

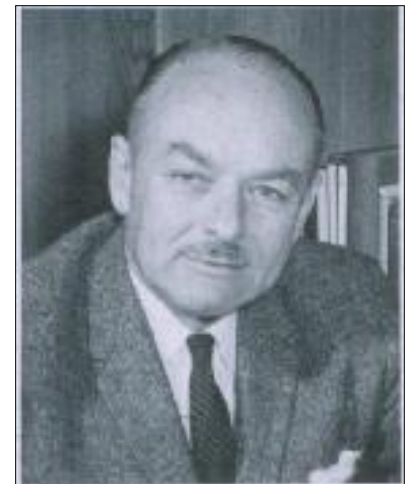
FOREST HEALTH: Fire Behavior Considerations

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Fire Behavior and the Forest Manager

“ The behavior of fires is an important factor in the growth, harvesting, and regeneration of forest crops. How often fires occur and how hot they burn affect ... the ... quantity of products harvested from the forest. The forest manager may influence fire behavior by the nature of his operations ... it is important for forest managers to know fire behavior and to be able to evaluate the influence of forest management operations on it.” – J.S. Barrows (1951)



Purpose of Presentation:

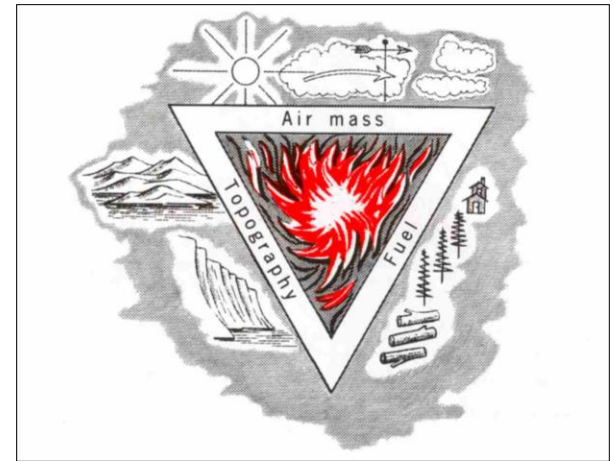
Provide a overview (for the non-specialist) of relevant fire behavior terms and concepts, existing tools for predicting fire behavior at the stand level (with particular emphasis on crown fire), and finally, to offer some suggestions for future direction

Outline of Presentation:

- I. Fire Behavior Fundamentals**
- II. Prediction of Fire Behavior**
- III. Conclusions and Suggestions on Future Direction**



I. “FIRE BEHAVIOR 101”: The Fundamentals



Fire behavior is defined as the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography (i.e., the fire environment).

Fire Environment Factors

Fuel Characteristics:

- Quantity
- Moisture
- Size & Shape
- Depth/Height
- Arrangement



Weather Characteristics:

- Wind Speed & Direction
- Relative Humidity
- Air Temperature
- Rainfall Amounts & Duration
- Cloud Cover
- Atmospheric Instability



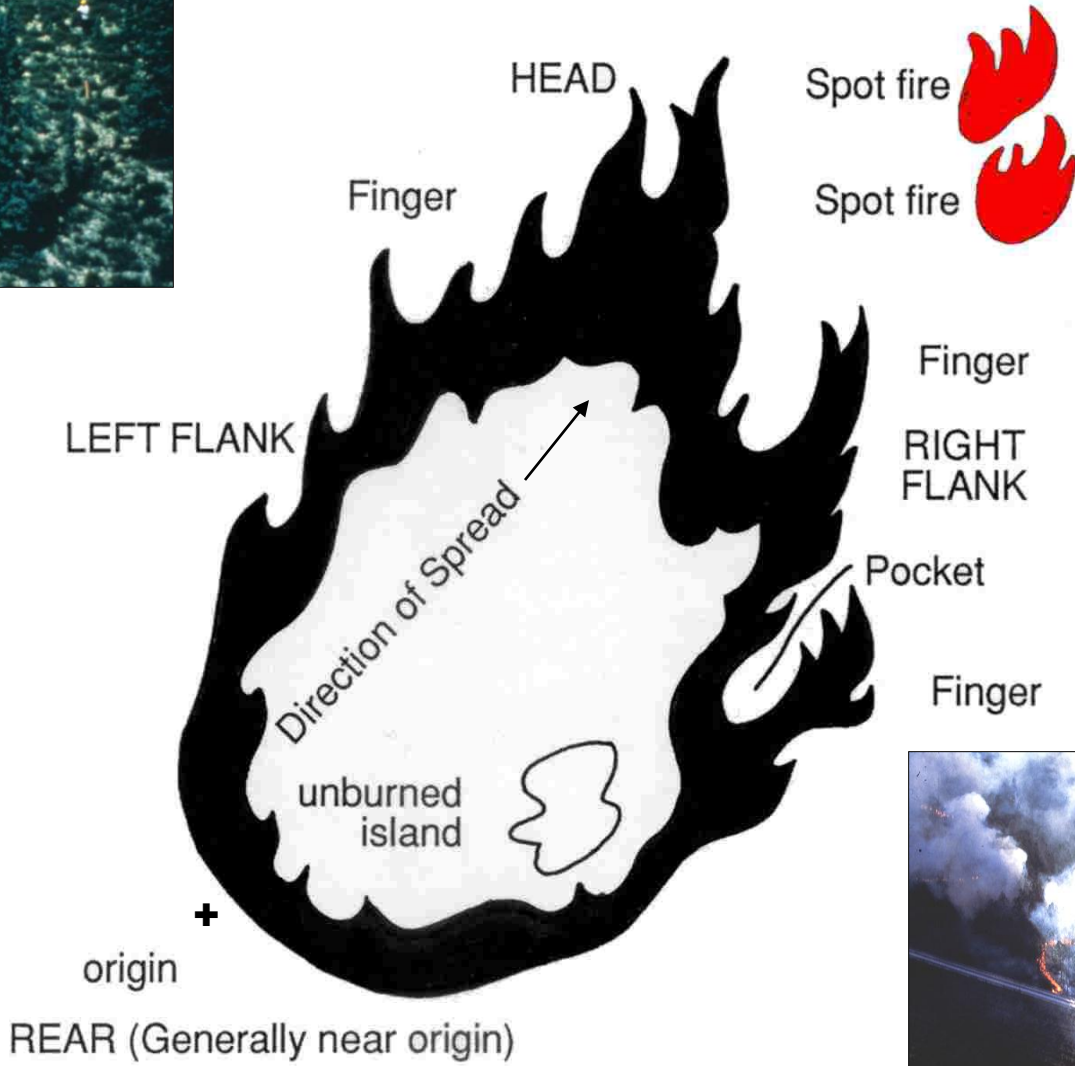
Topographic Characteristics:

- Slope Steepness & Aspect
- Elevation
- Configuration
- Barriers to Fire Spread





PARTS OF A FIRE



Nominal Spread Rates for Wildland Fires

Ground or Subsurface Fires: < 0.01 m/min

Surface Backfires

in Forests:

$0.1 - 1.0$ m/min



Surface Head Fires

in Forests:

$1 - 10$ m/min

Crown Fires in Forests:

$15 - 200$ m/min



Grass Fires:

up to $250 - 350$ m/min



Basic Features of a Forest Fire:

It spreads ...



**it
consumes
or
“eats” fuel
and ...**

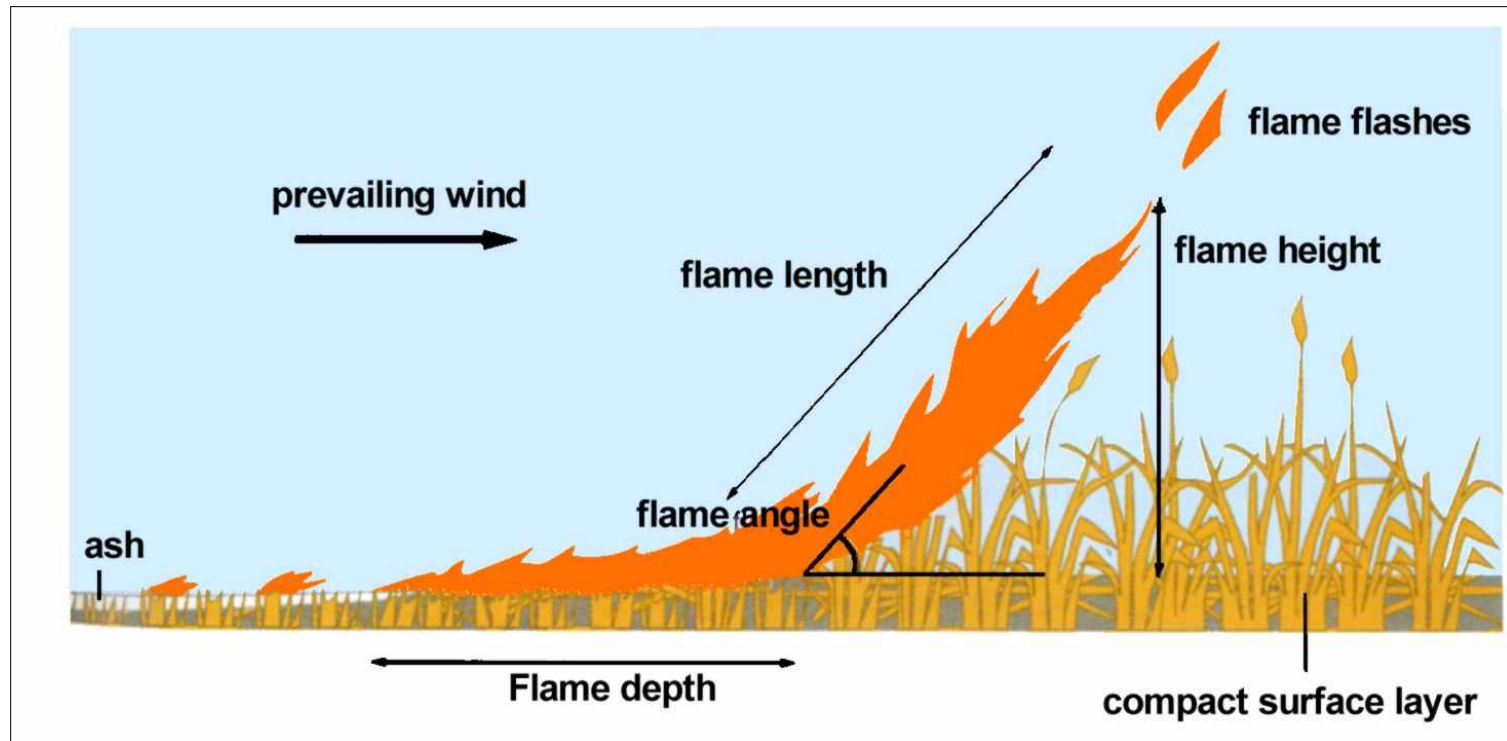


**it produces
heat energy
and light in
...**



**... a visible
flaming
combustion
reaction.**

Fire intensity is related to size of flames



Simple Formula for Field Use
(for surface fires & intermittent crown fires)

$$I = 300 \times (L)^2$$

L = Flame Length (metres)

