Latest Developments in Crown Fire Behavior Prediction

Marty Alexander, PhD, RPF
Senior Researcher
Wildland Fire Operations Research Group
Forest Engineering Research Institute of Canada
Western Division

FERIC

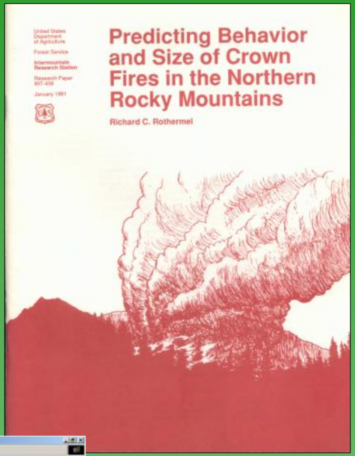
IWFC INTERIOR WEST FIRE COUNCIL
Alberta/Colorado/Idaho/Kansas/Montana/NW Territories/Nebraska/N. Dakota/Saskatchewan/S. Dakota/Utah/Wyoming

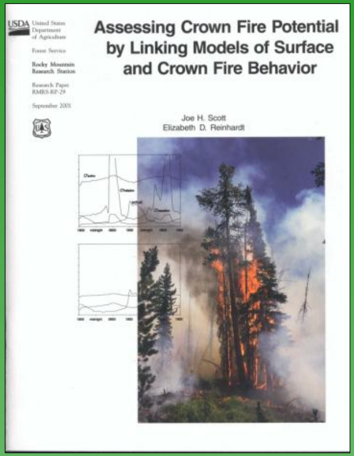
19th Interior West Fire Council Annual Meeting & Workshop, Canmore, AB, Oct. 25-27, 2005

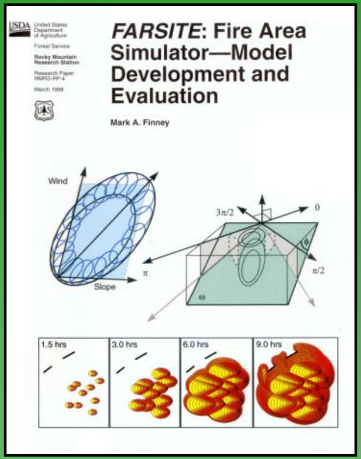
Crown Fire Behavior Models & Systems Currently Used Operationally in North America

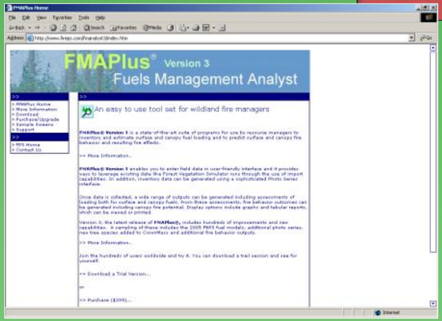
United States

- Rothermel (1991)
- FARSITE System
- NEXUS System
- Fuel Management Analyst



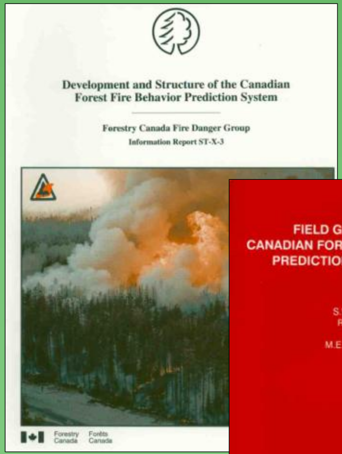


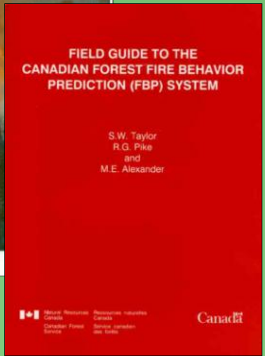




Canada

- Van Wagner (1977)
- Canadian Forest Fire Behavior Prediction System





Limitations

• Canada – empirical approach couldn't be sustained indefinitely

• United States – interim model only following 1988 fire season

This lead to the birth of International Crown Fire Modelling Experiment (ICFME) in the mid 90s

Characteristics of ICFME Fires

- Typical of Active Crown Fires in the Boreal Forest
- Rate of Advance: 1-5 km/h
- Fuel Consumed: 40-50 t/ha
- Fire Intensities: 13 000 – 90 000 kW/m
- Flame Front: 2-3 Times Tree Height
- Well-defined Convection Columns
- Spotting: prolific; up to 200-300 m
- 18 Experimental Crown Fire
- NO Escapes!

Long-Term Experiment Takes Some of the Mystery Out of Crown Fires

Natural Resources Canada / Ressources naturelles Canada — Canadian Forest Service / Service canadien des forêts

