics complexes.
• Doesn't allow for variable duration of heating (presently the flame front residence time is a constant 50 sec) – thus, quite possible for two surface fires to have the same intensity but significantly different residence times (e.g., grass vs. conifer needle forest floor).
• Surface burning conditions (i.e., temp, RH, plus in-stand wind and thus fire plume angle) a constant rather than a variable.

Under-prediction of crowning potential when Van Wagner (1977) model implemented in U.S. fire modeling **systems**



from Alexander and Cruz (2014)

Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model

Logistic regression model requires three environmental inputs and one fire behaviour descriptor:

- 10-m open wind speed (***U_{10}***)
- Canopy base height (***CBH***) or fuel strata gap (***FSG***)
- Estimated fine fuel moisture (***EFFM***); and one fire behavior
- Surface fuel consumption (***SFC***) class (<1, 1-2, >2 kg/m^2)

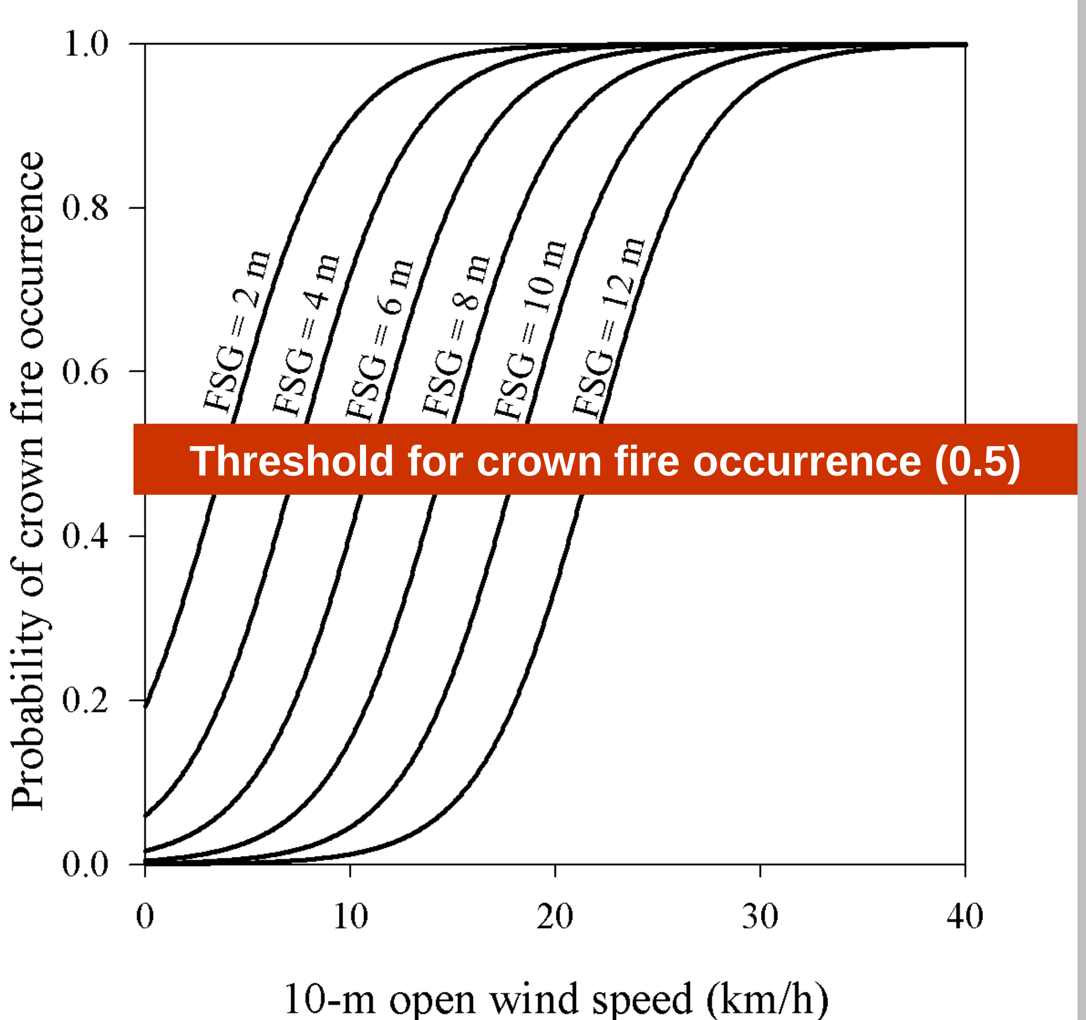
Threshold for crown fire occurrence judged to be 50% probability.

The Fuel Strata Gap Concept

Fuel strata gap (***FSG***) is defined as the distance from the lower limit of the crown fuel stratum that can sustain vertical fire propagation and the top of the surface fuel layer.

FSG is equivalent to canopy base height (CBH) in the absence of appreciable ladder fuels when the surface fuel height is minimal.

Cruz, Alexander and Wakimoto (2004)
Crown Fire Occurrence Probability Model



Effect of 10-m Open Wind Speed (*U_{10}*) under variable Fuel Strata Gap (*FSG*)

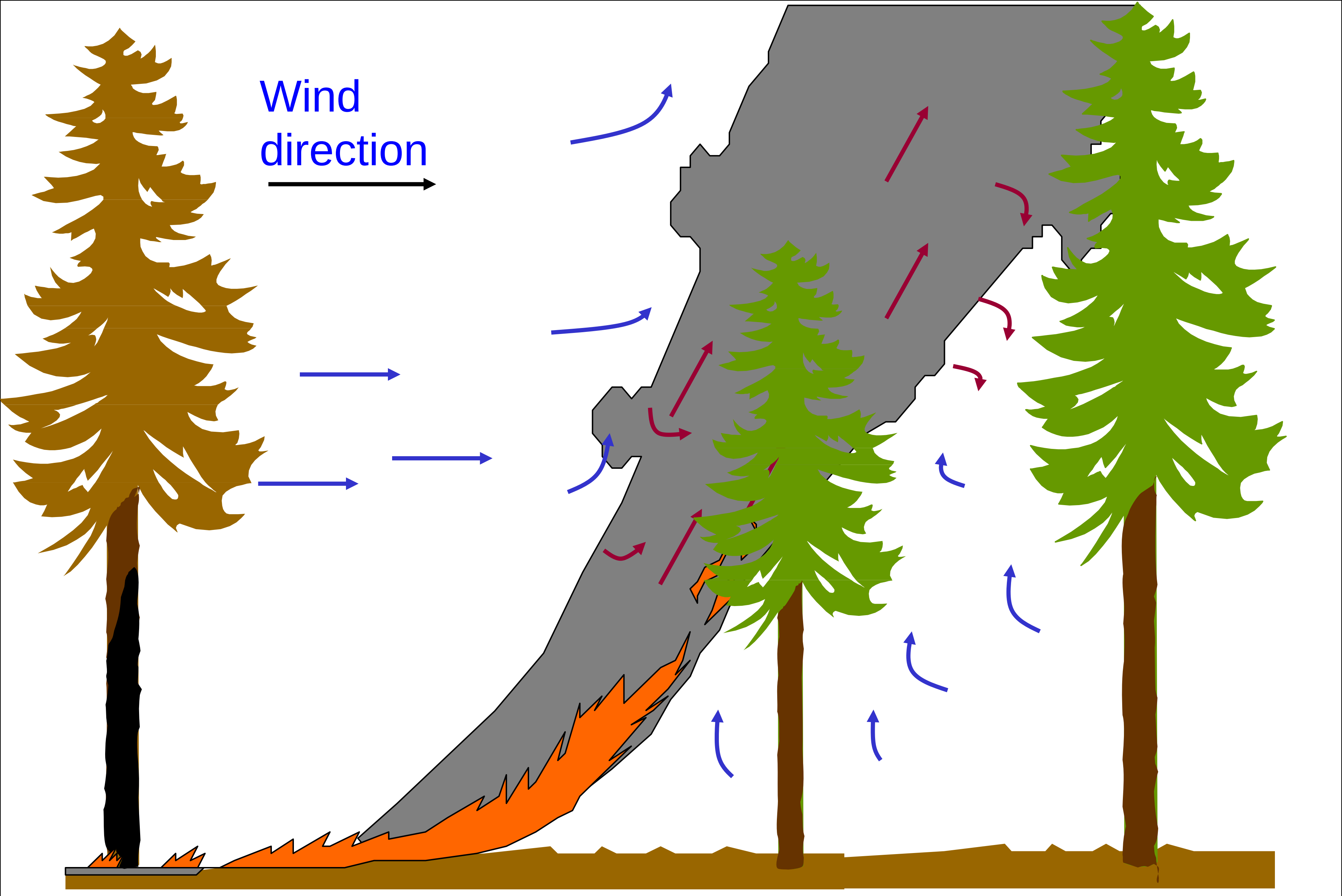
Assume:

EFFM = 6%

SFC = 1-2 kg/m^2

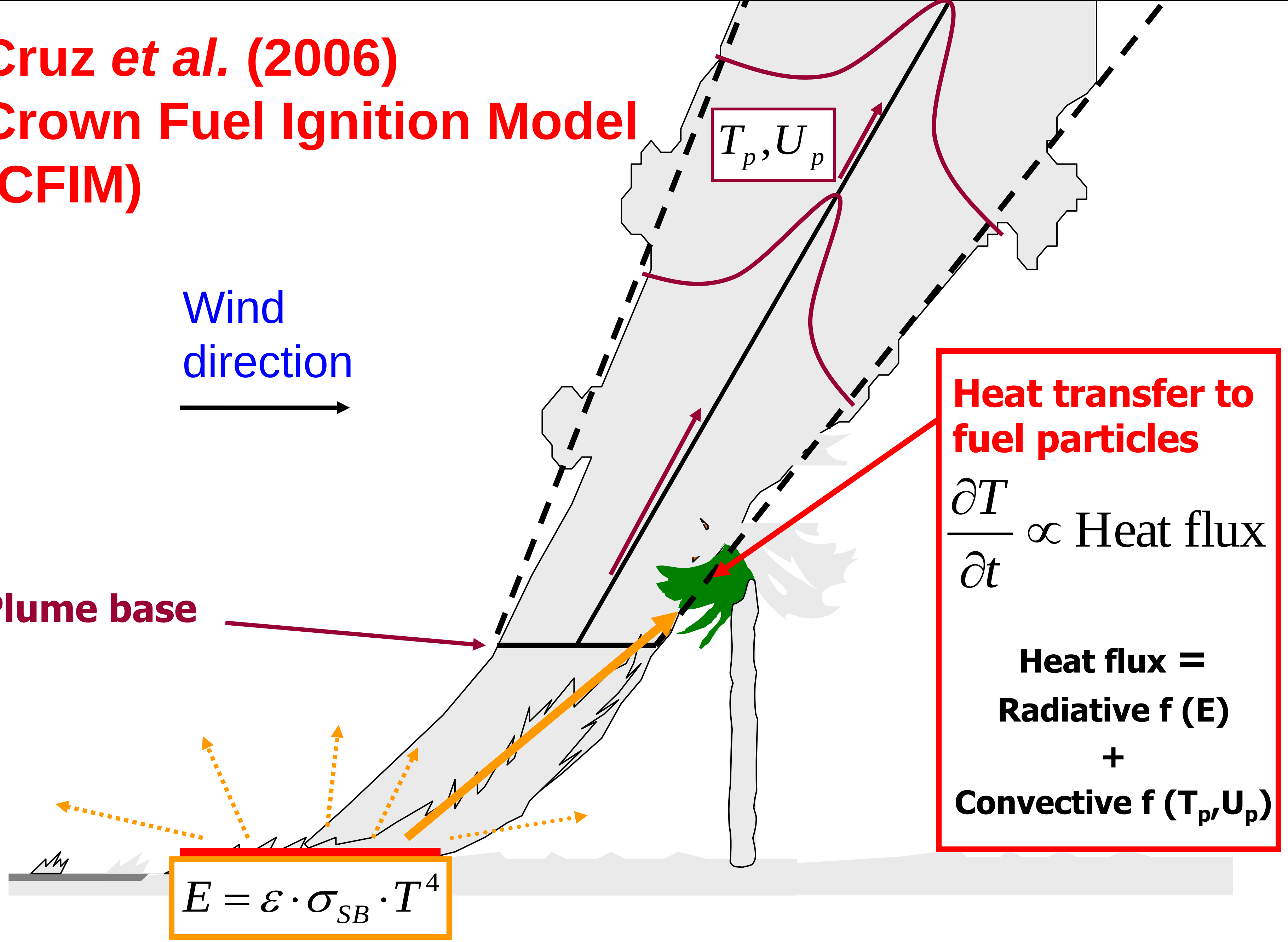
Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model: Evaluation Results