For active crown fires, flame height ~ 2X stand height



Extreme fire behavior represents a level of fire activity that often precludes any fire suppression action. It usually involves one or more of the following:

- **High Rate of Spread & Intensity**



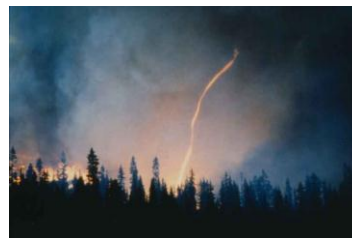
- **Crowning**



- **Prolific Spotting**



- **Large Fire Whirls**



- **Well-developed Convection Column**



Comparison of Fire Behavior in a Pine Plantation under High Fire Danger Conditions

(adapted from McArthur 1965)

Fire Description and Characteristics	Stand A (pruned up to 5 m)	Stand B (unpruned)
Type of fire	Surface	Crown
Forward spread rate (m/min)	5	10
Fuel Consumed (t/ha)	18	28
Head fire intensity (kW/m)	2700	8400
Flame height (m)	2	12
Fire area @ 1 hour (ha)	4.86*	19.44*
Fire perimeter @ 1 hour (km)	0.83	165
Spotting distance (m)	<200	up to 2000

***Area enlargement = (Rate of Spread Increase)²**

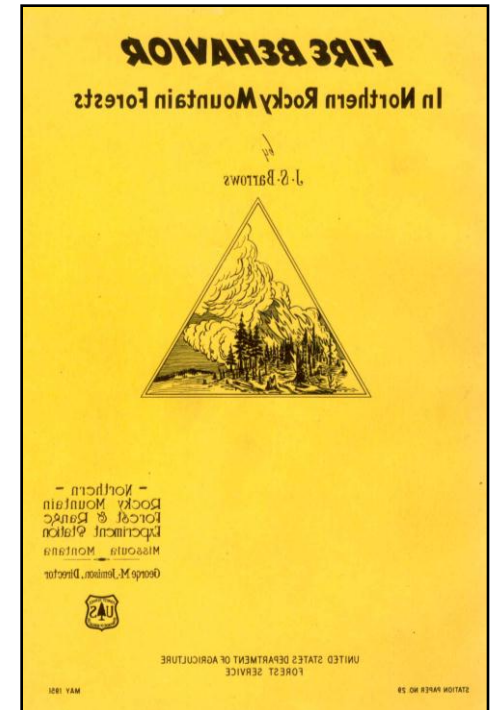
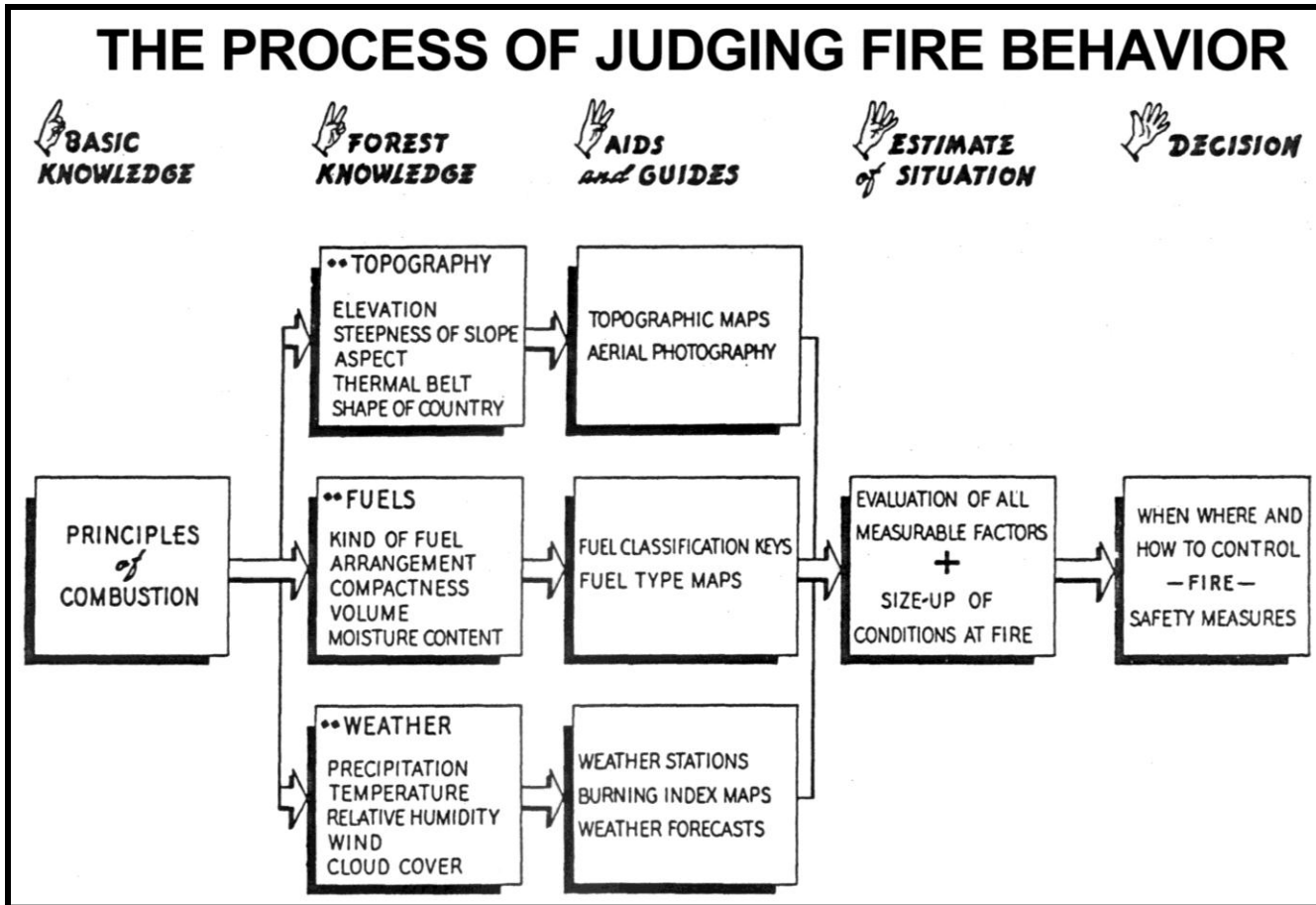
The more important fire behavior characteristics from the practical standpoint of fire suppression are:

- **Forward Rate of Spread**
- **Fire Intensity**
- **Flame Front Dimensions**
- **Spotting Pattern (densities & distances)**
- **Fire Size and Shape**
- **Rate of Perimeter Increase**
- **Burn-out Time**

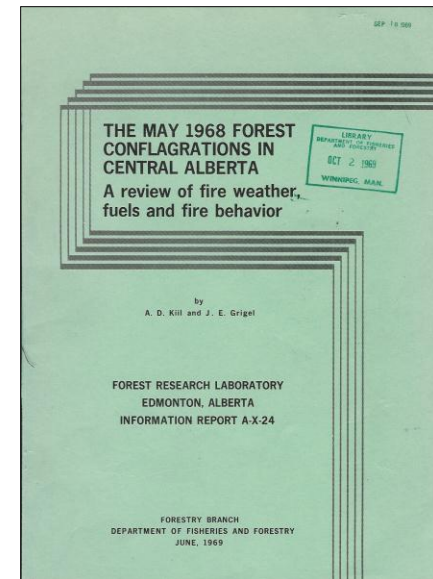
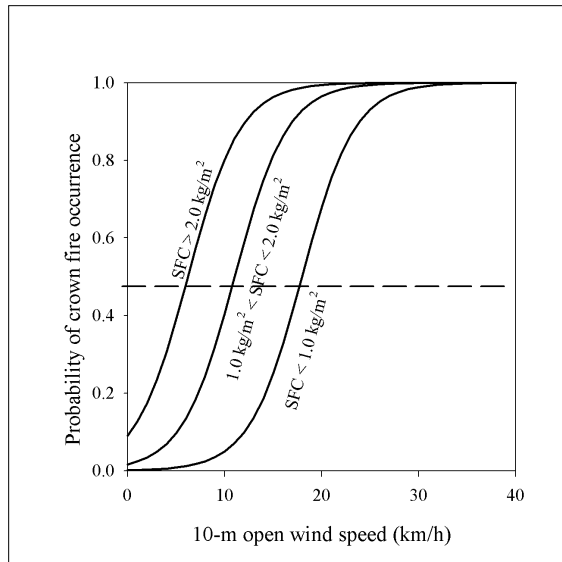


II. Predicting Fire Behavior

Systematic analysis that combines “art and science”



The most effective means of appraising or evaluating potential fire behavior is considered to be the coupling of mathematical modelling with experienced judgement (e.g., “expert opinion”), and published case study knowledge (e.g., experimental, wild and prescribed fires)



Fuel dynamics and variation of flammability during the development of jack pine/black spruce stands

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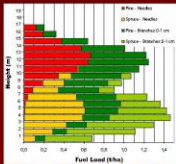
FIRE ENVIRONMENT



We first selected 14 stands belonging to the same chronosequence and originating from a high intensity crown fire. The stands were between 1 and 109 years since fire.

FUELS

The ground, surface, ladder, and aerial fuels were sampled in each stand. Stand age/height data was also collected.



Vertical distribution of the fine fuels (needles and branches) in the canopy of a mature stand.

WEATHER

The historical weather and Fire Weather Index System components were analysed for the closest weather stations.



Results of the frequency analysis for some of the Fire Weather Index System components.

TOPOGRAPHY

The stands selected were located on flat terrain to eliminate the slope effect on fire behavior.

ACKNOWLEDGEMENTS

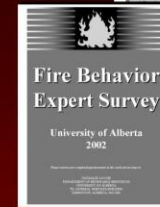
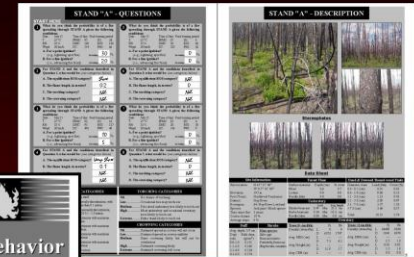
We would like to thank:
- The Government of the Northwest Territories, Department of Resources, Wildlife and Economic Development for its support during this project.
- The Canadian Natural Sciences and Engineering Research Council of Canada for its support during this project.
- The Canadian Natural Sciences and Engineering Research Council of Canada for its support during this project.