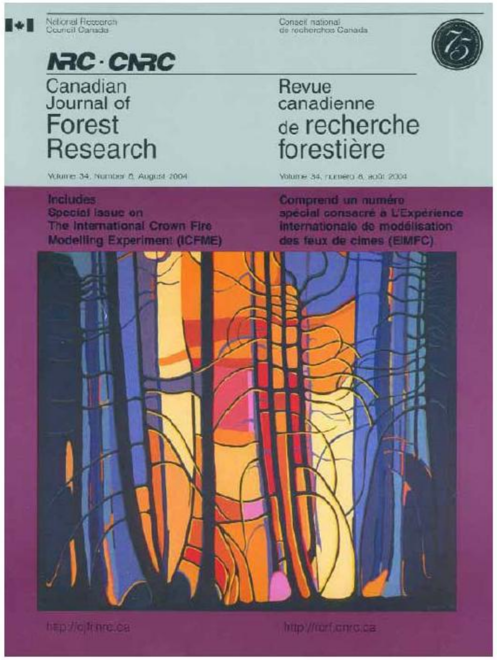
FERIC

Martin E. Alexander

The August 2004 issue of the *Canadian Journal of Forest Research* (volume 34[8]) is devoted to a special topic: "The International Crown Fire Modelling Experiment (ICFME) in Canada's Northwest Territories: Advancing the Science of Fire Behaviour." Running from 1994 to 2001 at a site about 30 miles (50 km) north of Fort Providence, the ICFME was a major international wildland fire research effort organized by the Canadian Forest Service and the Forest Management Division in the Department of Resources, Wildlife and Economic Development (DRWED) of the Government of Northwest Territories (GNWT), with substantial cooperation from the USDA Forest Service.

> "What you guys envisioned and so many of us worked on will make fire history. Lots of excellent work, data, concepts and techniques to stoke the research fires for a long time to come."
>
> – Dr. Ted Putnam (2004)

Dr. Marty Alexander is a senior fire behavior research officer with the Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada. At the time of this writing, he was on assignment as a senior researcher with the Wildland Fire Operations Research Group, Forest Engineering Research Institute of Canada, Hinton, Alberta, Canada.



The special issue features 10 articles. The first article presents an overview and introduction to ICFME (Stocks and others 2004a). The other nine articles focus on some of the main research studies carried out during the course of the ICFME, including:

- Several aspects of crown fire behavior (Butler and others 2004a, 2004b; Stocks and others 2004b; Taylor and others 2004);
- Firefighter safety (Putnam and Butler 2004);
- The wildland/urban interface (Cohen 2004);

Overview of the International Crown Fire Modelling Experiment (ICFME)

B.J. Stocks, M.E. Alexander, and R.A. Lanoville

Abstract: The International Crown Fire Modelling Experiment (ICFME), carried out between 1995 and 2001 in Canada's Northwest Territories, involved 18 experimental high-intensity crown fires, with more than 100 participants representing 30 organizations from 14 countries. ICFME has provided valuable new data and insights into the nature and characteristics of crowning forest fires, which will assist in addressing fire management problems and opportunities affecting both people and ecosystems in future decades. ICFME evolved as the result of a number of converging issues: the recognition that the US and Canada could not continue separate approaches to fire behaviour model development, the opening of Russia to the western world, increased communication, and the formation of international associations to facilitate collaboration. While the initial impetus for ICFME was the desire to improve the physical modeling of crown fire propagation and spread, the project also created the opportunity to examine many other aspects and impacts of crown fires. This special issue of the *Canadian Journal of Forest Research* devoted to ICFME is intended to summarize most of the major research results from the project.

Résumé : Dans le cadre de L'Expérience internationale de modélisation des feux de cimes (EIMFC), 18 feux de cimes expérimentaux de forte intensité ont été provoqués dans les Territoires du Nord-Ouest du Canada. L'EIMFC, qui a mobilisé une centaine de chercheurs issus de 30 organismes et représentant 14 pays, a fourni de riches données et renseignements sur la nature et les caractéristiques des feux de cimes en forêt, qui contribueront indubitablement à résoudre les difficultés de gestion des incendies qui affectent l'homme et les écosystèmes. Plusieurs facteurs ont influé sur la progression de L'EIMFC, notamment la mise en évidence du fait que les É.-U. et le Canada se devaient d'unir leurs efforts dans l'élaboration de modèles de comportement des feux, l'ouverture du rideau de fer en Russie, la multiplication des échanges et la constitution d'associations internationales destinées à favoriser la collaboration. Si cette expérience internationale avait pour principale visée d'améliorer la modélisation physique de la transmission et de la propagation du feu, elle a toutefois aussi permis d'examiner plusieurs autres aspects et facteurs d'incidence des feux de cimes. Le présent numéro de la *Revue canadienne de recherche forestière* consacré à L'EIMFC constitue une synthèse des constatations les plus marquantes de cette expérience.

[Traduit par la Rédaction]

Introduction

While some progress has been made in predicting and modeling the initiation and behaviour of crown fires at northern latitudes, a complete understanding of the phenomena has proven an elusive goal over the past half century.

Received 6 May 2004. Accepted 29 June 2004. Published on the NRC Research Press web site on 14 August 2004.

B.J. Stocks.[1] Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada.
M.E. Alexander. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB T6H 3S5, Canada.
R.A. Lanoville. Government of Northwest Territories, Department of Resources, Wildlife and Economic Development, Forest Management Division, P.O. Box 7, Fort Smith, NT X0E 0P0, Canada.

[1]Corresponding author: (e-mail: bstocks@nrcan.gc.ca).

The transition from surface to crowning fires represents a threshold beyond which suppression actions most often fail, and crown fires, spreading quickly at high intensity levels, continue to account for the vast proportion of the area burned in northern forests (Weber and Stocks 1998; Stocks et al. 2003), creating significant economic loss, and increasingly threatening human life and property. The International Crown Fire Modelling Experiment (ICFME) was designed to address modelling the propagation and spread of crown fires, using both modern instrumentation and a collaborative, multi-disciplinary international approach.