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

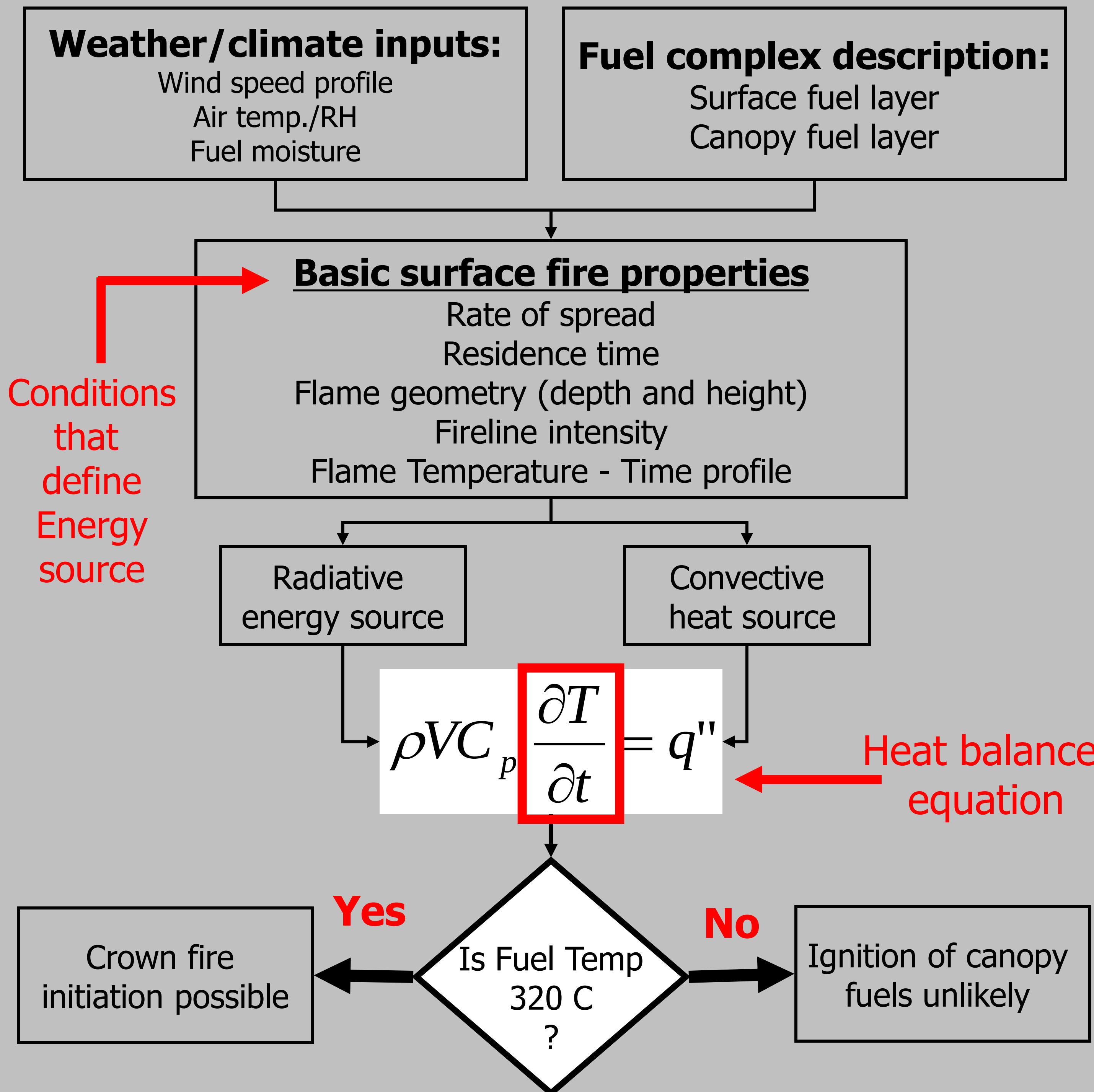


Cross section of a wind-driven surface fire

Cruz *et al.* (2006)
Crown Fuel Ignition Model (CFIM)



Cruz *et al.* (2006) Crown Fuel Ignition Model (CFIM)



Crown Fire Propagation and Rate of Spread

Van Wagner's (1977)
Criteria for Solid Crown Flame

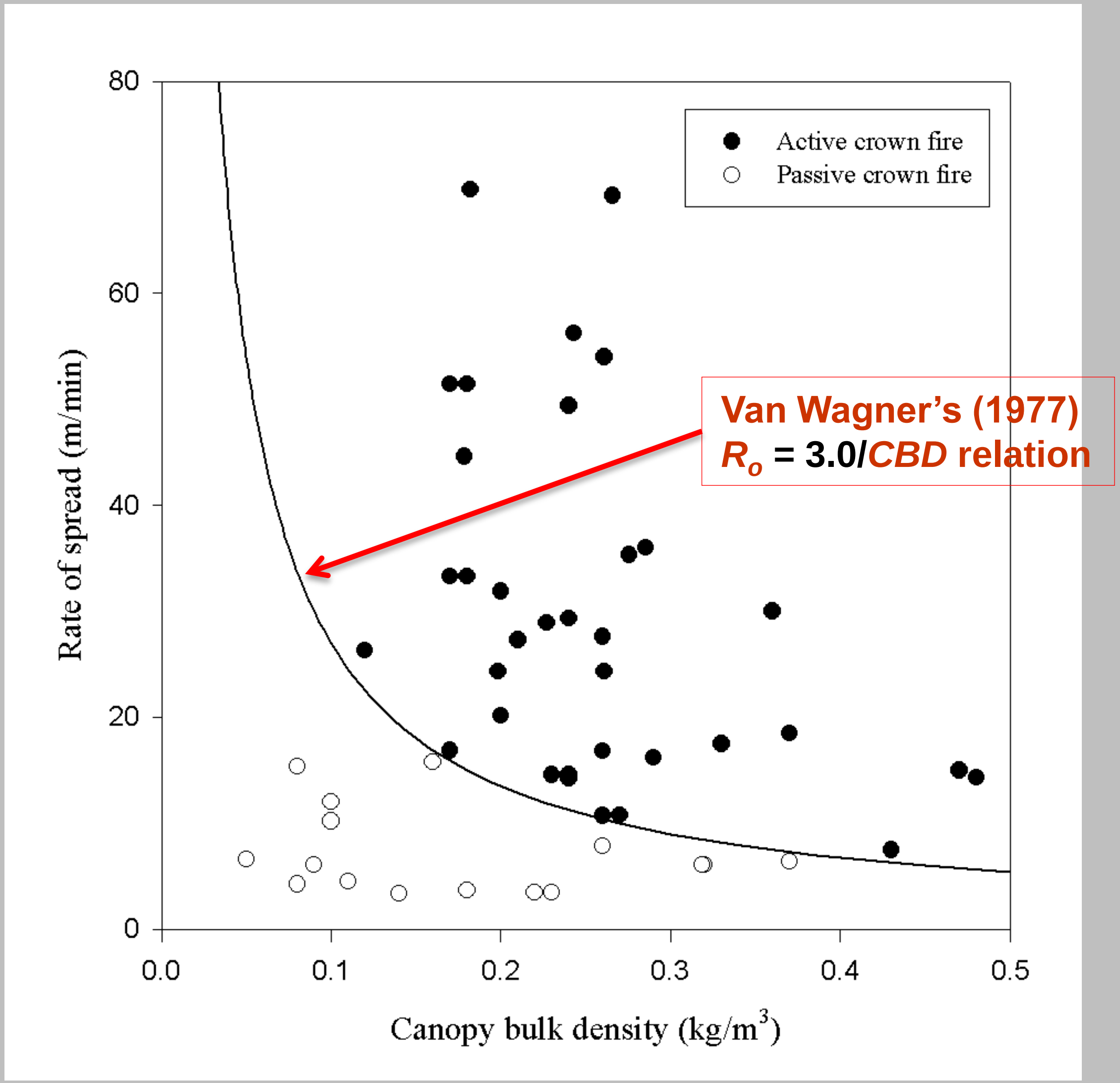
The following relation was proposed:

$$R_o = S_o / CBD$$

where R_o is the critical minimum spread (m/min) in order to sustain a continuous flame front within the crown fuel layer, S_o is the critical mass flow rate for solid crown flame (kg/m^2-min), and *CBD* is the canopy bulk density (kg/m^3).

S_o is regarded as an empirical constant to be derived from field observations. Best available estimate (3.0) based on experimental fires in red pine plantations.