References cited:
- Anderson, R. L., 1984. *Fire Behavior Prediction and Fuel Modeling Systems - A Review*, part 1. *Forest Fire: Soc. Am. Soc. For. Int.* 208.
- Côté, R.G., Desjardins, M.C., Gagnon, G., 2002. *Producing a Fuel Model for Forest Fire Research*. *Information Report NOR-X-389*. Northern Forestry Centre, Northern Forestry Centre, Northern Forestry Centre, Northern Forestry Centre.
- Jain, S. S., 1976. Succession. In: R. M. May (ed). *Theoretical Ecology: Principles and Applications*. McGraw-Hill, New York, 107-201.

Very little is known about the dynamics of the fuels during stand development and about the variation of flammability with time-since-fire... We used the following methodology to learn more about the topic.



EXPERT OPINION



- A scenario-based questionnaire allowed us to tap the collective experience and the knowledge of 50 forest fire behavior experts.
- The survey provided us with relevant information for the project based on a large number of fires - more than it is usually possible to observe and reproduce experimentally.

EXPERIMENTAL FIRES

- Experimental fires in young stands up to 4 years since a stand replacing crown fire indicated that a reburn is unlikely in those stands.
- Experimental fires in microplots also showed that the patchy surface vegetation does not burn in these young stands.
- Only certain materials (i.e., stumps, punky wood, logs) burnt during those experimental fires despite, sometimes, extreme fire danger conditions.
- Whenever possible, we performed simultaneous ignitions to observe the effect of different fuels on the fire behavior, while keeping the weather conditions constant.



Reburn of a 3-year-old stand (left) on the same day (June 28th, 2000) as an experimental crown fire in a mature stand (right).

Fire Weather Index System Components

Fine Fuel Moisture Code (FFMC)	932
Duff Moisture Code (DMC)	65
Drought Code (DC)	454
Initial Spread Index (ISI)	10.8
Buildup Index (BI)	93
Fire Weather Index (FWI)	32

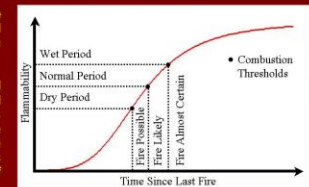
Weather Conditions

Temperature (C)	25.3
Relative Humidity (RH)	32
10-m open wind speed (km/h)	23.1
Days since rain	3

FIRE BEHAVIOR MODELS

- Within the next few months, we will proceed to the integration of the data from: a) the characterization of the fire environment, b) the expert opinion, and c) the experimental fires.
- That information will be supplemented with fire behavior models such as those presented by Andrews (1986) and Cruz *et al.* (2002).
- Our results will be compared with the model presented by Horn (1978).

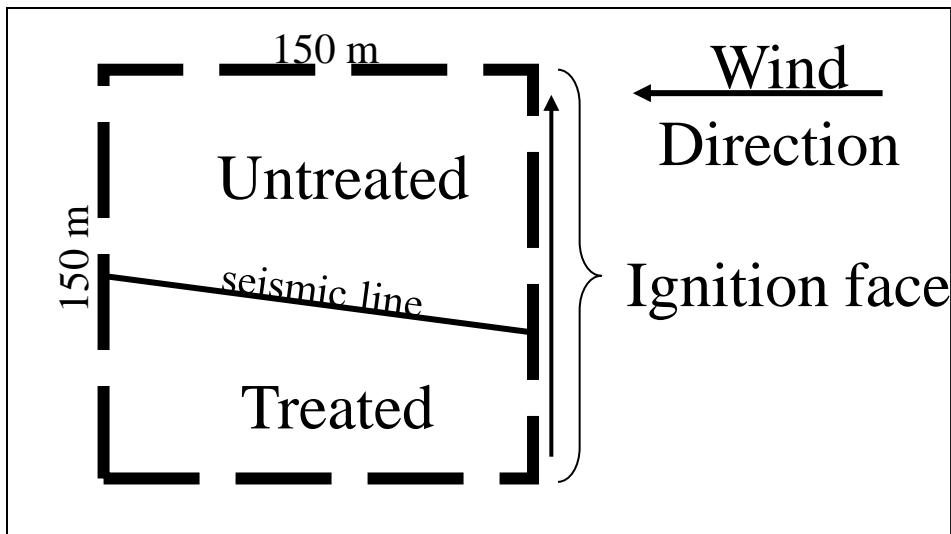
In his hypothetical model, the temporal pattern of fires depends as much upon the intrinsic shape of the curve of flammability as on the occurrence of droughts.



Representation of the hypothetical model presented by Horn (1978).

See Lavoie, N. 2004. Variation in flammability of jack pine/black spruce forests with time since fire in the Northwest Territories, Canada. Ph.D. Thesis, University of Alberta. 332 p.

ICFME Treated/Untreated Plot, NWT – June 14, 2000



At end of Treated half



At end of Untreated half



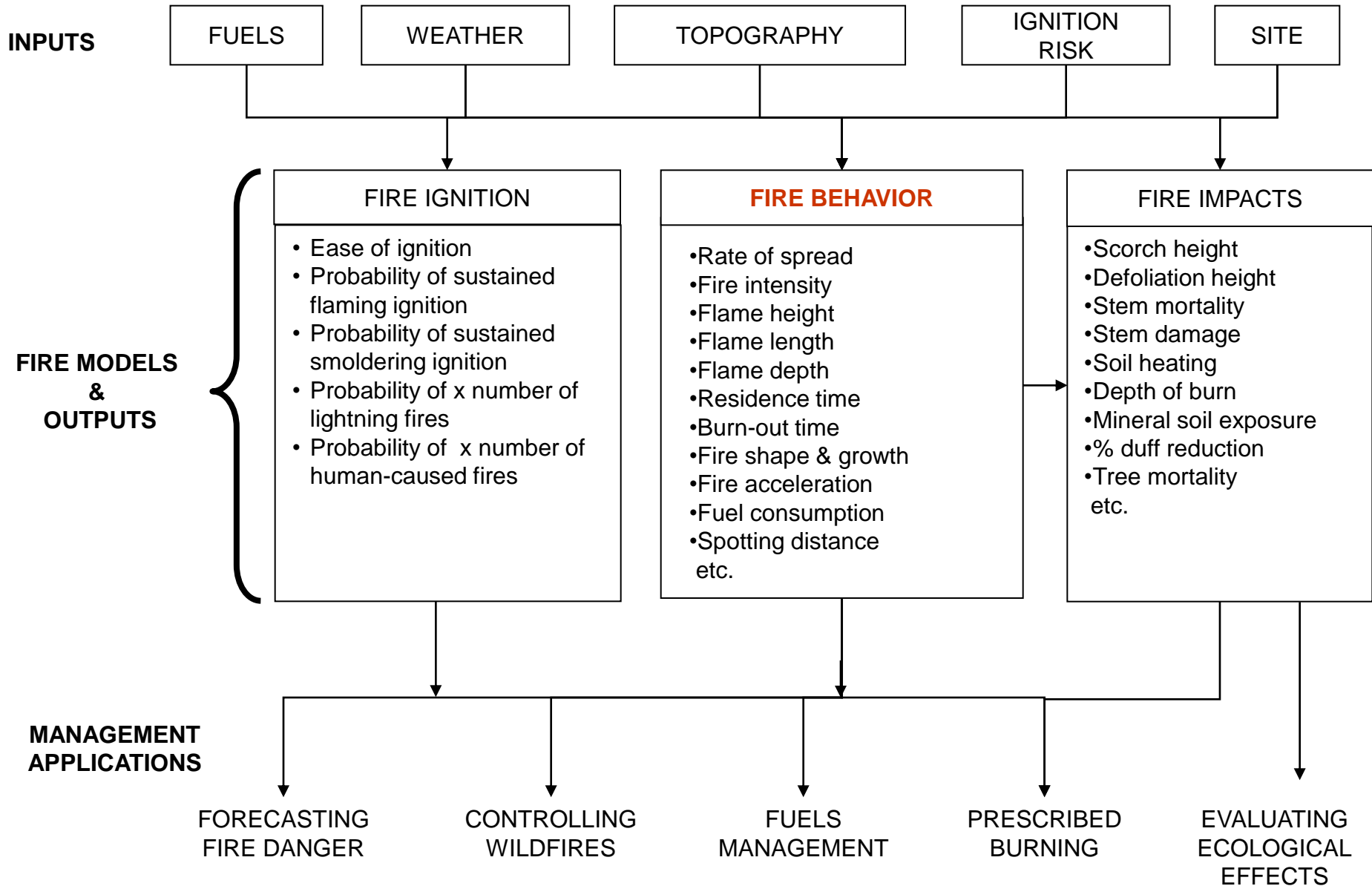
Note
“prune
line”