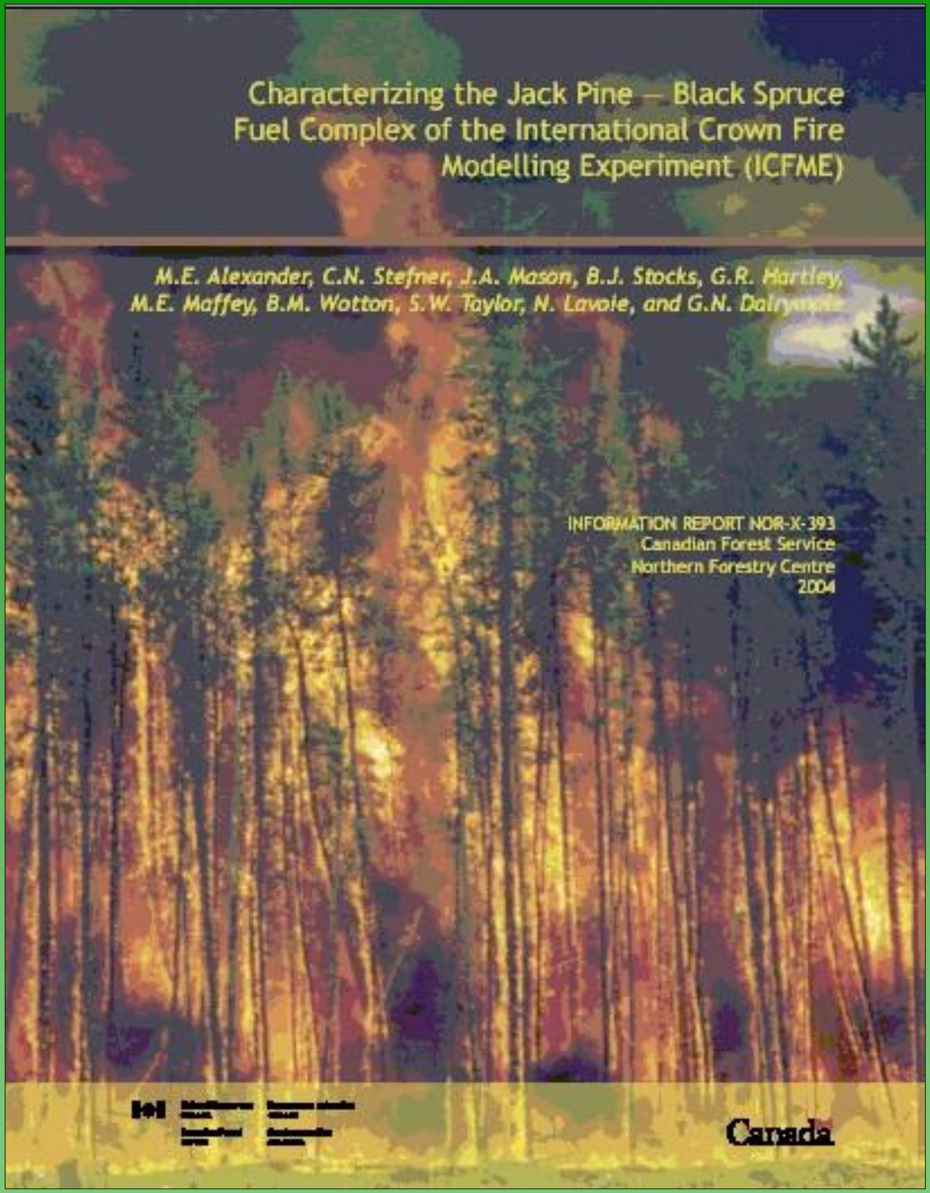
Background and genesis of ICFME

During the 1990s, a number of converging fire research issues made the development of ICFME both timely and relevant (Stocks and Conard 2000). Forest fire research scientists in Canada and the United States had worked independently for much of the previous half century on the development of fire danger and fire behaviour prediction systems, always using

Can. J. For. Res. 34: 1543–1547 (2004) doi: 10.1139/X04-905

Fire Management Today
Summer 2005 issue

Canadian Journal of Forest Research
July 2004 issue



Crown fire behaviour in a northern jack pine – black spruce forest[1]

B.J. Stocks, M.E. Alexander, B.M. Wotton, C.N. Stefner, M.D. Flannigan, S.W. Taylor, N. Lavoie, J.A. Mason, G.R. Hartley, M.E. Maffey, G.N. Dalrymple, T.W. Blake, M.G. Cruz, and R.A. Lanoville

Abstract: This paper reports on the behaviour of 10 experimental crown fires conducted between 1997 and 2000 during the International Crown Fire Modelling Experiment (ICFME) in Canada's Northwest Territories. The primary goal of ICFME was a replicated series of high-intensity crown fires designed to validate and improve existing theoretical and empirical models of crown fire behaviour. Fire behaviour characteristics were typical for fully developed boreal forest crown fires, with fires advancing at 15–70 m/min, consuming significant quantities of fuel (2.8–5.5 kg/m^2) and releasing vast amounts of thermal heat energy. The resulting flame fronts commonly extended 25–40 m above the ground with head fire intensities up to 90 000 kW/m. Depth of burn ranged from 1.4–3.6 cm, representing a 25%–65% reduction in the thickness of the forest floor layer. Most of the smaller diameter (<3.0 cm) woody surface fuels were consumed, along with a significant proportion of the larger downed woody material. A high degree of fuel consumption occurred in the understory and overstory canopy with very little material less than 1.0 cm in diameter remaining. The documentation of fire behaviour, fire danger, and fire weather conditions carried out during ICFME permitted the evaluation of several empirically based North American fire behaviour prediction systems and models.