Experimental crown fires used in the development of the Canadian FBP System plotted



Points of note:

- No passive crown fires with ***CBD*** < 0.05 kg/m^3
- No active crown fires with ***CBD*** < 0.11 kg/m^3

from Cruz, Alexander and Wakimoto (2005)

Crown Fire Rate of Spread Models

- **Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992)** – implemented in PROMETHEUS (Canadian wildland fire growth model) and Canadian Wildland Fire Information System

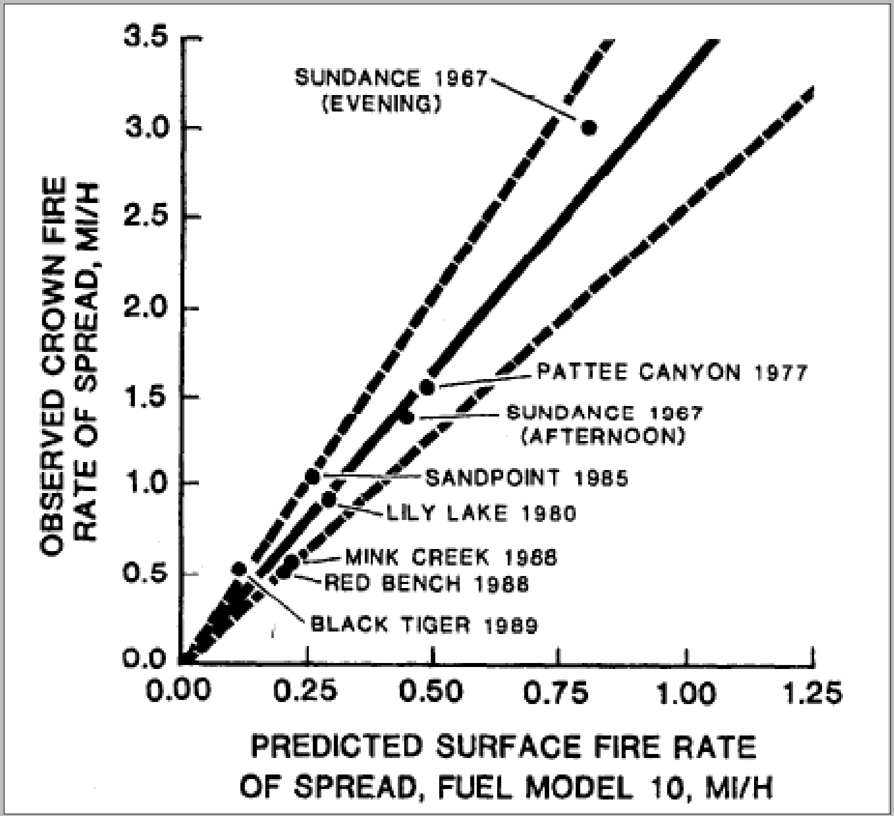
- **Rothermel (1991)** – implemented in U.S. fire modeling systems (e.g., BehavePlus, NEXUS, FARSITE)

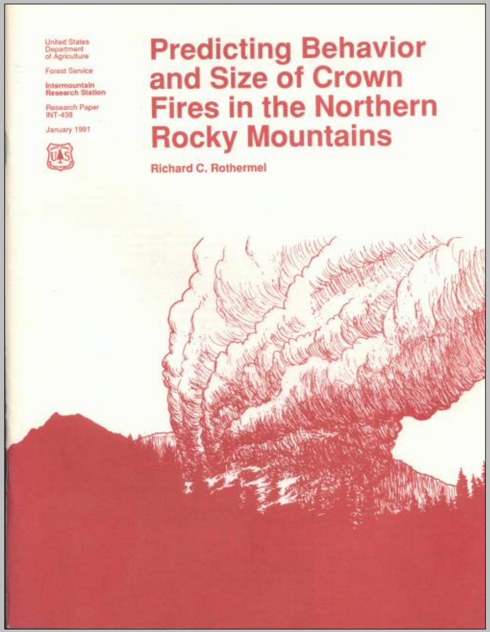
- **Cruz, Alexander and Wakimoto (2005)** – implemented in Crown Fire Initiation and Spread (CFIS) model system

- **Albini (1996)**

- **Schaaf *et al.* (2007)** – implemented in Fuel Characteristics Classification System (FCCS)

Rothermel (1991) Rate of Spread "Model" for Wind-driven Crown Fires





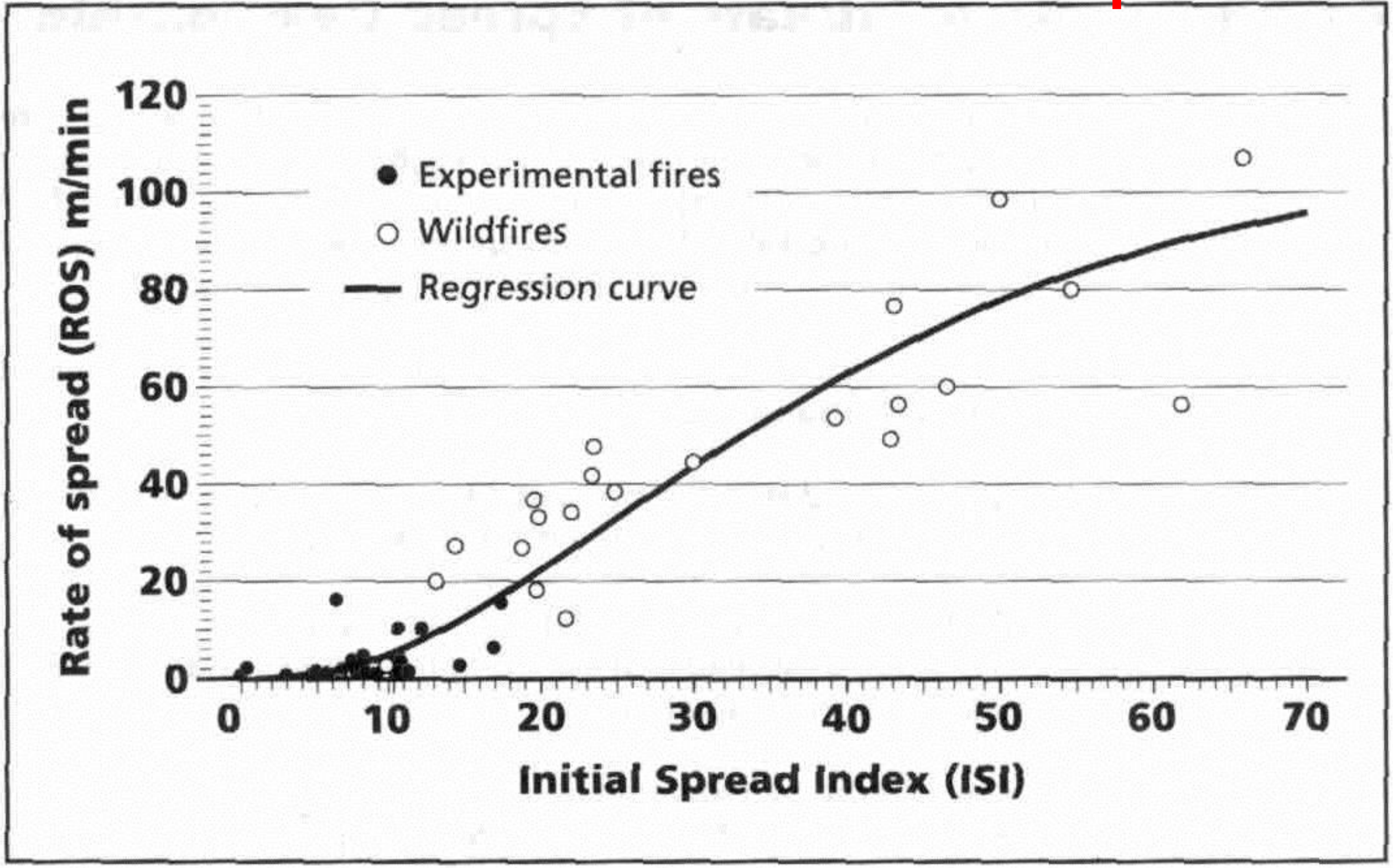
Dick Rothermel

Ave. Crown Fire ROS = 3.34 x Surface Fire ROS

A statistical correlation between the predicted surface fire rate of spread for Fuel Model 10 (wind reduction factor 0.4) and 8 western U.S. wildfire observations

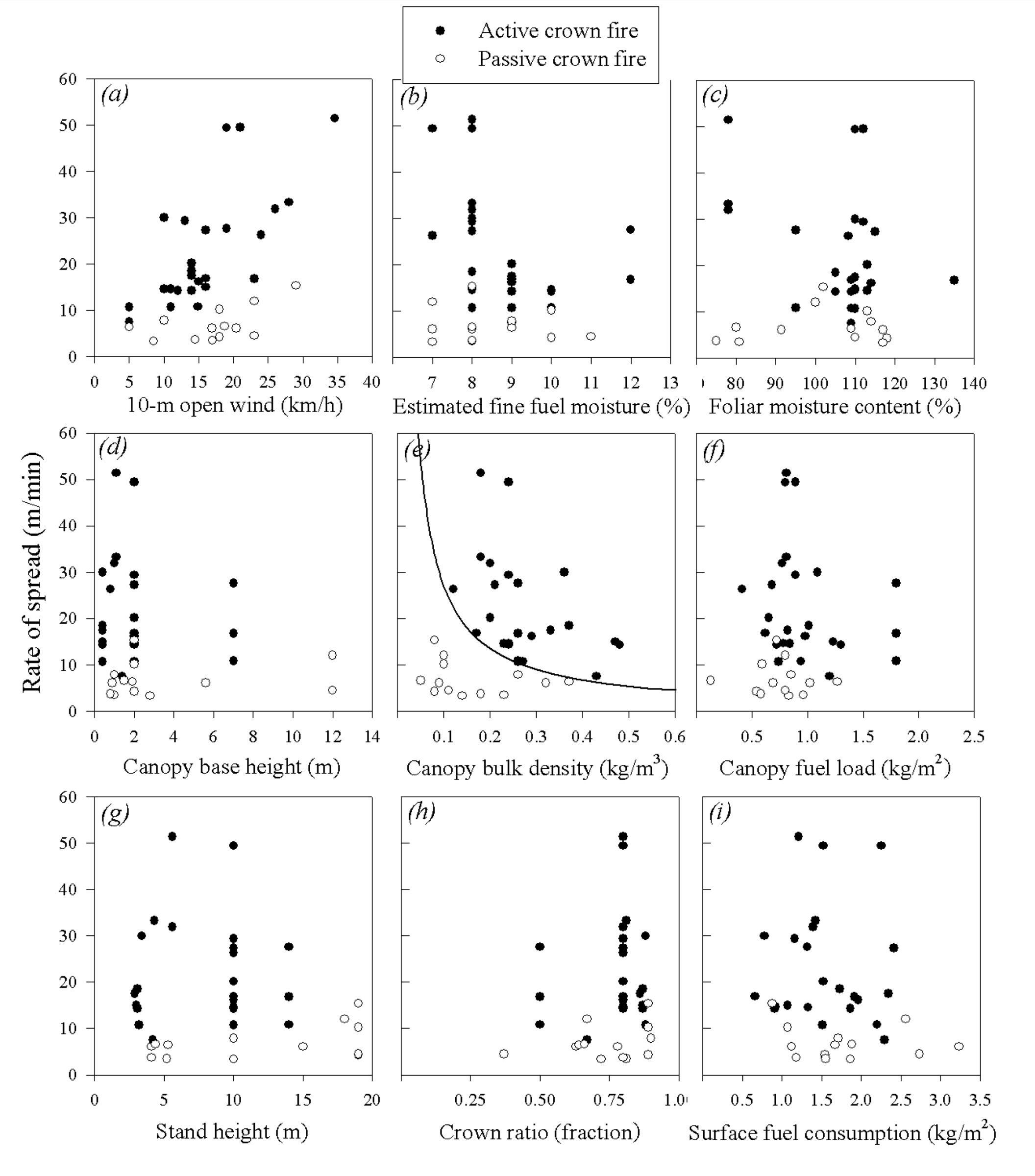
Canadian Forest Fire Behavior Prediction (FBP) System:

surface and crown fire rates of spread



Mature Jack or Lodgepole Pine (C-3) Fuel Type

Cruz, Alexander and Wakimoto (2005) Crown Fire Rate of Spread Models



- Data available 37 crown fires (24 active and 13 passive; all from Canada)
- Number of variables examined
- The criterion for active crowning (CAC) introduced:

$$CAC = \frac{\text{Predicted Active Crown Fire ROS}}{3.0/\mathbf{CBD}}$$

Cruz, Alexander and Wakimoto (2005)
Crown Fire Rate of Spread Models: The Equations