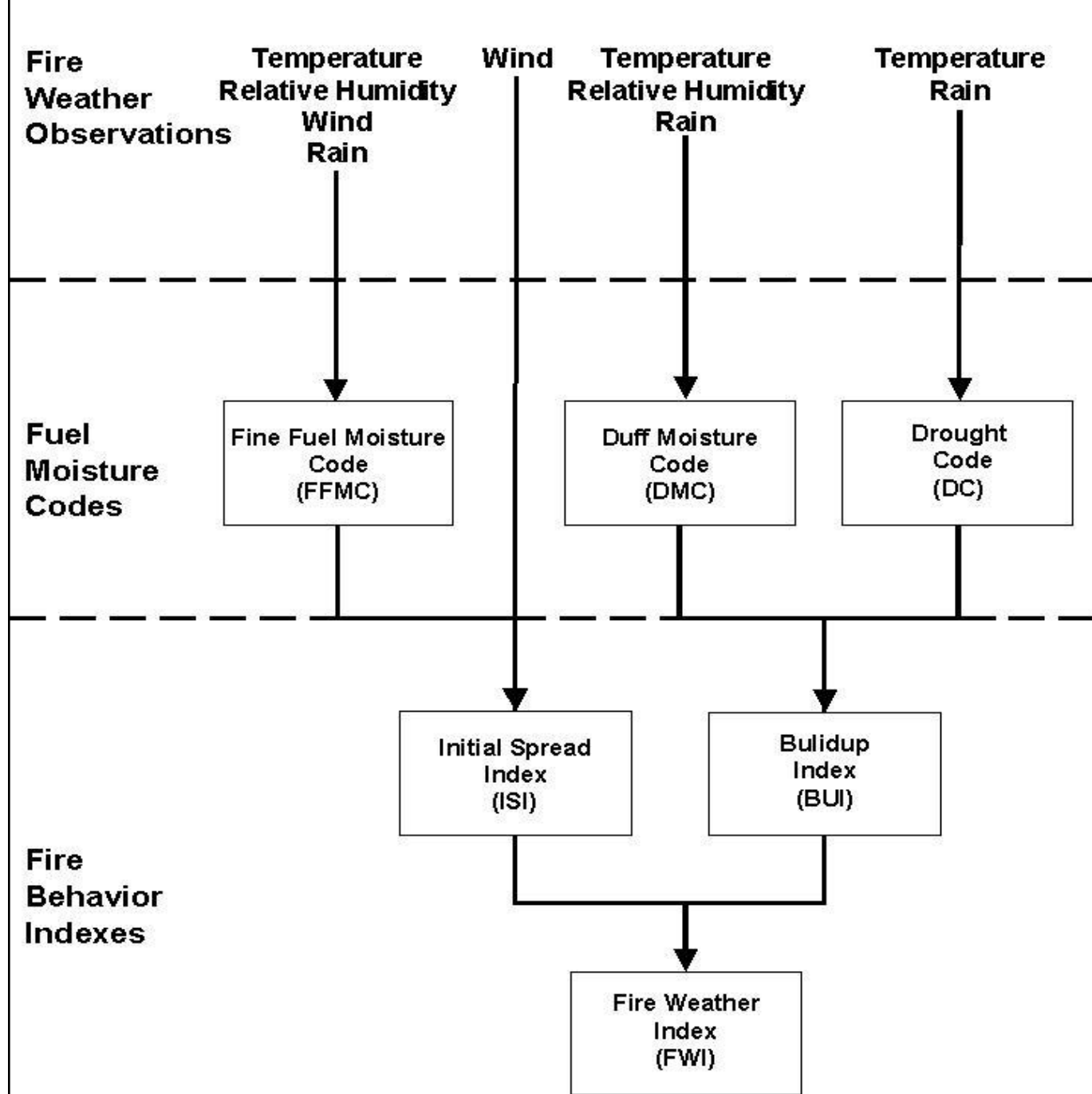
Fire in progress

ICFME
Treated/Untreated
Plot, NWT –
June 14, 2000

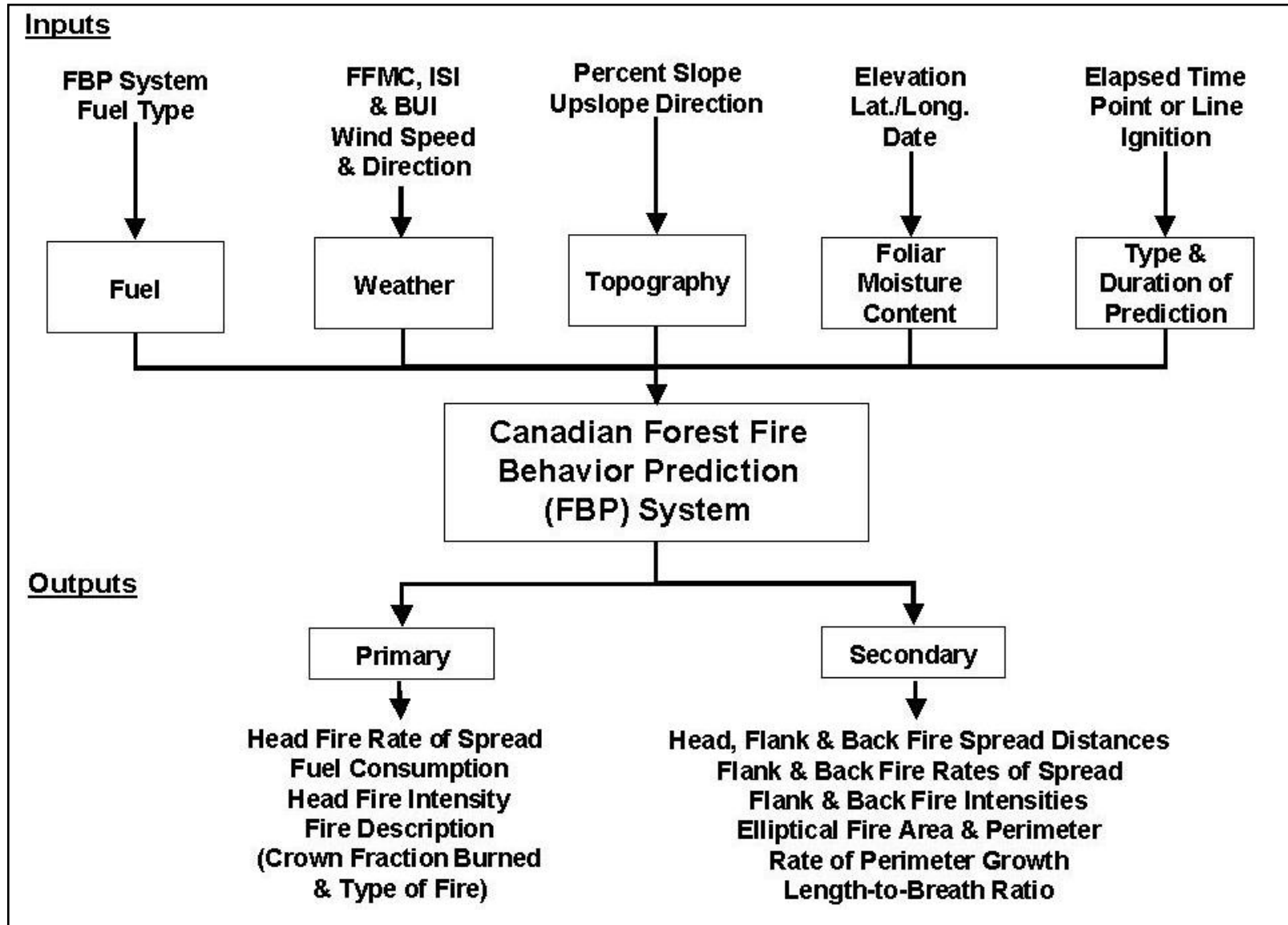
Conceptual Model of Scientifically-based Forest Fire Management



Structure of the Canadian Forest Fire Weather Index (FWI) System



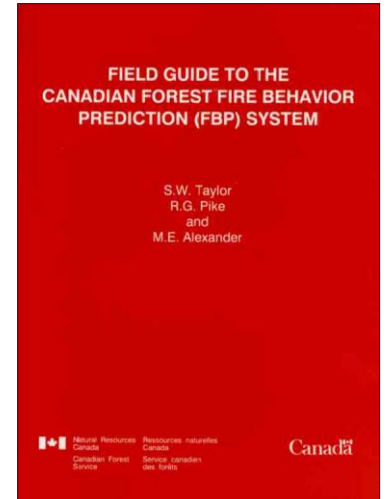
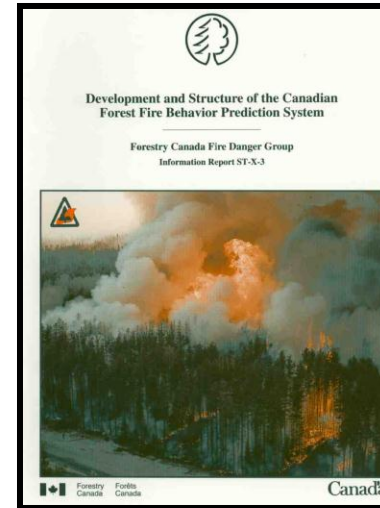
Structure of the Canadian Forest Fire Behavior Prediction (FBP) System



Experimental Fire



Basis of FBP System & Documentation

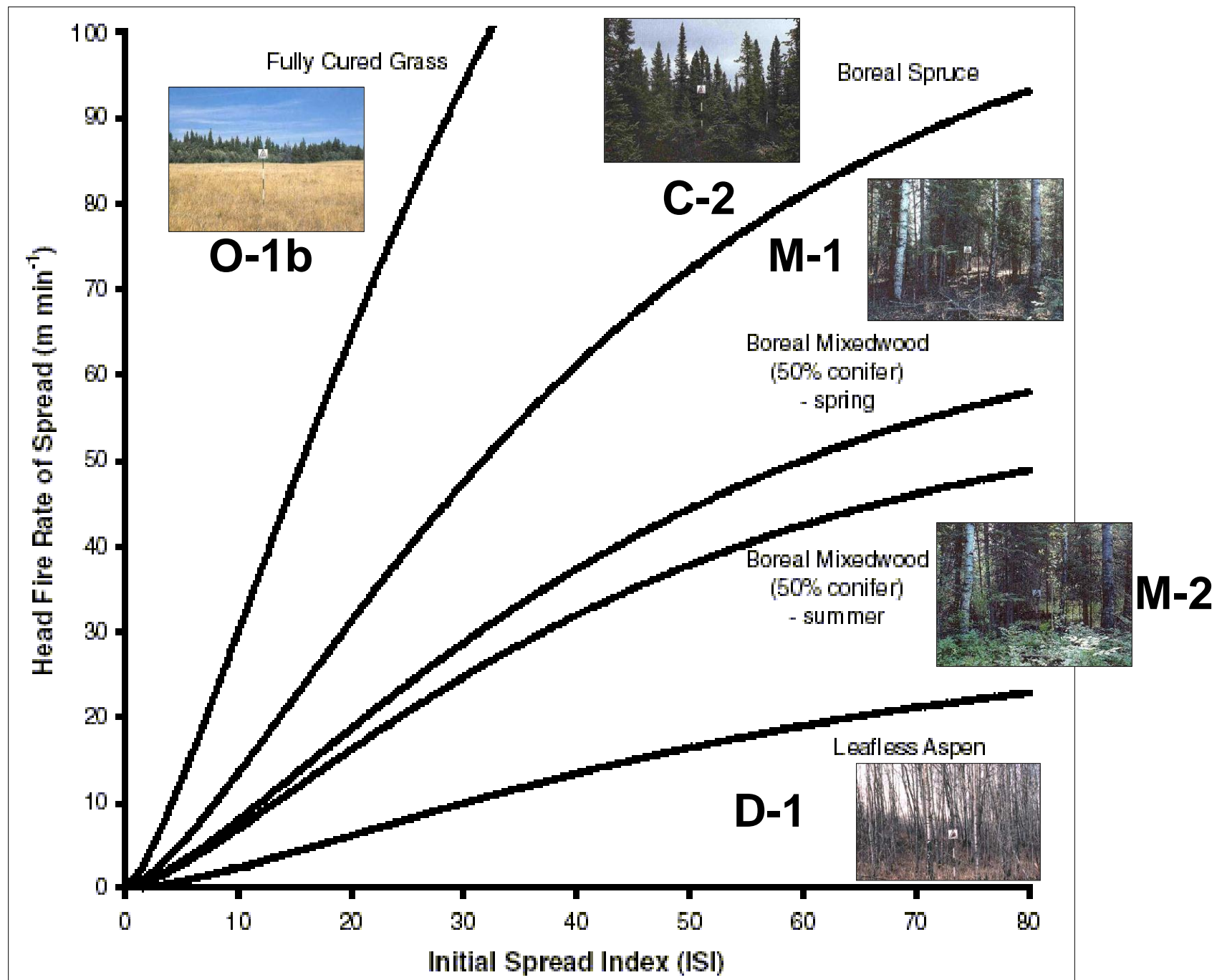


Operational Prescribed Fire



List of FBP System Fuel Types

General Category	Fuel Type	Input Modifier
Coniferous	C-1 Spruce-Lichen Woodland	-
	C-2 Boreal Spruce	-
	C-3 Mature Jack or Lodgepole Pine	-
	C-4 Immature Jack or Lodgepole Pine	-
	C-5 Red and White Pine	-
	C-6 Conifer Plantation	Live Crown Base Height
	C-7 Ponderosa Pine/Douglas-fir	-
Deciduous	D-1 Leafless Aspen	-
Mixedwood	M-1 Boreal Mixedwood-Leafless	% Conifer/Hardwood
	M-2 Boreal Mixedwood-Green	% Conifer/Hardwood
	M-3 Dead Balsam Fir/Mixedwood-Leafless	% Dead Fir
	M-4 Dead Balsam Fir/Mixedwood-Green	% Dead Fir
Slash	S-1 Jack or Lodgepole Pine Slash	-
	S-2 Spruce/Balsam Slash	-
	S-3 Coastal Cedar/Hemlock/Douglas-fir Slash	-
Open	O-1a Matted Grass	% Degree of Curing
	O-1b Standing Grass	% Degree of Curing