Résumé : Cet article traite du comportement de 10 feux de cime expérimentaux provoqués entre 1997 et 2000 dans le cadre de l'Expérience internationale de modélisation des feux de cimes (EIMFC) dans les Territoires du Nord-Ouest au Canada. Le principal objectif de cette expérience consistait à reproduire une série de feux de cime de forte intensité conçus pour valider et améliorer les modèles théoriques et empiriques existants de comportement des feux de cime. Les caractéristiques du comportement des feux de cime étaient typiques des feux de cime en forêt boréale mature, où les feux progressent à 15 à 70 m/min, en consumant d'importantes quantités de combustibles (2,8 à 5,5 kg/m^2) et génèrent de fortes quantités d'énergie thermique sous forme de chaleur. Les fronts de flamme qui en résultent s'élevaient généralement à 25 à 40 m au-dessus du sol avec des intensités à la tête du feu allant jusqu'à 90 000 kW/m. La profondeur de brûlage variait de 1,4 à 3,6 cm, ce qui représentait une réduction de 25 % à 65 % de l'épaisseur de la couverture morte. La plupart des combustibles de surface de plus petit diamètre (<3,0 cm) ont été consumés de même qu'une importante proportion du plus gros matériel ligneux au sol. Il y a eu une forte consommation de combustibles dans le couvert des étages inférieur et supérieur où il restait très peu de matériaux d'un diamètre inférieur à 1,0 cm. La documentation du comportement du feu, le danger de feu et les conditions météorologiques propices aux incendies forestiers ont permis d'évaluer plusieurs systèmes et modèles empiriques nord-américains de prédiction du comportement des feux.

[Traduit par la Rédaction]

Received 26 September 2003. Accepted 10 February 2004. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 12 August 2004.

B.J. Stocks,[2] B.M. Wotton, M.D. Flannigan, J.A. Mason, G.R. Hartley, and T.W. Blake. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada.
M.E. Alexander, C.N. Stefner, and M.E. Maffey. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320–122 Street, Edmonton, AB T6H 3S5, Canada.
S.W. Taylor and G.N. Dalrymple. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada.
N. Lavoie. University of Alberta, Faculty of Agriculture, Forestry, and Home Economics, Department of Renewable Resources, Edmonton, AB T6G 2H1, Canada.
M.G. Cruz. University of Montana, College of Forestry and Conservation, Missoula, MT 59812, USA.
R.A. Lanoville. Government of Northwest Territories, Department of Resources, Wildlife and Economic Development, Forest Management Division, P.O. Box 7, Fort Smith, NT X0E 0P0, Canada.

[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: bstocks@nrcan.gc.ca).

 doi: 10.1139/X04-054

CFS companion publication on ICFME fuel complex characteristics

Canadian Journal of Forest Research **July 2004 issue**

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-

Received 14 October 2003. Accepted 16 April 2004. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 24 August 2004.

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).

Can. J. For. Res. 34: 1588–1599 (2004) doi: 10.1139/X04-074

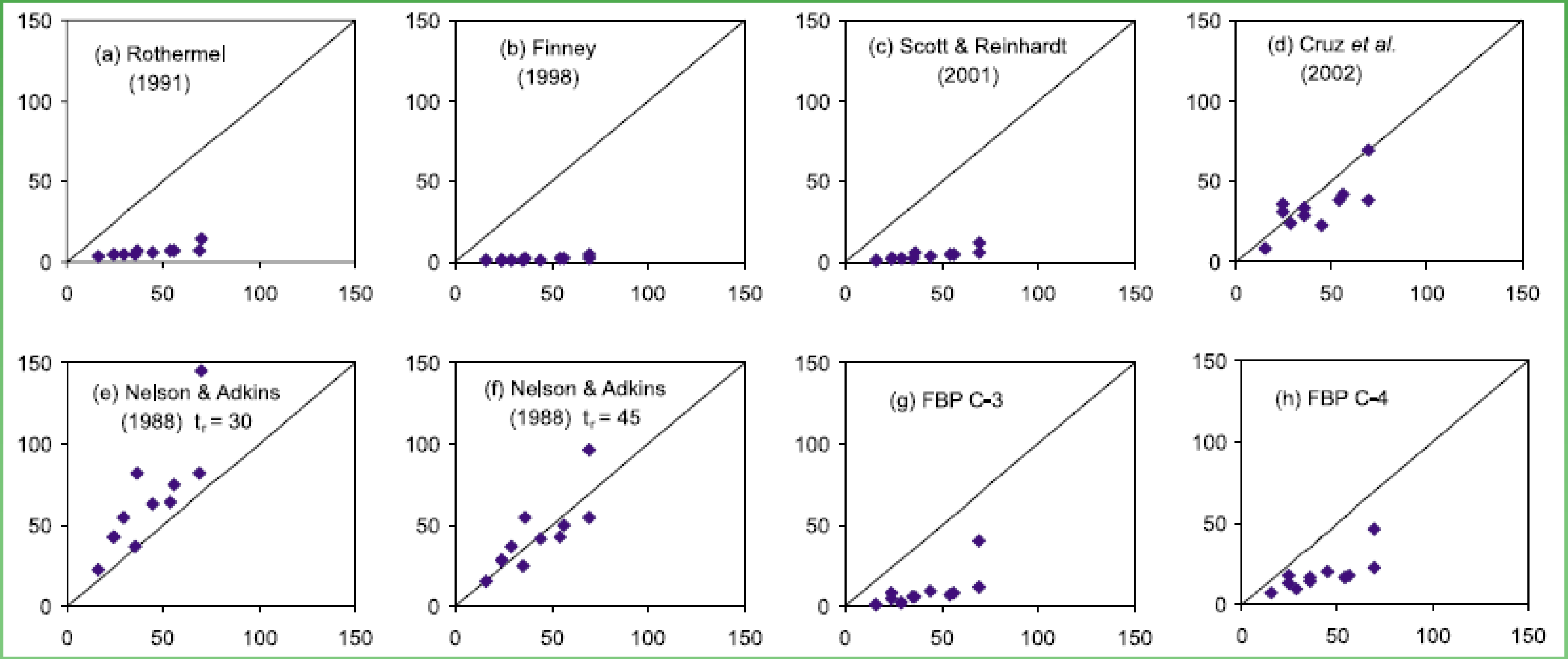
Canadian Journal of Forest Research
July 2004 issue