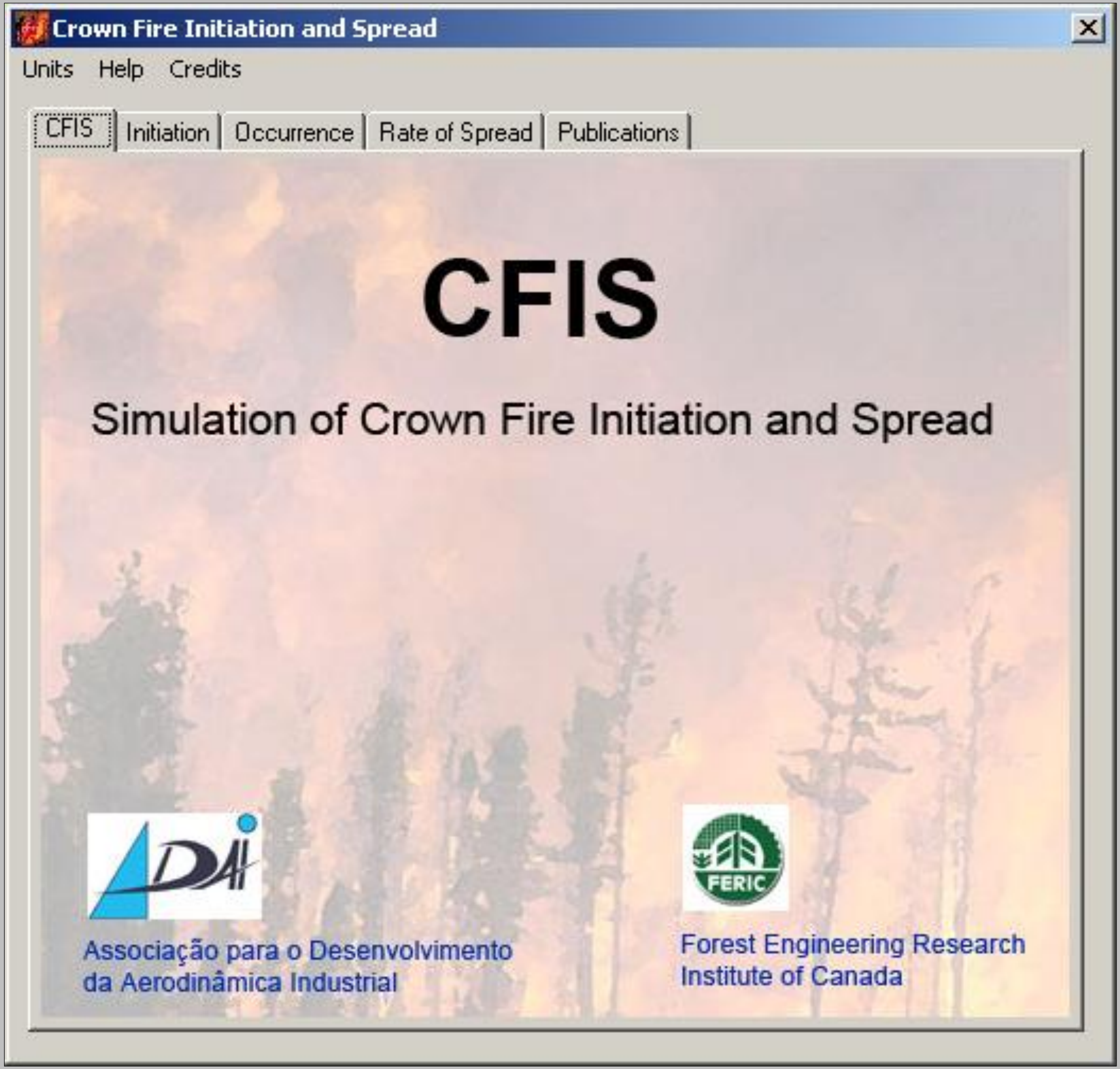
***Active Crown Fires*: CAC $\geq$ 1.0**

$$CROS_A = 11.02 \times (U_{10})^{0.9} \times CBD^{0.19} \times exp(-0.17 \times EFFM)$$

***Passive Crown Fires*: CAC < 1.0**

$$CROS_P = CROS_A \times exp(-CAC)$$

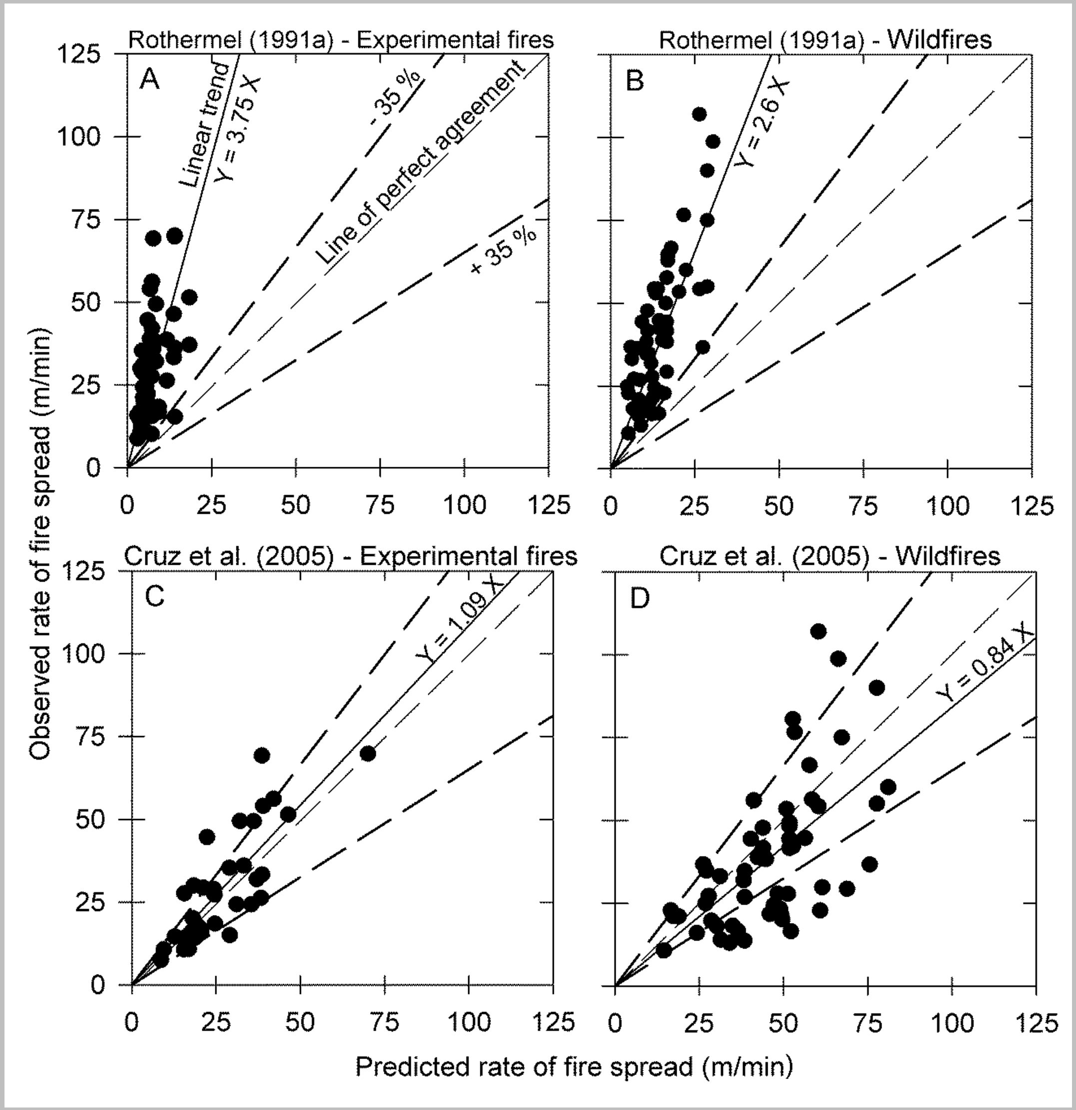
where ***CAC*** is the criterion for active crowning dimensionless), ***CBD*** is the canopy bulk density (kg/m^3), U_{10} is the 10-m open wind speed km/h), ***EFFM*** is the estimated fine fuel moisture (%), $CROS_A$ is the active crown fire rate of spread (m/min), and $CROS_P$ is the passive crown fire rate of spread (m/min).



Work started on incorporating the Cruz, Alexander & Wakimoto (2003, 2004, 2005) and Alexander & Cruz (2006) models into a software package in 2005.

https://www.frames.gov/partner-sites/applied-fire-behavior/cfis/

Rothermel (1991) & Cruz, Alexander and Wakimoto (2005) Active Crown Fire Rate of Spread Model Evaluations



Rothermel model under-predicts by a factor of 2.6-3.8 and shows little sensitivity to burning conditions.

The Cruz *et al.* (2005) model slightly over-predicted.

after Cruz and Alexander (2010)

Albini Physics-based Active Crown Fire ROS Model

1588

A radiation-driven model for crown fire spread[1]

B.W. Butler, M.A. Finney, P.L. Andrews, and F.A. Albini

Abstract: A numerical model for the prediction of the spread rate and intensity of forest crown fires has been developed. The model is the culmination of over 20 years of previously reported fire modeling research and experiments; however, it is only recently that it has been formulated in a closed form that permits a priori prediction of crown fire spread rates. This study presents a brief review of the development and structure of the model followed by a discussion of recent modifications made to formulate a fully predictive model. The model is based on the assumption that radiant energy transfer dominates energy exchange between the fire and unignited fuel with provisions for convective cooling of the fuels ahead of the fire front. Model predictions are compared against measured spread rates of selected experimental fires conducted during the International Crown Fire Modelling Experiment. Results of the comparison indicate that the closed form of the model accurately predicts the relative response of fire spread rate to fuel and environment variables but overpredicts the magnitude of fire spread rates.

Résumé : Les auteurs ont développé un modèle numérique pour prédire le taux de propagation et l'intensité des feux de cimes. Le modèle est l'aboutissement d'expérimentations et de recherches sur la modélisation du feu rapportées depuis plus de 20 ans. Cependant, ce n'est que récemment qu'une formulation dans une forme analytique a permis la prédiction a priori du taux de propagation d'un feu de cimes. Cet article présente une brève revue du développement et de la structure du modèle suivie d'une discussion des modifications récentes qui ont été apportées pour formuler un modèle entièrement prédictif. Le modèle est basé sur l'hypothèse voulant que le transfert d'énergie de rayonnement domine les échanges d'énergie entre le feu et les combustibles non enflammés en tenant compte du refroidissement des combustibles par convection à l'avant du front. Les prédictions du modèle sont comparées aux mesures du taux de propagation de certains feux expérimentaux allumés dans le cadre de L'Expérience internationale de modélisation des feux de cimes. Le résultat des comparaisons indique que la forme analytique du modèle prédit correctement la réaction relative du taux de propagation aux combustibles et aux variables environnementales mais surestime l'ampleur du taux de propagation du feu.