C-6 Fuel Type - Conifer Plantation



(Allowance for variable
crown base height)



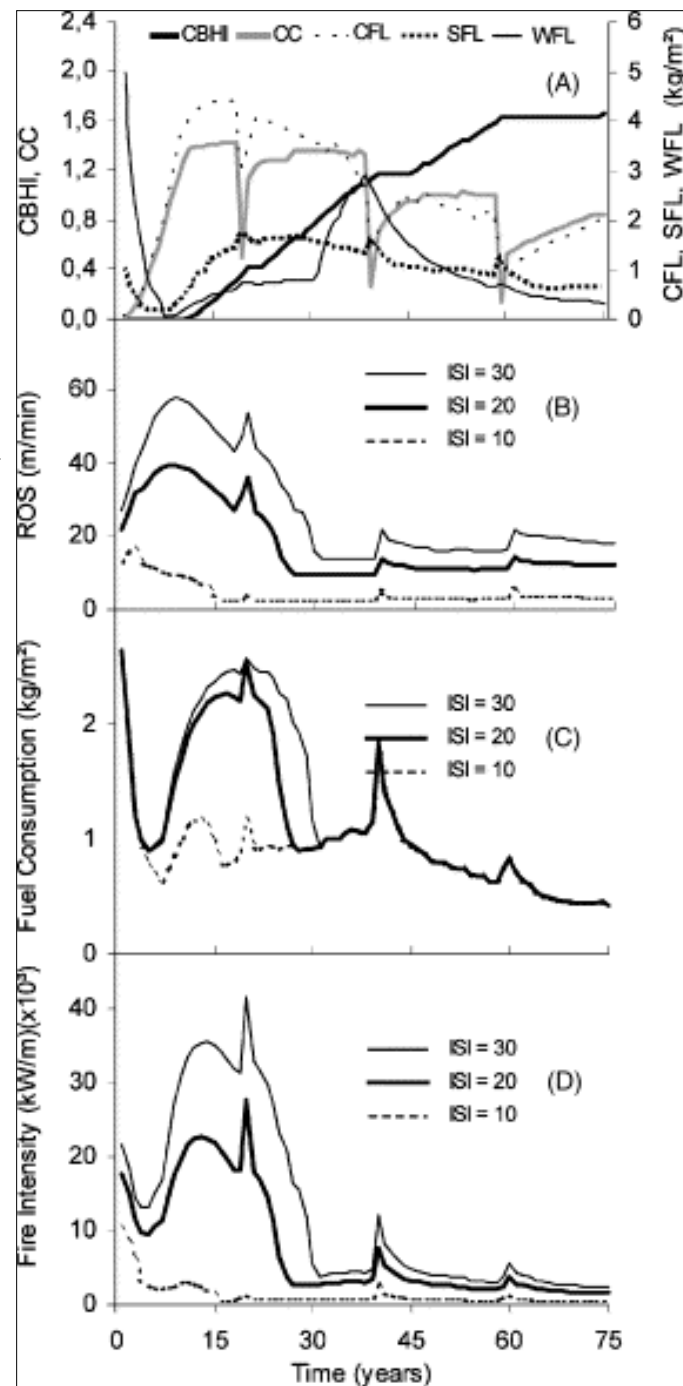
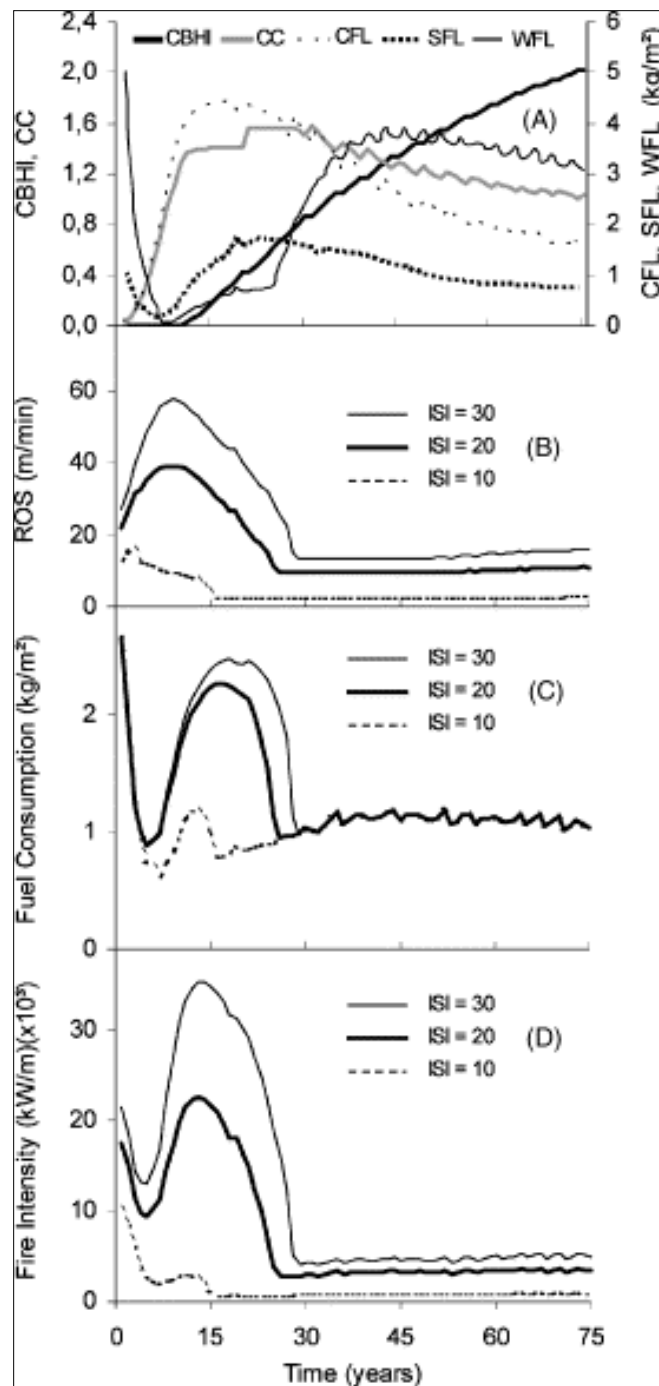
**Experimental Fires in Red Pine Plantation,
Petawawa Forest Experiment Station, Ontario**

Bilgili (2003)

← No treatment
(2 x 2 spacing)

Treatment: →
thinnings at 20,
40 & 60 yrs – 30,
50 & 50% of
trees removed

- CBH** – Crown Base Height
- CC** – Crown Closure
- CFL** – Crown Fuel Load
- SFL** – Surface Fuel Load
- WFL** – Woody Fuel Load



Limitations of FBP System Fuel Types

- Some allowance for seasonal changes in flammability and stand composition**
- Fuel types are static and not “dynamic” in nature (i.e., no variation in fuel complex structure and fire behavior with stand age *per se*)**
- Except for C-6, the emphasis to date has been on natural fire-origin forest stands**
- There is at present no capacity to alter any crown fuel characteristics, other than crown base height in C-6**
- Slash fuel types reflect logging methods and utilization standards of the 1960s**

FBP System Software

Behave by Remsoft®



<http://www.remsoft.com/>

FBP Primary Inputs		FBP Primary Outputs	
Fuel Type	C1	Final ISI (wind & slope)	11.8
Grass weight	3.0 tonnes/ha	Spread direction azimuth	290.6 °
Grass percent cured	80.0 %	Net vector	20.1 kph
Softwood composition	%	Critical rate of spread	2.1 m/min
Percent dead fir	%	Critical fire intensity	810.1 kW/m
Fine fuel moisture code	90.0	Equilibrium Spread Rates	
Buildup index	81.3	Head fire rate of spread	5.4 m/min
10 metre wind speed	20.4 kph	Flank fire rate of spread	1.0 m/min
Percent slope	7.0 %	Back fire rate of spread	0.0 m/min
Aspect of slope	NORTH	Elliptical Outputs	
Cardinal wind direction	ESE	Length-to-breath ratio	2.59
Slope azimuth, upslope	180.0 °	Elliptical fire area	1.4 ha

PROMETHEUS – Canadian Wildland Fire Growth Model



<http://www.firegrowthmodel.com/>

Date and Time	Time Step	Temperature (C)
2001 10:00:00	00:00	15.0
2001 10:19:59	00:20	15.0
2001 10:39:59	00:40	15.0
2001 10:59:59	01:00	15.0

U.S. Fire Behavior Prediction System

- Based largely on Rothermel's (1972) surface fire rate of spread model involving laboratory test fires and physical theory (some empiricism)