Dr. Frank Albini
ICFME 1997

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.

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

Observed forward spread rates (y axis) of the ICFME fires in comparison to predictions (x axis) from a number of North American fire behavior prediction systems and models. Unit of measure: m/min (150 m/min = ~500 ft/min)



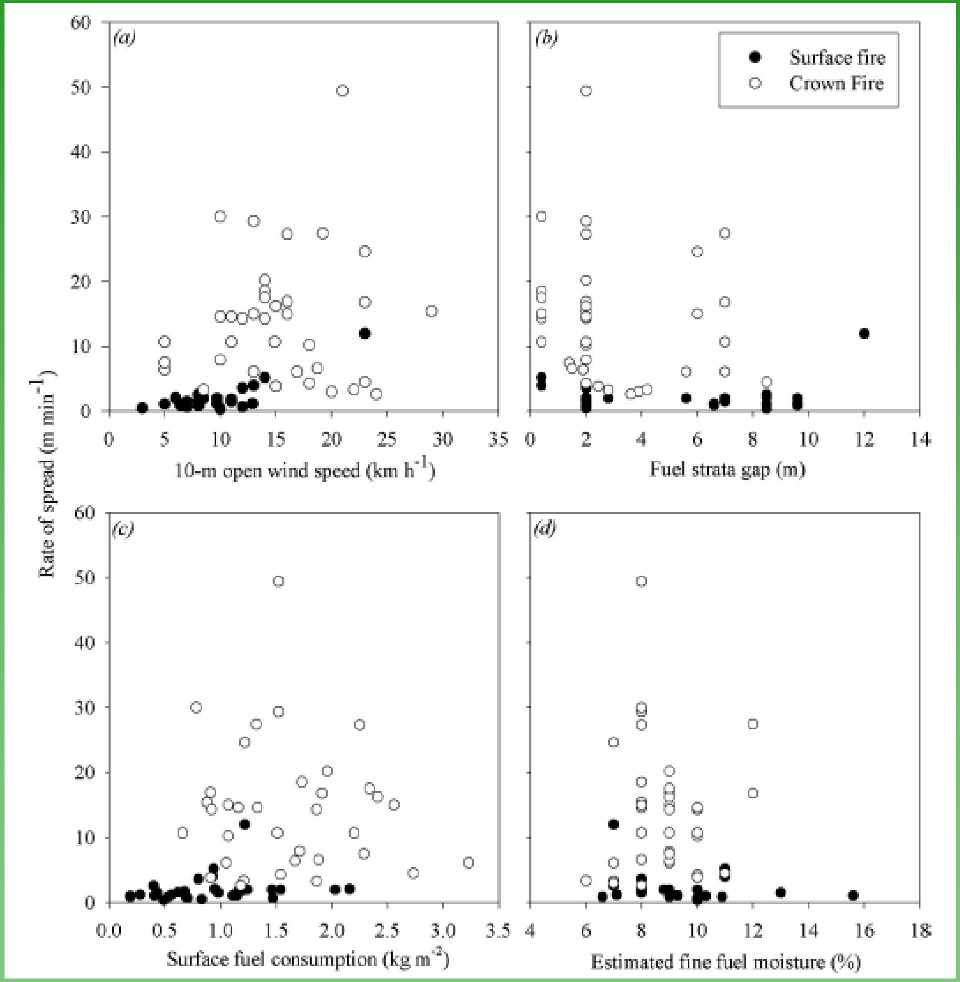
Working Towards an Alternative Approach

Miguel Cruz, a Portuguese Forester, interested in crown fire initiation and spread enrols in graduate program at University of Montana in 1998

Cruz, M.G. 1999. Modeling the initiation and spread of crown fires. University of Montana, Missoula, MT. 162 pp.