[Traduit par la Rédaction]

Introduction

Fire behaviour models form the foundation of decision support systems (Andrews 1986; Andrews and Queen 2001). Historically, crown fires account for only a small percentage of the total number of wildland fires that occur each fire season. However, it is this small number of fires burning with relatively high intensities that result in the majority of acreage burned (Pyne et al. 1996). Methods and models for predicting the onset and spread of crown fire have been used extensively by fire and land managers to minimize risk to life and property, project the growth of ongoing fires, plan for prescribed fires, and examine trade-offs in vegetation treatment options. Limitations exist in currently available models (Deeming et al. 1977; Van Wagner 1977; Xanthopoulos 1990; Rothermel 1991; Forest Canada Fire Danger Group 1992; Canadian Forestry Service 1997; Alexander 1998; Cruz et al. 2002, 2003). Such models are useful, relatively fast to compute, but also inherently limited in their range of applicability. Models based on physical principles, on the other hand, have the potential to accurately predict the parameters of interest over a broader range of input variables than empirically based models. Physics-based models can also provide the basic information needed for proper description of physical processes (i.e., fluid flow, heat transfer, and chemical kinetics). But physics-based models also include inherent weaknesses; they imply that the developer has an adequate understanding of the underlying physical relations sufficient to achieve the desired objectives, that the underlying physics can be represented mathematically in a manner that permits numerical solution while retaining adequate realism, that the informational needs of the mathematics can be met by the user, and that the predicted variables are in a form to be useful by the practitioner. Improved models are needed for increased accuracy in fire behaviour prediction, fire danger rating calcu-

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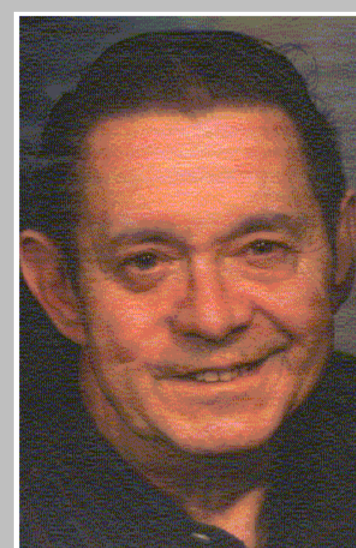
B.W. Butler,[2] M.A. Finney, and P.L. Andrews. USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, P.O. Box 8089, Missoula, MN 59807, USA.
F.A. Albini. Montana State University Bozeman, 114 Arrowhead Trail, Bozeman, MN 59718, USA.

[1]This article is one of a selection of papers published in this Special Issue on The International Crown Fire Modelling Experiment (ICFME) in Canada's Northwest Territories: Advancing the Science of Fire Behaviour.
[2]Corresponding author (e-mail: email: bwbutler@fs.fed.us).

In the mid to late 90s Dr. Frank Albini was supported by the Canadian Forest Service and USDA Forest Service to develop a new physically-based rate of spread model for crown fires. The testing and calibration of this model was largely the impetus for ICFME.



Dr. Frank Albini ICFME 1997

Albini Physics-based Crown Fire Rate of Spread Model: Comparison Against ICFME Fires

“*Results of the comparison indicate that the model … accurately predicts the relative response of fire spread rate to fuel and environment variables but overpredicts the magnitude of fire spread rates.*” – Butler *et al.* (2004)

Plot	Effective radiometric temperature (K)	Radiation ratio	Predicted rate of spread ($m \cdot min^{-1}$)	Measured spread rate ($m \cdot min^{-1}$)
A	1200	0.30	34	56
A	1200	0.35	62	56
A	1250	0.325	91	56
5	1200	0.35	61	29
5	1250	0.325	89	29
6	1200	0.35	86	36
6	1250	0.325	127	36
7	1200	0.35	74	69
7	1250	0.325	104	69
8	1200	0.35	121	24–54

Note sensitivity to temperature and radiation

Crown fire potential in FCCS (Schaaf *et al*. 2007)

A conceptual framework for ranking crown fire potential in wildland fuelbeds[1]

Mark D. Schaaf, David V. Sandberg, Maarten D. Schreuder, and Cynthia L. Riccardi

Abstract: This paper presents a conceptual framework for ranking the crown fire potential of wildland fuelbeds with forest canopies. This approach extends the work by Van Wagner and Rothermel, and introduces several new physical concepts to the modeling of crown fire behaviour derived from the reformulated Rothermel surface fire modeling concepts proposed by Sandberg et al. (this issue). This framework forms the basis for calculating the crown fire potentials of Fuel Characteristic Classification System (FCCS) fuelbeds (Ottmar et al., this issue). Two new crown fire potentials are proposed (*i*) the torching potential (TP) and (*ii*) the active crown potential (AP). A systematic comparison of TP and AP against field observations and Crown Fire Initiation and Spread (CFIS) model outputs produced encouraging results, suggesting that the FCCS framework might be a useful tool for fire managers to consider when ranking the potential for crown fires or evaluating the relative behaviour of crown fires in forest canopies.

Résumé : Cet article présente un cadre conceptuel pour classer le potentiel de feu de cimes des couches de combustibles en milieu naturel où il y a des canopées forestières. Cette approche pousse plus loin les travaux de Van Wagner et de Rothermel et introduit plusieurs concepts physiques nouveaux dans la modélisation du comportement des feux de cimes dérivés des concepts reformulés de Rothermel pour la modélisation des feux de surface proposés par Sandburg et al. (ce numéro). Ce cadre forme la base pour calculer les potentiels de feu de cimes des couches de combustibles du système de classification des caractéristiques des combustibles (SCCC) (Ottmar et al., ce numéro). Deux nouvelles possibilités de feux de cimes sont proposées : (*i*) la possibilité de flambée en chandelle et (*ii*) la possibilité de feu de cime dépendant. Une comparaison systématique de ces deux types de feux de cimes avec des observations sur le terrain et les prévisions du modèle de l'École canadienne d'enquêtes sur les incendies a donné des résultats encourageants. Ces résultats indiquent que le cadre du SCCC pourrait s'avérer un outil utile que les responsables de la gestion des incendies devraient considérer pour classer le potentiel de feu de cimes ou pour évaluer le comportement relatif des feux de cimes dans les canopées forestières.

[Traduit par la Rédaction]

Introduction

The Fuel Characteristic Classification System (FCCS; Ottmar et al. 2007) offers the capacity to describe the physical characteristics of any wildland fuelbed no matter how complex, and the capacity to compare one fuelbed with another. FCCS enables the user to assess the absolute and relative effects of fuelbed differences due to natural events, fuel management practices, or the passage of time. The differences can be expressed as native physical differences, such as changes in loadings and arrangements of fuelbed components, or as changes in the potential fire behaviour and effects, such as fire behaviour or fuel consumption (Sandberg et al. 2007*b*). Comparing the potential for crown fire initiation and spread among the various FCCS fuelbeds is problematic because there is no broadly applicable and physics-based crown fire model available that accounts for these fuelbed differences. FCCS does not require specific prediction of crown fire behaviour across the full range of fire environments, but does require a relative ranking of crown fire potential over the full range of wildland fuelbed characteristics.

The past 40 years or so of fire research and observations have produced a significant body of literature on crown fires. Van Wagner's (1964, 1968) papers on experimental crown fires in red pine (*Pinus resinosa* Ait.) plantations may be considered the start of the modern era of crown fire research. Subsequent studies ranged from observations of the characteristics of intense, rapidly moving wildfires, to descriptions of fire types (e.g., Van Wagner 1977, Rothermel 1991), to a heuristic key for rating crown fire potential (e.g., Fahnestock 1970), to the development of various mathematical models for predicting crown fire behaviour (e.g., Kilgore and Sando 1975; Scott and Reinhardt 2001; Van Wagner 1977, 1989, 1993). The identification of dependent crown fire thresholds by Scott and Reinhardt (2001) based on stylized fuelbeds and Rothermel's (1972)

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M.D. Schaaf[2] and M.D. Schreuder. Air Sciences Inc. 421 SW 6th Avenue, Suite 1400, Portland, OR 97204, USA.
D.V. Sandberg. USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis OR 97331, USA.
C.L. Riccardi. Pacific Wildland Fire Science Laboratory, USDA Forest Service, Pacific Northwest Research Station, 400 N. 34th St., Suite 201, Seattle WA 98103-8600, USA.

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[2]Corresponding author (e-mail: mschaaf@airsci.com).

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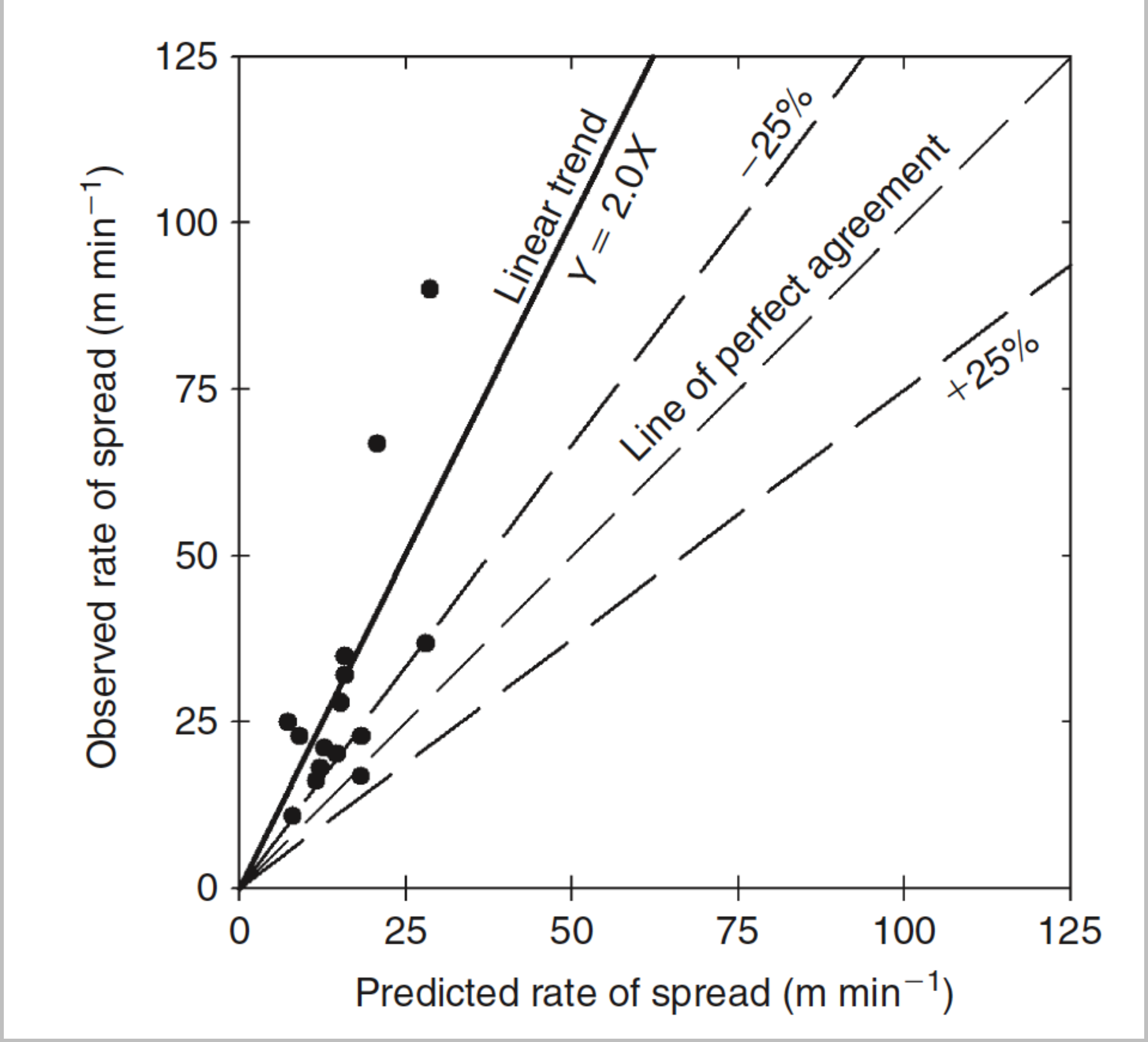
Re-parameterization of Rothermel surface (1972) and crown fire (1991) rate of spread models with updated linkages.