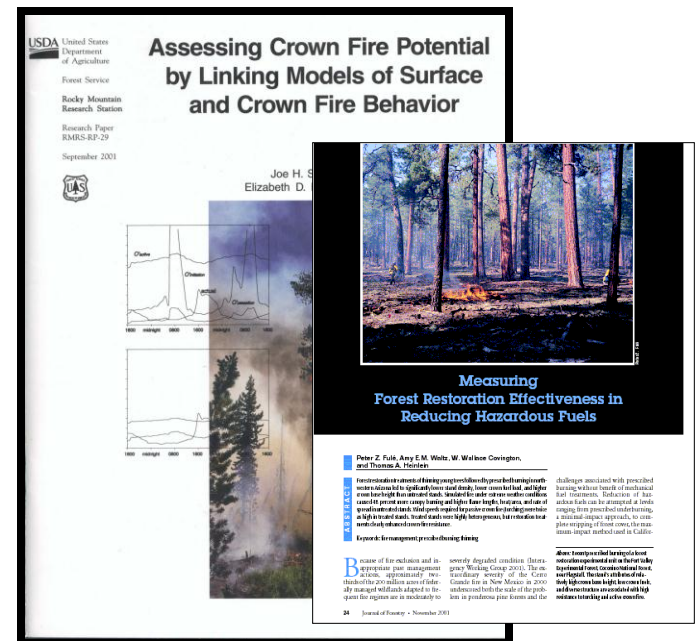
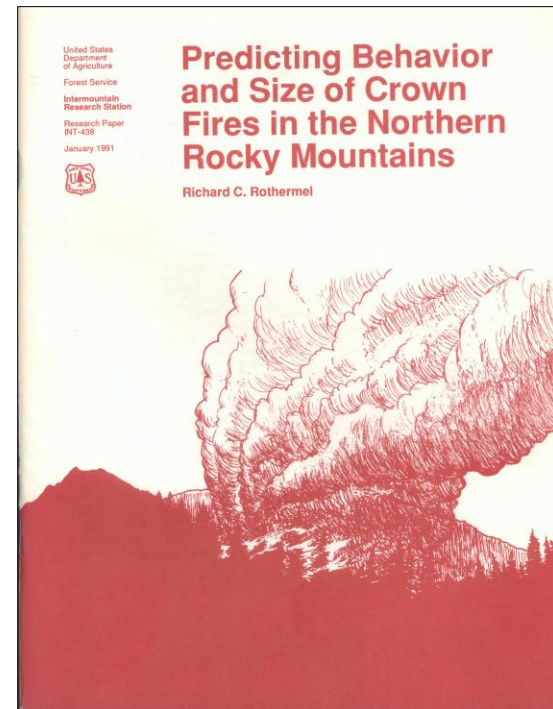


<http://www.fire.org>

- Limited validation
- Does not consider duff layer

BehavePlus System now includes Rothermel's (1991) crown fire rate of spread model which is based on an empirically derived multiplier (3.34) between the predicted surface fire rate of spread and a limited number of wildfire observations (8).

Nearly all simulations undertaken in the U.S. regarding the impacts or effectiveness of fuel treatments on fire behavior involve the BehavePlus System (or its derivatives – NEXUS, FARSITE, Fuel Management Analyst), and the Rothermel (1991) model.



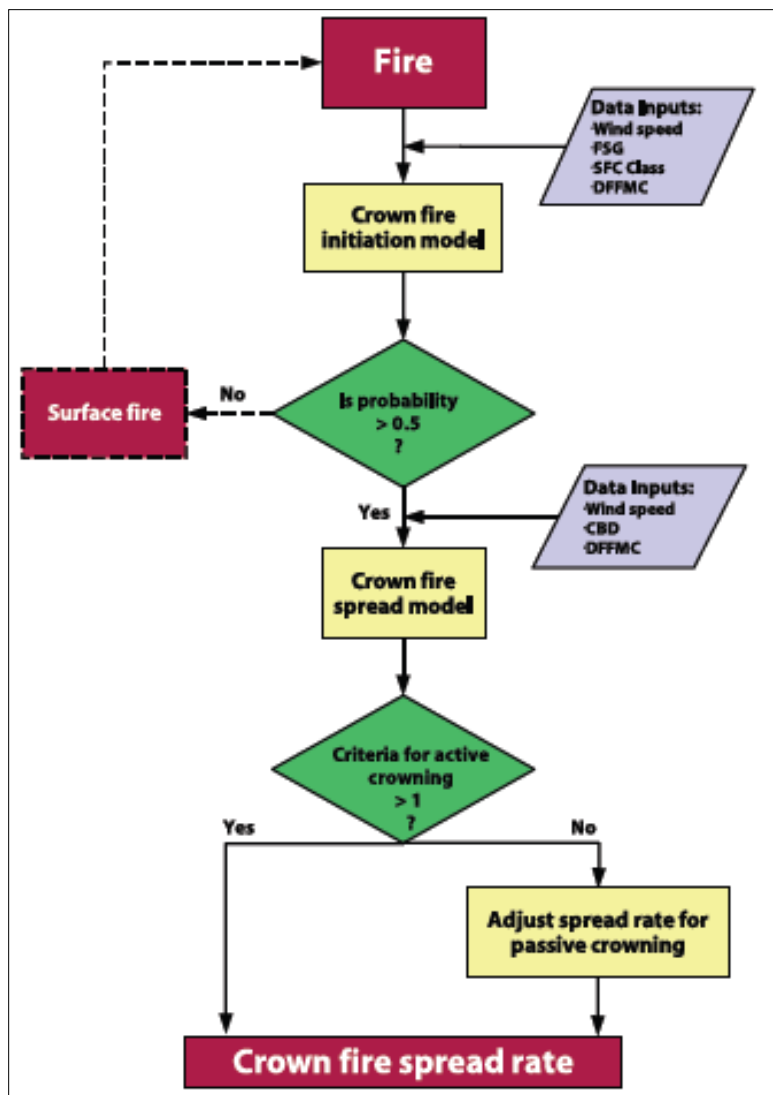


Diagram of information flow for predicting crown fire initiation* and spread potential based on the models developed by Cruz, Alexander and Wakimoto (2004, 2005).

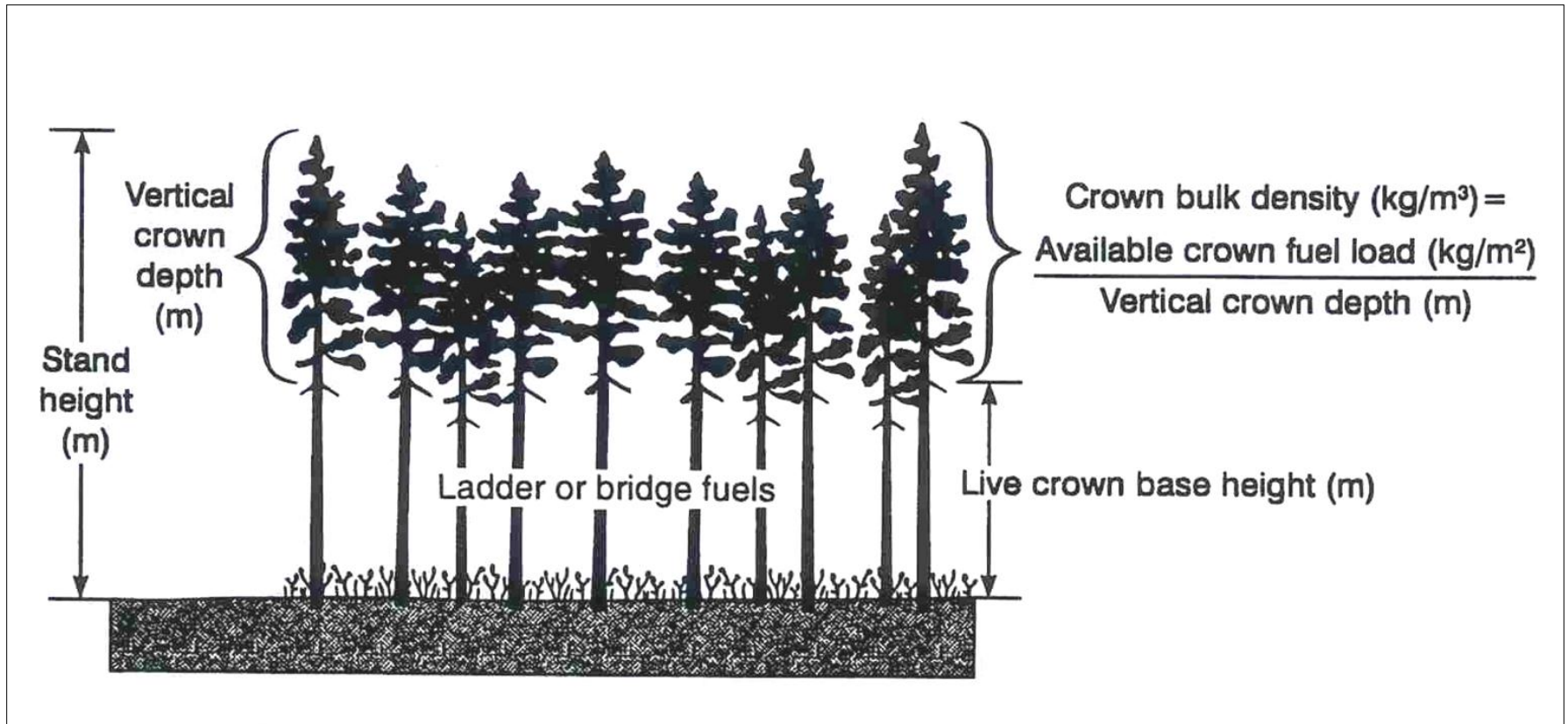
***Alternatively, crown fire initiation can be predicting using crown base height, 10-m open wind speed, and FWI System components (Cruz, Alexander and Wakimoto 2003)**