Reanalysis of the Experimental fires used in the development of the Canadian Forest Fire Behavior Prediction (FBP) System

Probability of Crown Fire Occurrence – Analysis & Model Development



- Comprehensive review of the literature
- Number of variables examined
- Data available for 34 surface fires & 37 crown fires (principally Canadian but a few fires from Portugal and Australia)

Probability of Crown Fire Occurrence – Analysis & Model Development

Statistics on Assembled Database

Independent variables	*n*	Minimum	Maximum	Mean	SD
Stand basal area ($m^2\ ha^{-1}$)	55	4.3	50.0	23.7	11.2
Stand density (trees ha^{-1})	64	532	9,276	3,952	3,076
Stand height (m)	69	2.9	20	13.1	5.6
Fuel strata gap (m)	71	0.4	12.0	4.3	3.4
10-m open wind speed ($km\ h^{-1}$)	71	3.0	32.1	12.5	6.0
Estimated fine fuel moisture content (%)	71	6.0	15.6	9.1	1.7
Surface fuel consumption ($kg\ m^{-2}$)	71	0.19	3.23	1.26	0.64
Foliar moisture content (%)	41	80.0	168.0	114.6	19.4
Rate of fire spread ($m\ min^{-1}$)	71	0.4	49.4	8.1	10.0
Fireline intensity ($kW\ m^{-1}$)	71	62	45,200	5,903	9,180

Probability of Crown Fire Occurrence - Results

Modeling the Likelihood of Crown Fire Occurrence in Conifer Forest Stands

Miguel G. Cruz, Martin E. Alexander, and Ronald H. Wakimoto

ABSTRACT. The unknowns in wildland fire phenomenology lead to a simplified empirical model approach for predicting the onset of crown fires in live coniferous forests on level terrain. Model parameterization is based on a data set ($n = 71$) generated from conducting outdoor experimental fires covering a significant portion of the spectrum of burning conditions associated with the initiation of crown fires. A logistic model is developed to predict the likelihood of crown fire occurrence based on three fire environment variables, namely the 10-m open wind speed, fuel strata gap (equivalent to live crown base height in some stands), estimated moisture content of fine dead fuels, and one fire-behavior descriptor—surface fuel consumption. The model correctly predicts 85% of the cases in the data set used in its development, and the receiver operating characteristic statistic is 0.94. The model is evaluated for its sensitivity to its inputs, and its behavior is compared with other models used in decision support systems to operationally predict crown fire initiation. The results of a limited test of the model against two independent experimental fire data sets for distinctly different fuel complexes is encouraging. FOR. SCI. 50(5):640–653.

Key Words: Forest fires, crown fire, crown fire initiation, crowning, experimental fire, fire behavior, fire-behavior prediction, logistic model.

A FOREST FIRE IS in essence the result of fire behavior. Its spread, its effects on soil and vegetation properties, and the difficulty of controlling the fire depend mostly on the fire behavior exhibited. The estimation of fire behavior is of utmost importance in any fire management approach, allowing for the determination of the impacts of fire on ecosystem components and supporting forest fire management decisionmaking. Wildland fire researchers have produced models to predict fundamental fire-behavior characteristics or descriptors, such as rate of fire spread (Rothermel 1972), flame geometry (Albini 1981, Nelson and Adkins 1986), and fuel consumption (Reinhardt et al. 1991, 1997, Albini and Reinhardt 1995), from easily recognized or measured fire environment variables (i.e., fuels, weather, and topographic inputs). These models have been integrated into decision support systems that have found widespread use for management and research activities in the United States (Finney 1998, Scott 1998a, Andrews et al. 2003). Nevertheless, our incomplete understanding of the processes and interactions determining

Miguel G. Cruz, Associação para o Desenvolvimento da Aerodinâmica Industrial, Apartado 10131, 3031-601 Coimbra, Portugal—Phone: +351-239-708580; Fax: +351-239-708589; pyro_gest@hotmail.com. Martin E. Alexander, Senior Fire Behavior Research Officer, Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB, Canada T6H 3S5—Phone: 780-435-7210; Fax: 780-435-7359; malexand@nrcan.gc.ca (presently senior researcher, FGRIC Wildland Fire Operations Group, Hinton, AB, Canada). Ronald H. Wakimoto, Professor, College of Forestry and Conservation, University of Montana, Missoula, MT 59812—Phone: 406-243-6201; Fax: 406-243-4845; wakimoto@forestry.umt.edu.

Acknowledgments: We would like to thank the Canadian Forest Service, especially B.J. Stocks, for making available its experimental fire-behavior database for the present study and its staff for the collection and safekeeping of such unique data through the years. Thanks also to Dick Lane of the University of Montana for the statistical advice, and Charles McHugh, USDA Forest Service for helpful discussions. We extend our gratitude for the valuable suggestions of three anonymous reviewers. This research was completed in part while MGC was a M.Sc. graduate student at the University of Montana and supported in part by funds from the Blackfoot Forest Protective Association and Fundação Luso-Americana para o Desenvolvimento, Portugal.

Manuscript received April 1, 2002, accepted March 23, 2004.

Logistic regression model requires three environmental inputs:

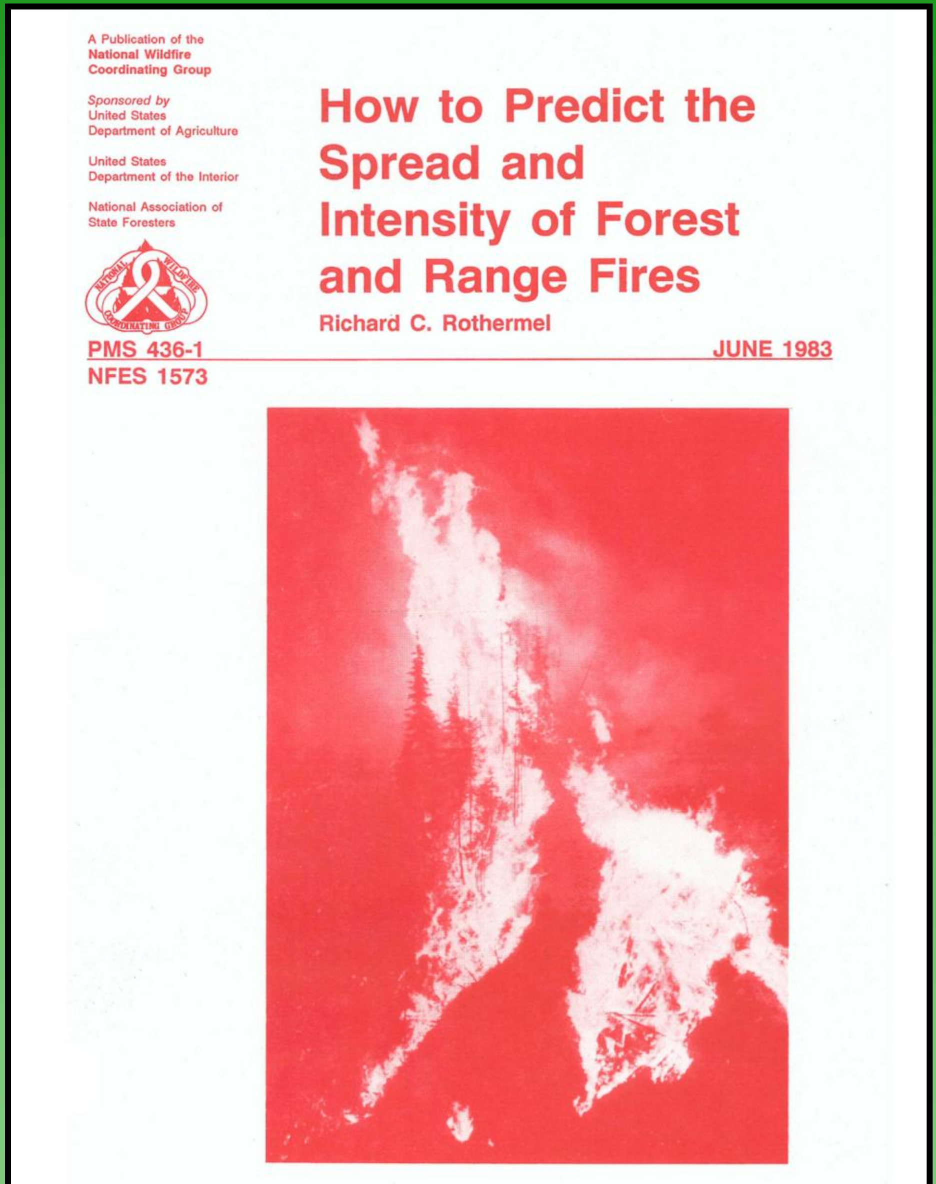
- **10-m open wind speed**
- **Fuel strata gap (FSG)**
- **Effective fine fuel moisture (EFFM)**

And one fire behavior description:

- **Surface fuel consumption (SFC)**

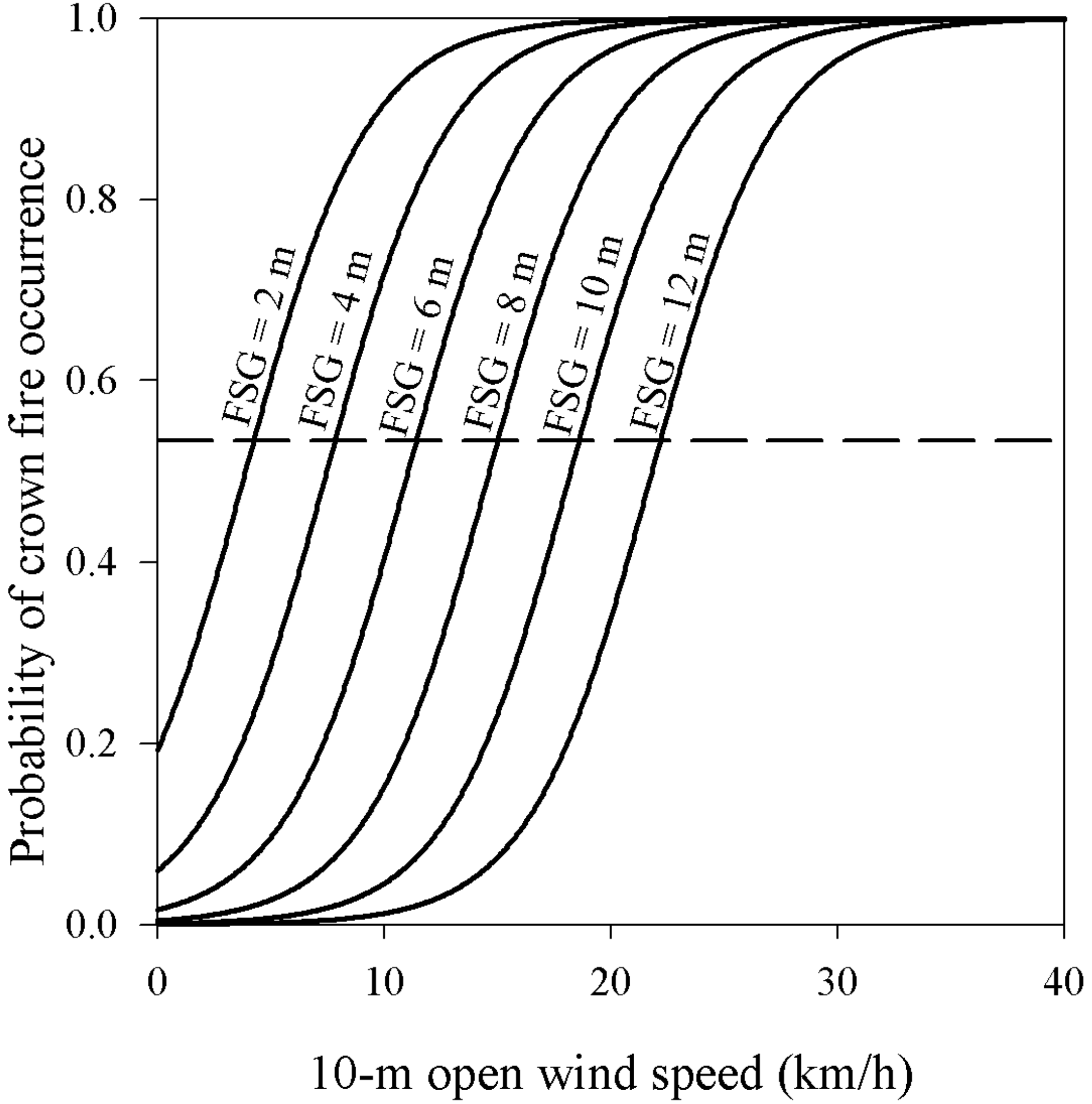
***Forest Science* - October 2004 issue**