Aimed to describe crown fire potential with Fuel Characteristics Classification System.

Outputs are:

- Torching potential (TP)
- Active crowning potential (AP)
- Crown fire rate of spread

Schaaf et al. (2007) Model Evaluation:
Comparison Against Wildfires in Black Spruce Forests
(data from Alexander and Cruz 2006)



Model output showed under-prediction trend by a factor of 2.

Elliptical Fire Area and Perimeter Growth Potential of Crown Fires

- Area burned by a crown fire is at least 4-9 times greater than a surface fire for the same elapsed time (i.e., ROS Increase to the Power of 2.0).

- Assuming unlimited fuel continuity, crown fires are capable of burning an area of upwards to 70,000 ha with a perimeter length of 160 km in a single burning period.

Crown Fire Flame Dimensions and Spotting Characteristics

Flame flashes in excess of 50 m above the tree tops commonly occur

Wandong, Victoria 1999-00

Byram (1959) indicated that his fire intensity-flame length equation would under-predict the flame length for "… *high intensity crown fires because much of the fuel is a considerable distance above the ground*."

He suggested, on the basis of personal visual estimates, that "… *this can be corrected for by adding one-half of the mean canopy height* …" to the flame length value obtained by his equation. Thus, the equation for crown fire flame lengths (L_c) taking into account stand height (***SH***) becomes :

$$L_c = 0.0775 \cdot (I)^{0.46} + (SH/2)$$

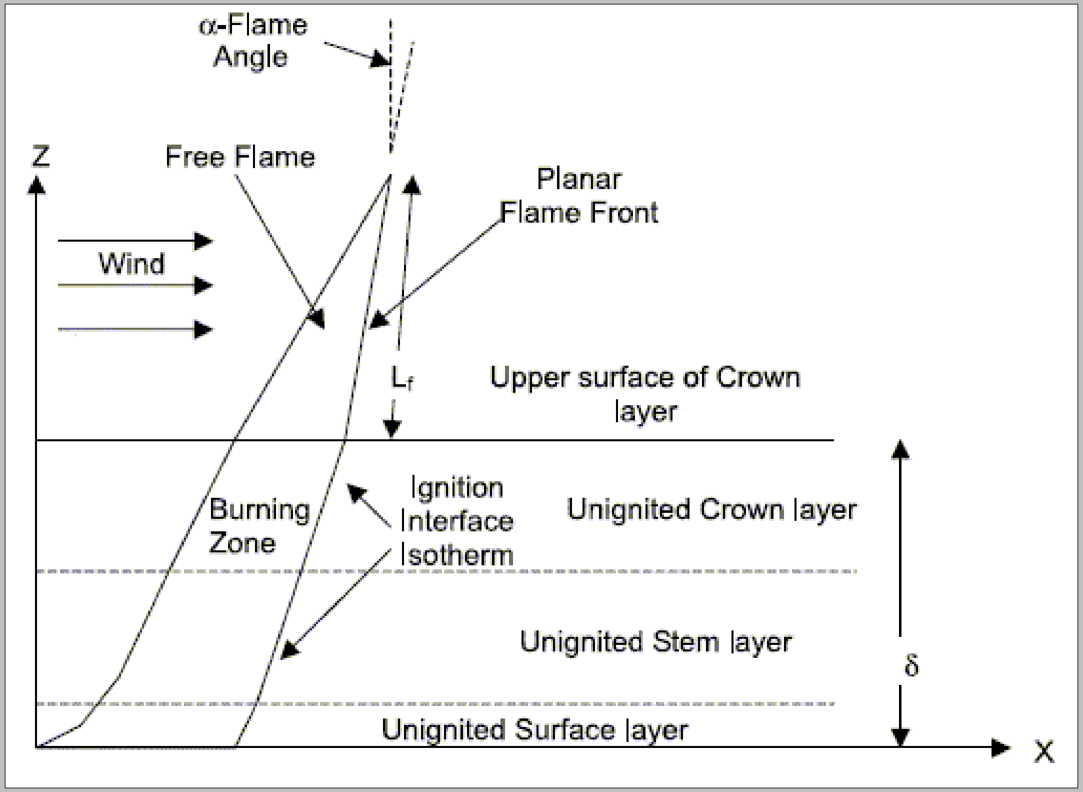
Rothermel (1991) suggested using Thomas' (1963) relation to estimate the flame lengths of crown fires from fire intensity:

$$L_c = 0.0266 \cdot (I)^{2/3}$$

More recently Butler *et al.* (2004) proposed the following relation for calculating the flame lengths of crown fires from fire intensity:

$$L_f = 0.0175 \cdot (I)^{2/3}$$

Where L_f is the flame length measured from the upper surface of the fuel array.



None of these methods seem to work consistently well based on comparisons against experimental crown fires undertaken in Canada. Take, for example, the following experimental crown fires in red pine plantations (***SH*** = 15 m) documented by Van Wagner (1977).

		------------- Predicted L_c (m) ---------		
Exp. Fire	**Obs. L_c (m)**	**Byram (1959)**	**Thomas (1963)**	**Butler *et al.* (2004)**
C4	**19.8**	**15.1**	**20.2**	**28.8**
C6	**30.5**	**15.3**	**21.2**	**29.4**

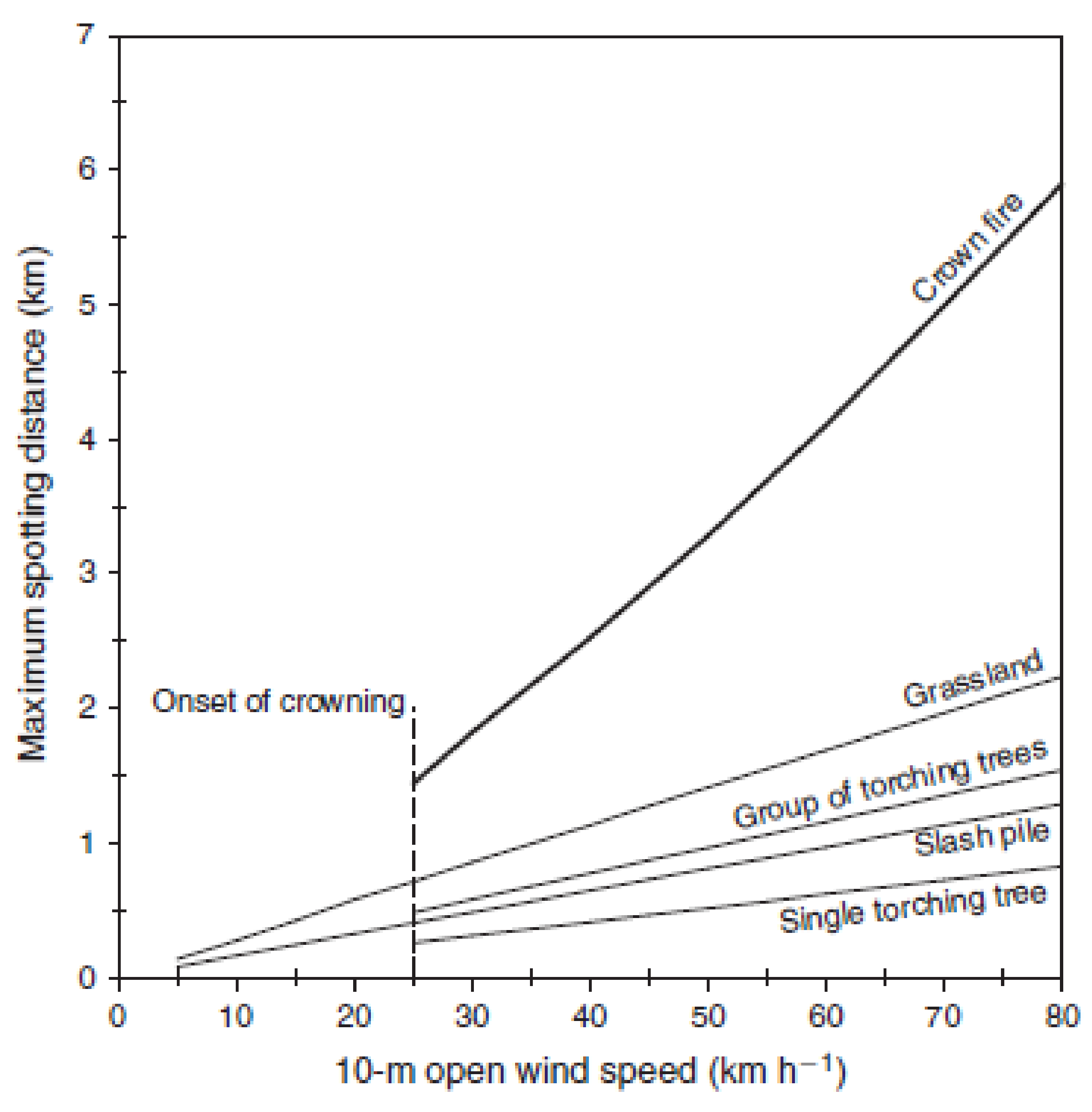
General Observation Based on Experimental Crown Fires:

The flame front depth increases as fire intensity increases rather than a corresponding increase in the vertical flame length.