Model Inputs

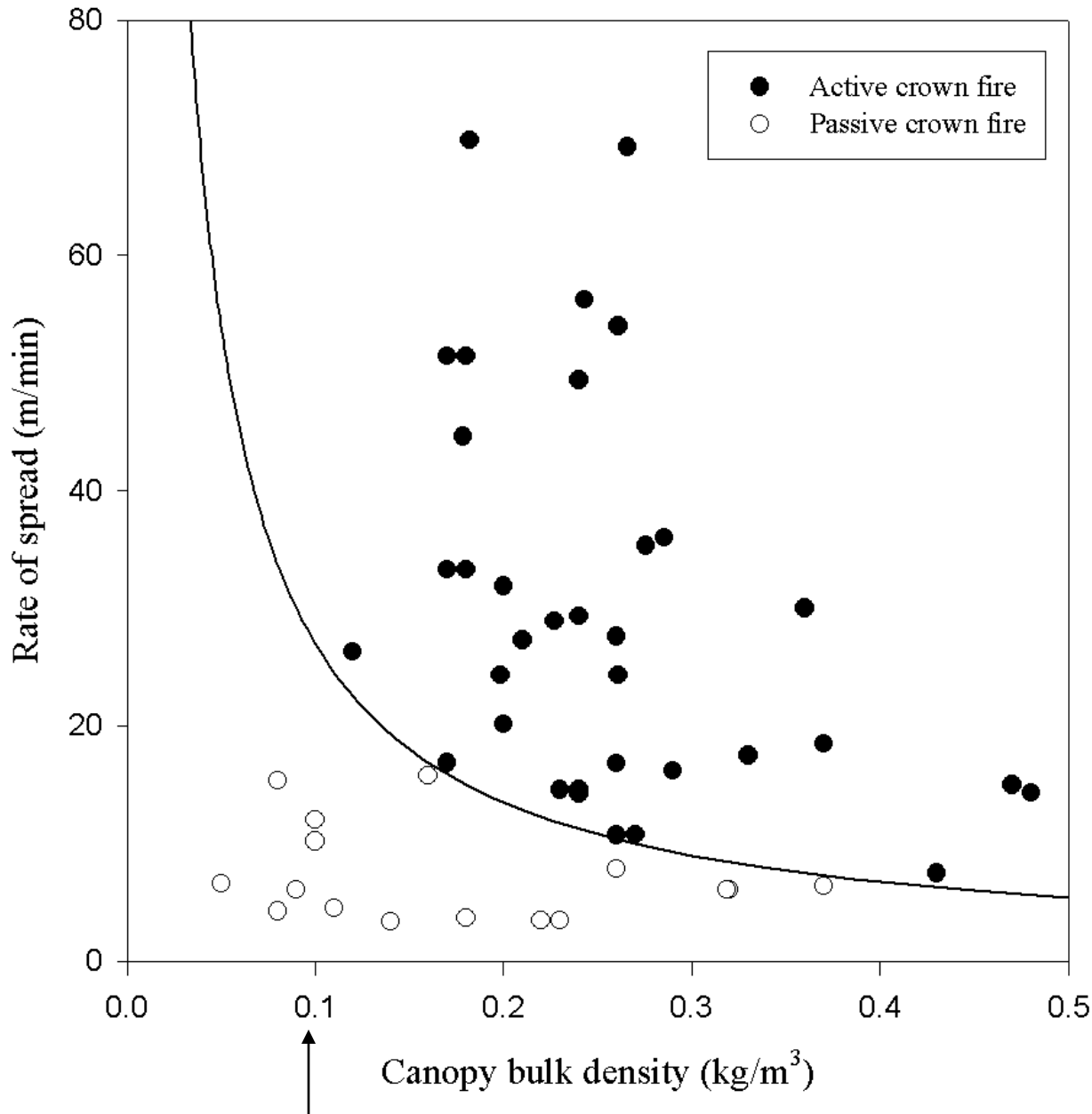
- **Estimated Fine Fuel Moisture (determined from air temperature, relative humidity, time of year & day, and degree of shading)**
- **Surface Fuel Consumption (<1, 1-2 or > 2 kg/m²)***
- **Fuel Strata Gap or Canopy Base Height***
- **10-m Open Wind Speed**
- **Canopy or Crown Bulk Density***

***These three characteristics of a forest stand or fuel complex are subject to manipulation by silvicultural and other vegetation management techniques**

Canopy or Crown Bulk Density Concept



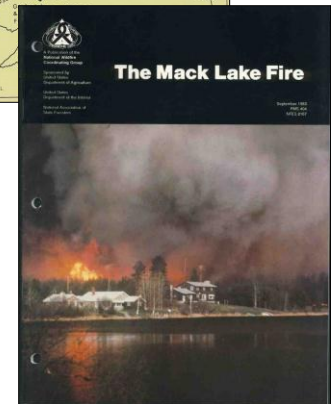
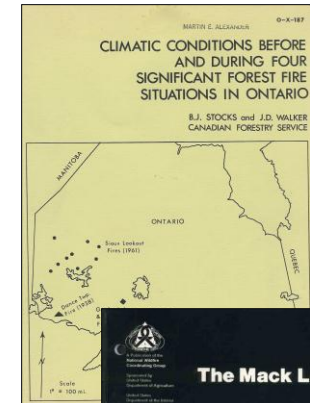
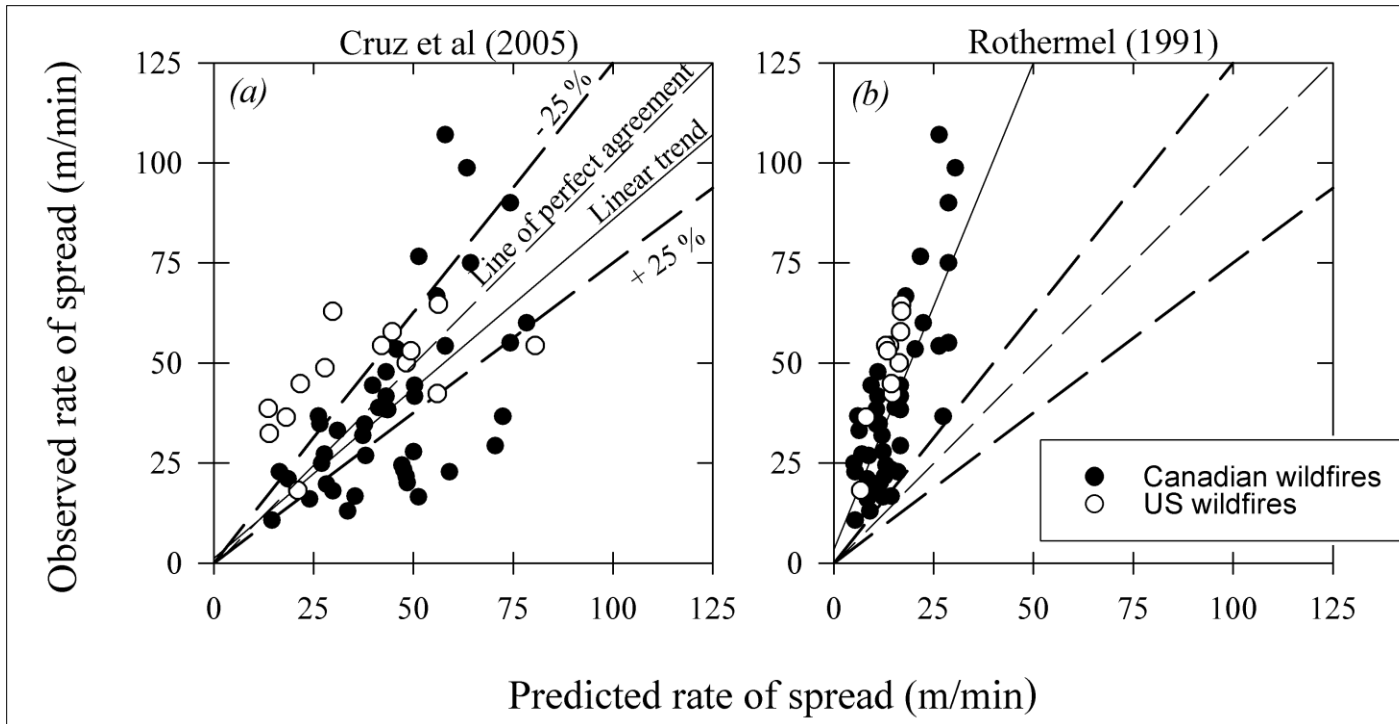
Available crown fuel load determined from stand data (i.e., number of stems per hectare by DBH size class) and foliage/twig vs. DBH relationships



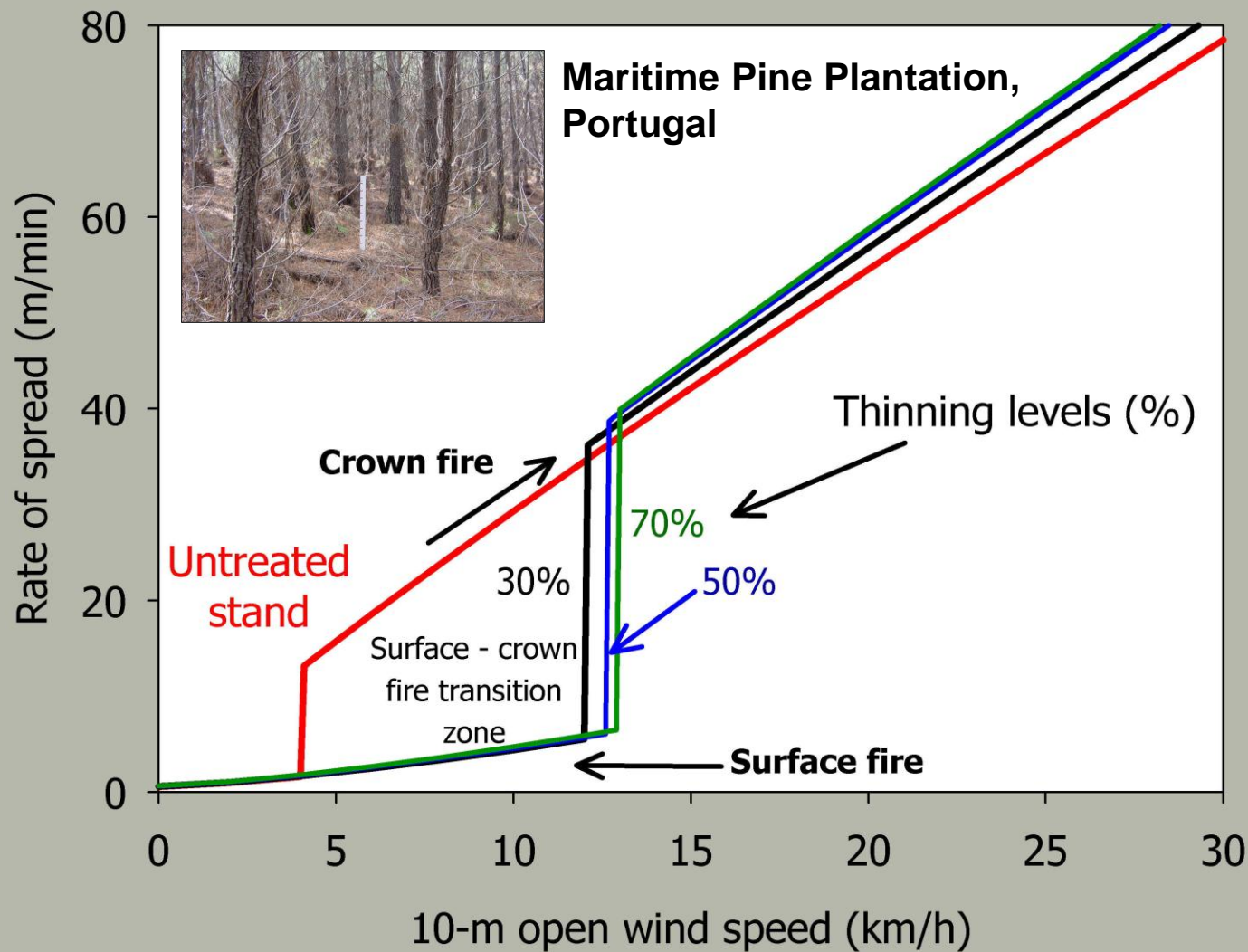
Van Wagner's (1977) critical minimum spread rate criterion for active or continuous crowning as related to canopy bulk density (curve) in relation to experimental crown fire data

Model Evaluation

The Cruz, Alexander and Wakimoto (2003, 2004, and 2005) model outputs have been compared to two independent experimental datasets (ICFME & Porter Lake) as well as 57 wildfire observations (43 Canadian & 14 U.S.) obtained from case studies. The results have been quite favourable.