ICFME Plot 9 – Fireline Intensity ~93,000 kW/m

Alexander’s Simple Rule of Thumb for Crown Fire Flame Heights:
2-3 x Stand Height for Active Crown Fires

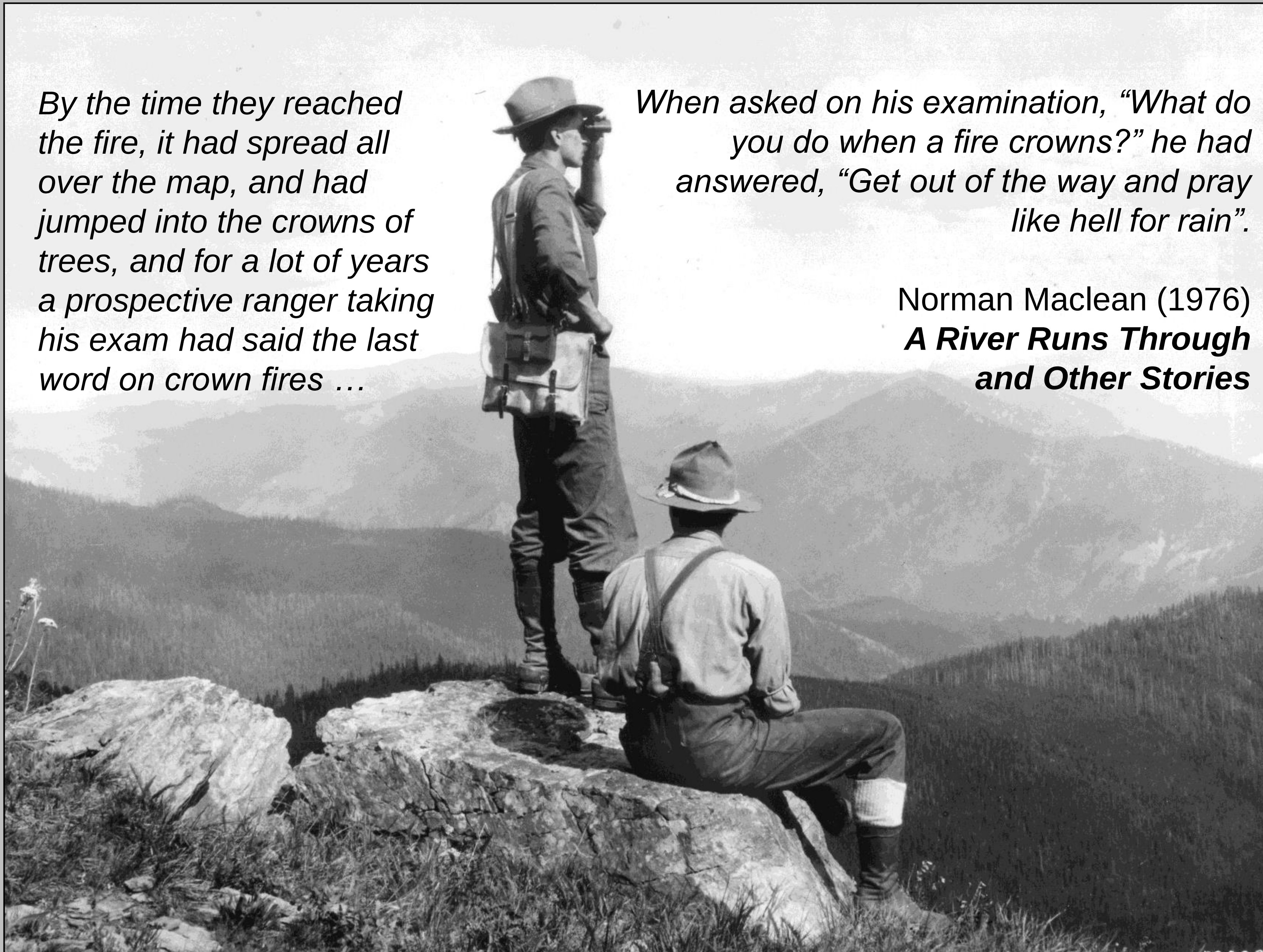
Albini's Maximum Spotting Distance Models Output



from Albini, Alexander and Cruz (2012)

Some Salient Points Regarding Crown Fires

How crown fires were handled by the U.S. Forest Service in the 1900s?



By the time they reached the fire, it had spread all over the map, and had jumped into the crowns of trees, and for a lot of years a prospective ranger taking his exam had said the last word on crown fires …

When asked on his examination, “What do you do when a fire crowns?” he had answered, “Get out of the way and pray like hell for rain”.

Norman Maclean (1976)
A River Runs Through and Other Stories

Basic Features of a Crown Fire

- Fierce radiation due to large flame depth/heights (up to 50+ metres).
- Sustained fire runs possible (e.g., 64 km in 10 hours)
- Wide range in rate of fire spread (0.6 – 12 km/h)
- Very wide range in fire intensities (2500 – 100,000 kW/m)
- Flame front residence time in tree crowns at least half that of ground surface
- Contributes to medium and long-range spotting and in turn breaching of major barriers to fire spread
- High amounts of convective energy produce massive convection columns

What happens when a fire "crowns"?

1. Additional fuel is consumed primarily in the form of needle foliage but also in mosses and lichens, bark flakes, and small diameter woody twigs.

2. The additional canopy fuel consumed by a crown fire combined with the increase in rate of fire spread that occurs after crowning can easily lead to a quadrupling in fireline intensity.

3. A dramatic increase in both flame height and depth and in turn radiant and convective heat takes place within a few seconds.

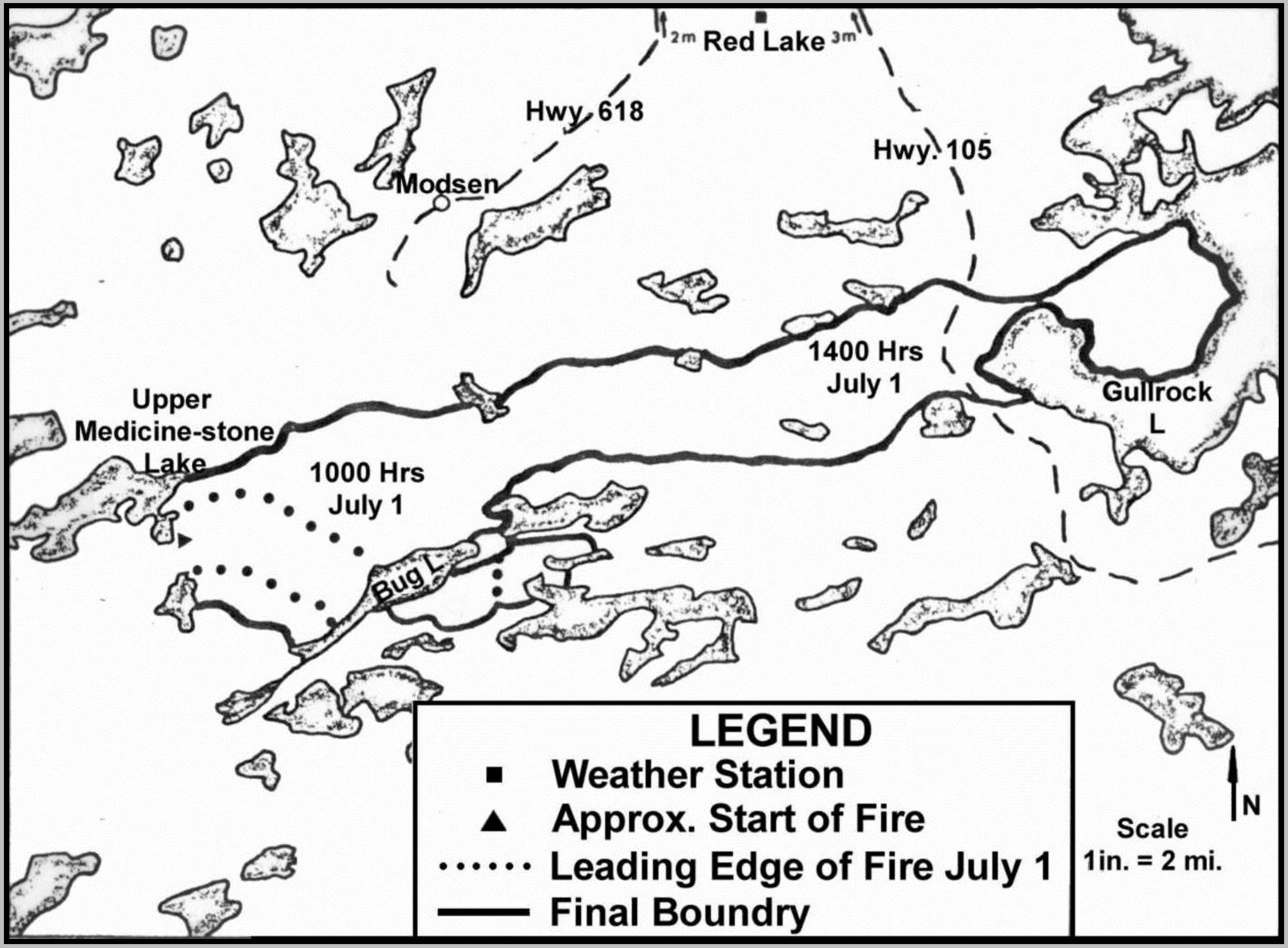
4. Spotting activity can also very quickly increase in both density and distance.

So Is there any wonder why crown fires seem to literally "blowup"?!

The situation is further exacerbated by a fire:

- **transitioning from a point to a line source;**
- **encountering a major change in slope steepness;**
- **entering a chimney or chute; or**
- **any combination of the above, including all three**

Operational fire personnel can readily help themselves by increasing the amount of wildfire monitoring and case study documentation

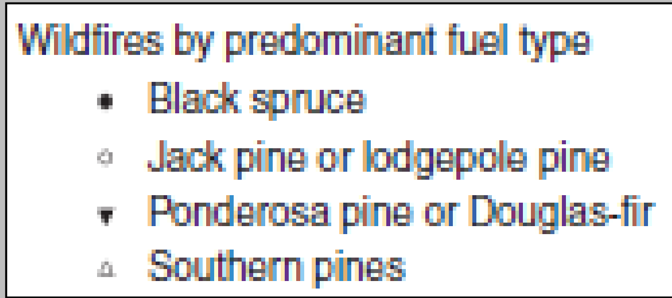


Crown Fire Model Development and Evaluation

- A universally accepted model or model system for predicting the basic characteristics of crown fire behaviour (i.e., the start, spread and demise) has yet to be developed, although Van Wagner's (1977) seminal paper has proved useful.

- Empirical-based systems for predicting crown fire behaviour operationally have been developed from Canadian experimental fires (i.e., Canadian Forest Fire Behavior Prediction System, Crown Fire Initiation and Spread (CFIS) model system). The models incorporated into CFIS have been extensively tested and shown to be reasonably reliable.

- Under-prediction bias evident in simulation studies involving U.S. fire modelling systems (e.g., BehavePlus, NEXUS, FARSITE) when compared to empirical observations.



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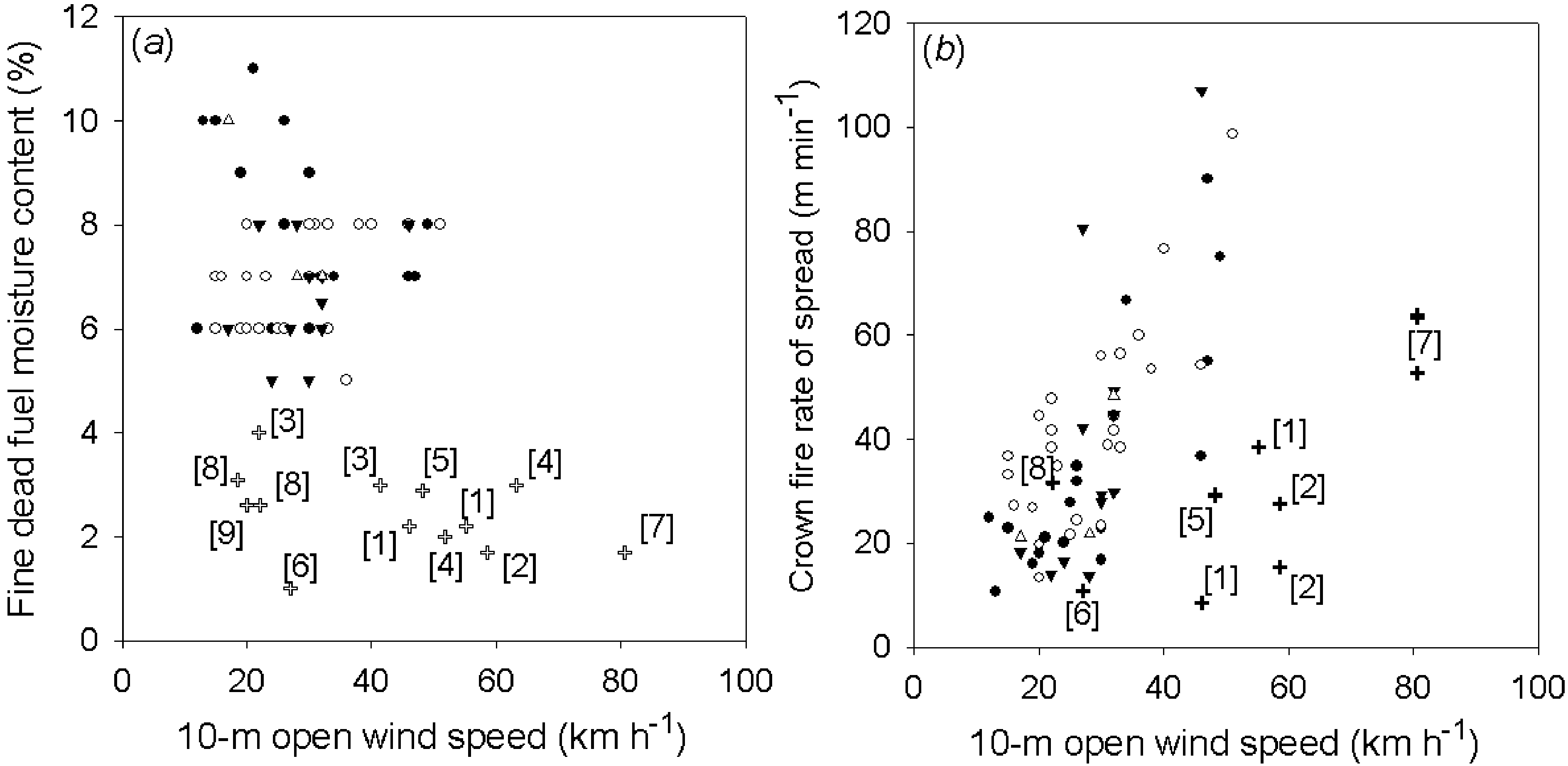
Simulation Studies



from Cruz and Alexander (2010)

Topics Considered Worthy of Investigation/Study:

- ❑ Model for predicting crown fire flame height.

- ❑ A model for predicting crown fire cessation based on wind and fuel characteristics.

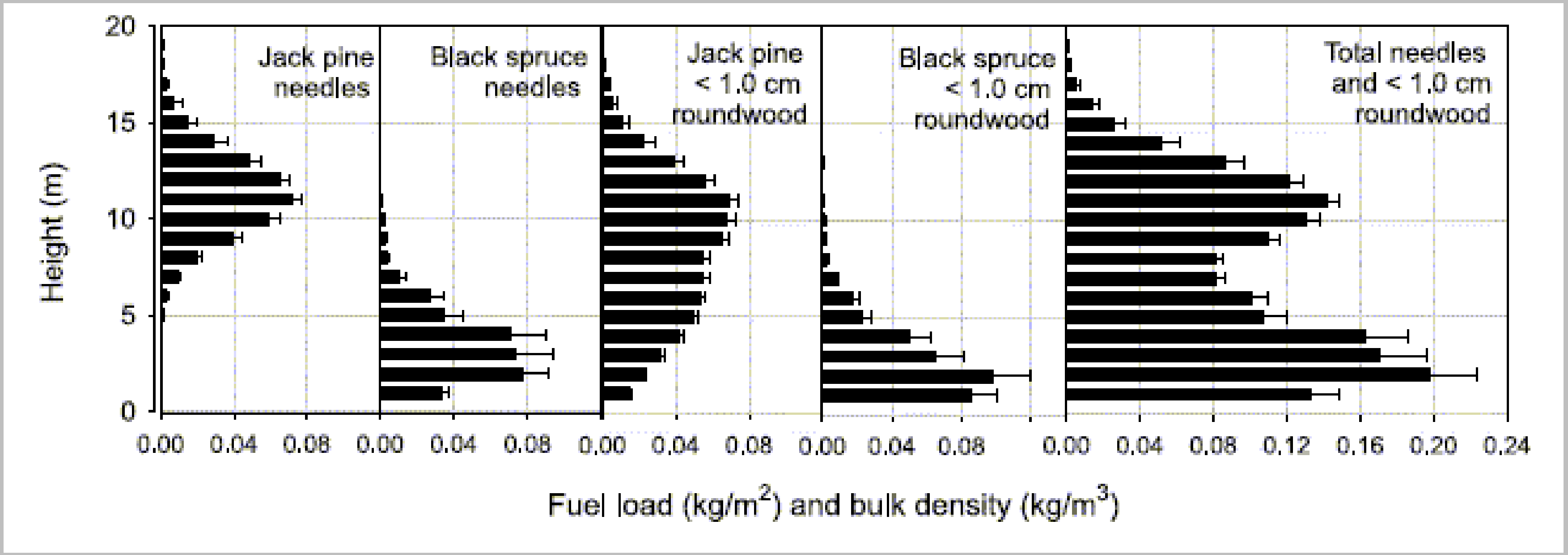
- ❑ Additional emphasis placed on the prediction of surface fire rate of spread and flame front characteristics (e.g., flame front residence time).

- ❑ Vertical fire spread (critical ***CBD***) into the overstory canopy, including ladder fuel effects (e.g., bark flakes).

How to define Crown Base Height (CBH)?

Van Wagner's (1977) Assumptions:

• "*Vertical spread of fire into the overstory canopy is for practical purposes independent of the canopy bulk density*".



Minimum Crown Bulk Density to Define the (CBH)

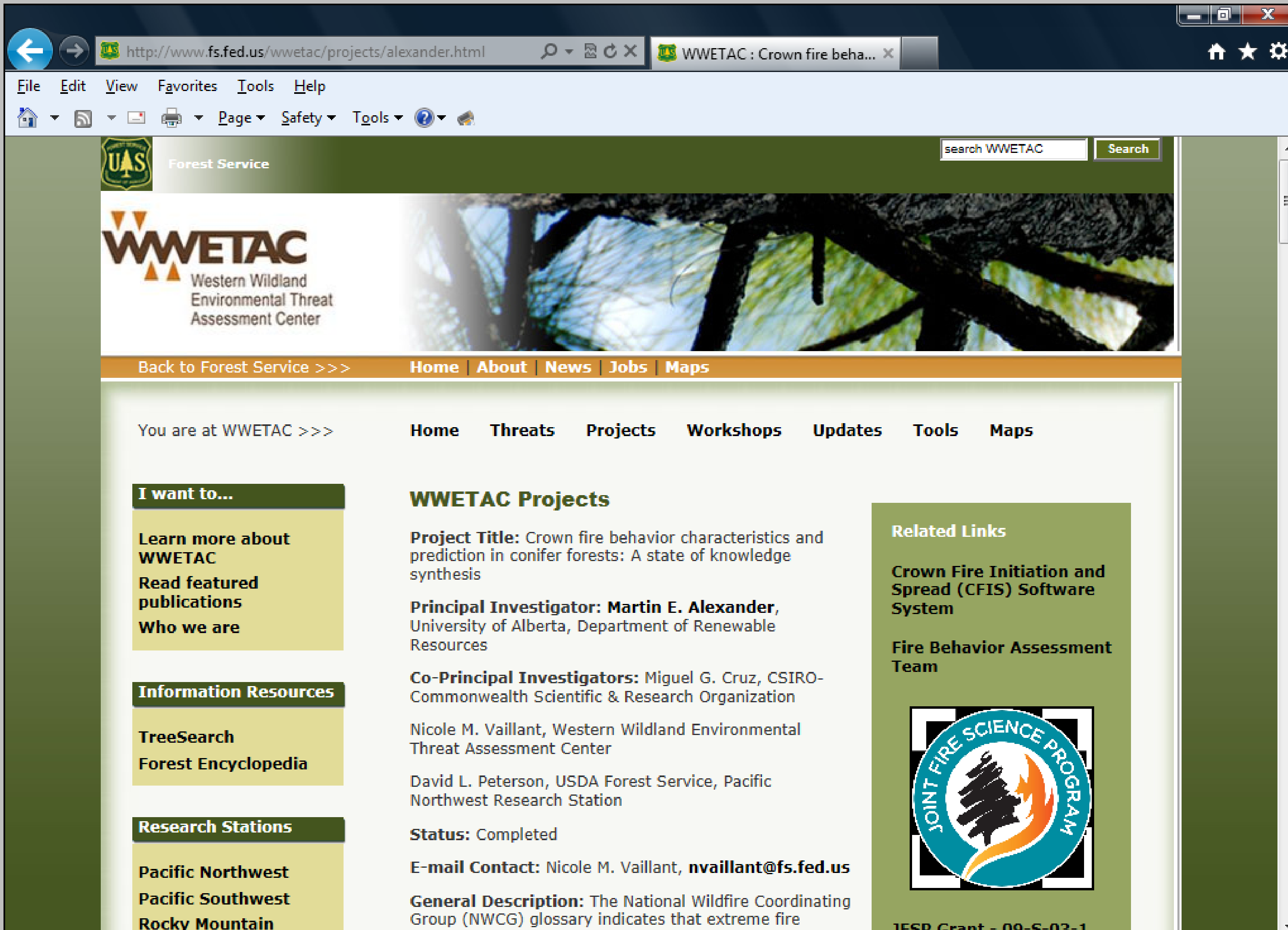
• Sando and Wick (1972) – 0.037 kg/m³

• Williams (1977) – 0.074 kg/m³

• Scott and Reinhardt (2001) – 0.011 kg/m³

"…but little or no laboratory research to quantify threshold value"

For More Information



http://www.fs.fed.us/wwetac/projects/alexander.html

E-mail Contacts

Marty Alexander
mea2@telus.net

Miguel Cruz
miguel.cruz@csiro.au

THE END

Thank you for your attention.

Do you have questions or comments?