Simulation Using the Models Contained in CFIS





**Cruz,
Alexander
and
Wakimoto
(2003, 2004,
2005) crown
fire behavior
models have
now been
incorporated
into a
software
package**

<http://www2.dem.uc.pt/antonio.gameiro/ficheiros/CFIS.exe>

Screen captures from CFIS

Crown Fire Initiation and Spread

Units

Initiation | Occurrence | Rate of Spread | Help | Credits

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

Models

- LOGIT 1
- LOGIT 2
- LOGIT 3
- LOGIT 4

Input Data

CBH [m]:

10-m wind [km/h]:

FFMC:

DC:

ISI:

BUI:

Run

Reset

Close

Output

Probability of Crown Fire Initiation [%]: 87

Crown Fire Initiation and Spread

Units

Initiation | Occurrence | Rate of Spread | Help | Credits

Quick help and useful references

QUICK HELP

This program shows the estimation of the likelihood of crown fire initiation and the spread rate of crown fires from the knowledge of Canadian Forest Fire Danger Rating System (CFDRS) components, weather and fuel complex variables.

The Tab - Initiation - incorporates four distinct models that predict the likelihood of crown fire occurrence from Canadian Forest Fire Danger Rating System components (Cruz, Alexander and Wakimoto 2005; see below).

The Tab - Occurrence - predicts the likelihood of crown fire occurrence based on three fire environment variables, namely the 10-m open wind speed, fuel strata gap, estimated moisture content of fine dead fuels, and one fire behavior descriptor - surface fuel consumption (Cruz, Alexander and Wakimoto, 2004; see below).

The Tab - Rate of Spread - predicts the regime and spread rate of crown fires from the knowledge of 10-m open wind speed, estimated moisture content of fine dead fuels, and canopy bulk density (Cruz, Alexander and Wakimoto, 2005; see below).

Close

Crown Fire Initiation and Spread

Units

Initiation | Occurrence | Rate of Spread | Help | Credits

Likelihood of Crown Fire Occurrence (%)

Input Data

FSG [m]:

10-m wind:

Estimated Fine Fuel Moisture

EFFM [%]:

Calculate from weather and site variables

SFC Class: < 1 kg/m²

1 - 2 kg/m²

> 2 kg/m²

Crown Fire ROS

Select

CBD [kg/m³]:

Spotting Separation Distance

Select

ID [min]:

Run

Reset

Close

Output

Prob. crown fire occurrence [%]: 63

Type of Fire: Crown fire

Crown Fire ROS [m/min]:

Critical Spotting Distance [m]:

Crown Fire Initiation and Spread

Units

Initiation | Occurrence | Rate of Spread | Help | Credits

Crown Fire Rate of Spread (ROS)

Input Data

CBD [kg/m³]:

10-m wind:

Estimated Fine Fuel Moisture

EFFM [%]:

Calculate from weather and site variables

Spotting Separation Distance

Select

ID [min]:

Run

Reset

Close

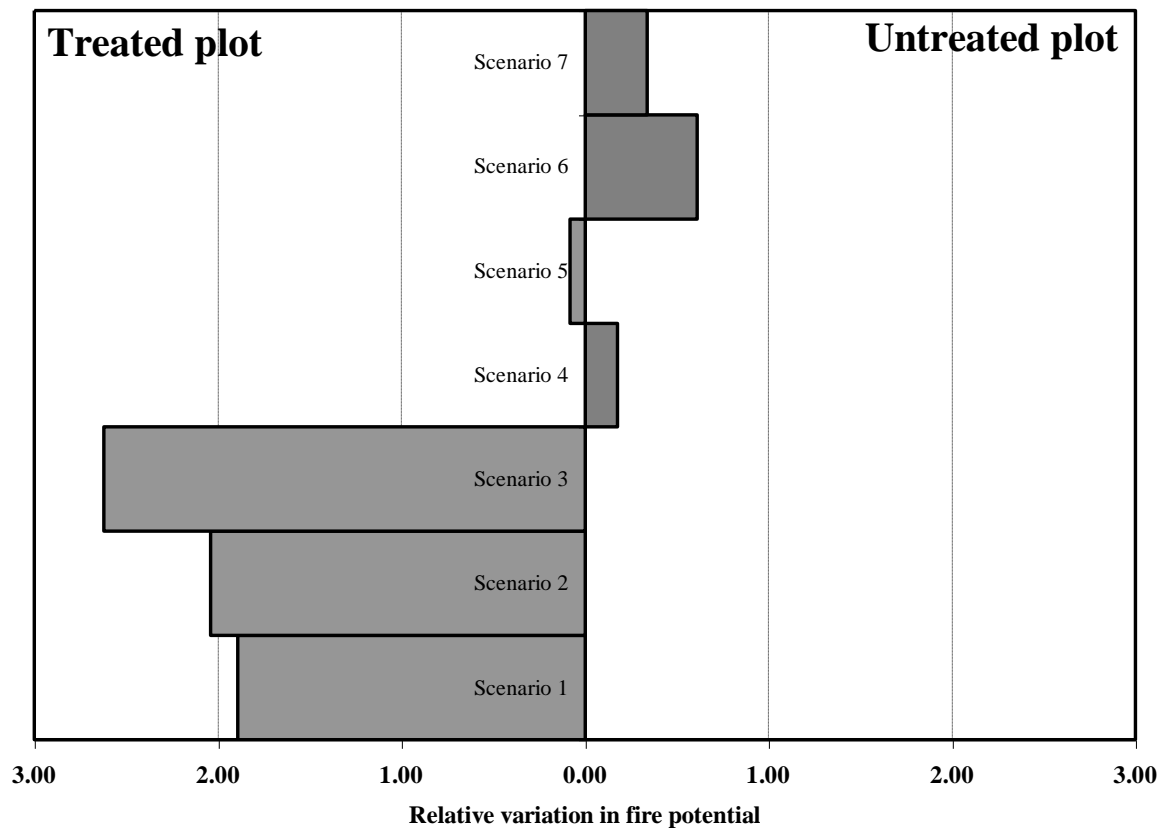
Output

Type of Fire: Active crown

Crown ROS [m/min]: 20.8

Critical Spotting Distance [m]: 383.3

Relative Increases in Fire Intensity and Crowning Potential due to fuel manipulation in a Lodgepole Pine Stand* near Whitecourt, AB (as described by Dam 2000) based on various fire behavior models



* Dam, J. 2000. Effects of thinning in fire behavior: a case study in lodgepole pine in Canada. M.Sc. Thesis, Wageningen University, Holland. 60 p.

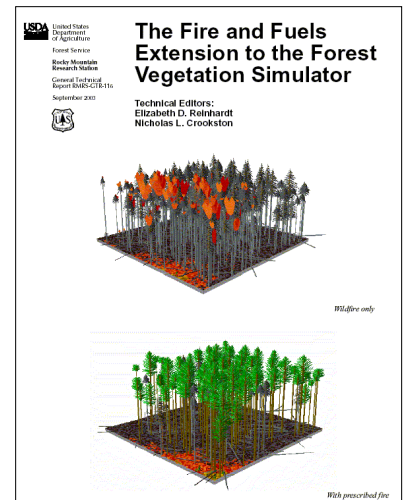
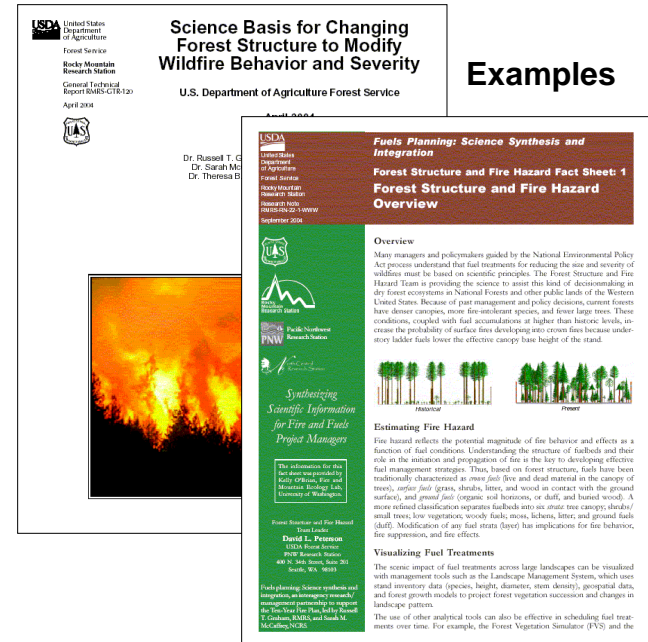
III. Conclusions & Some Suggestions for the Future

- **Fire behavior is a multi-faceted subject area**
- **While acknowledging that the processes involved are complex with numerous controlling factors, qualitatively we know a great deal about fire behavior**
- **Fire behavior research and associated model development has matured greatly in recent years**
- **Rudimentary modelling of fire behavior potential in relation to post-harvest stand development is now possible; such efforts will no doubt identify critical knowledge gaps and research needs**

• We know nothing specific about fuel and fire behavior characteristics in young, post-harvest stands in western Canada

• Existing knowledge should be summarized and made available to managers & other researchers in order to continue the process of communication across disciplines

• Consider extension of the *Forest Vegetation Simulator* to post-harvest stand development as a means of integrating and “housing” our collective knowledge, not just for fire considerations



Fire behaviour as a factor in forest and rural fire suppression

Martin E. Alexander

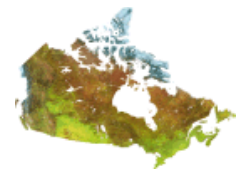


Forest Research Bulletin No. 197
Forest and Rural Fire Scientific and Technical Series
Report No. 5



... further major advances in combating wildfire are unlikely to be achieved simply by continued application of the traditional methods. What is required is a more fundamental approach which can be applied at the design stage ... Such an approach requires a detailed understanding of fire behaviour ...

Drysdale (1985)
Introduction to Fire Dynamics



Acknowledgments



Wildland Fire Operations
Research Group



Miguel Cruz
CSIRO Australia



Ron Wakimoto
University of Montana

Thank you for your attention! 😊

See Supplementary Handout. Questions?