Effective Fine Fuel Moisture (EFFM) (Rothermel 1983)



Determined from:

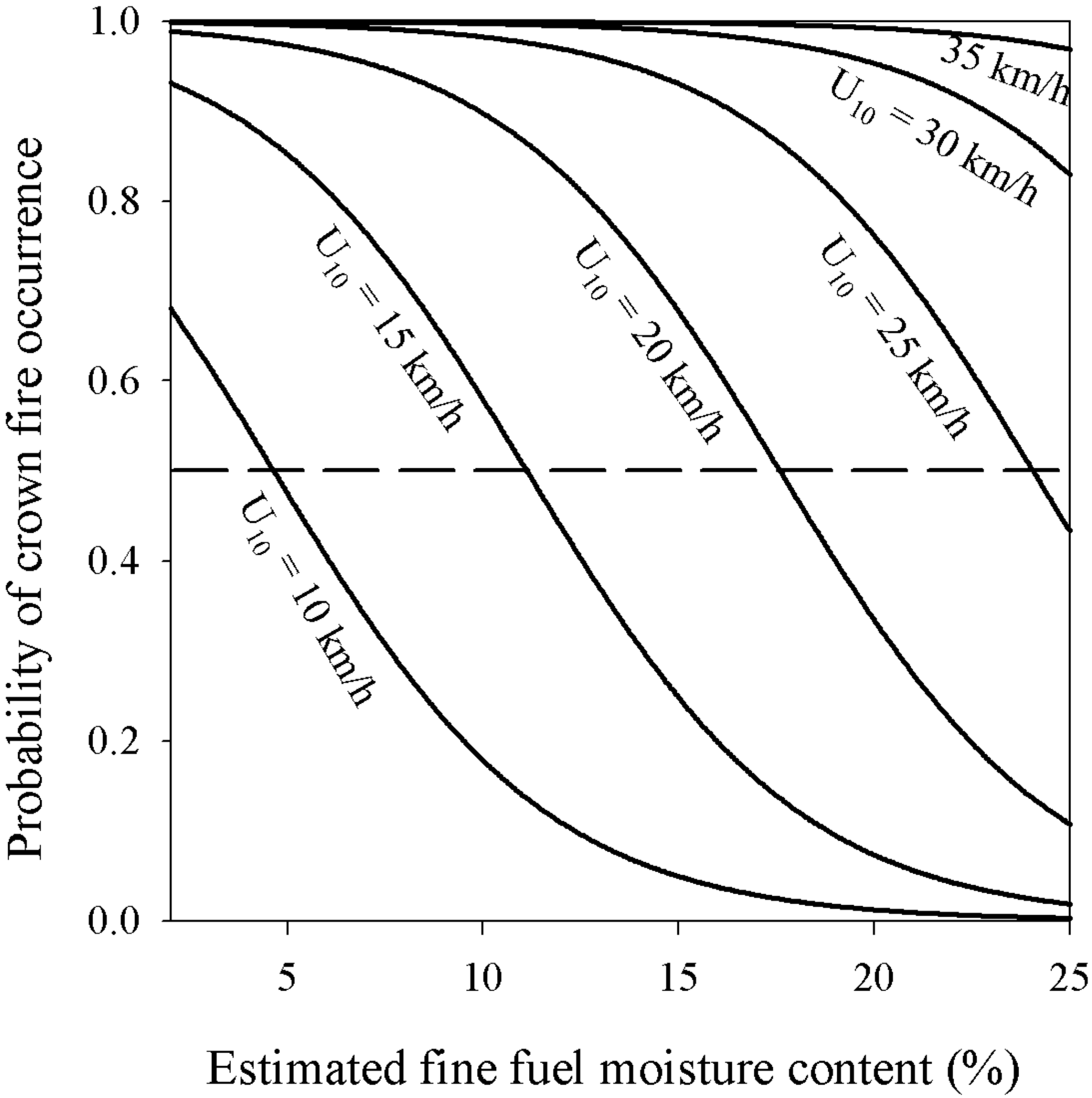
- Air temperature
- Relative Humidity
- Time of Year
- Time of Day
- Degree of Shading (cloud cover & canopy coverage)



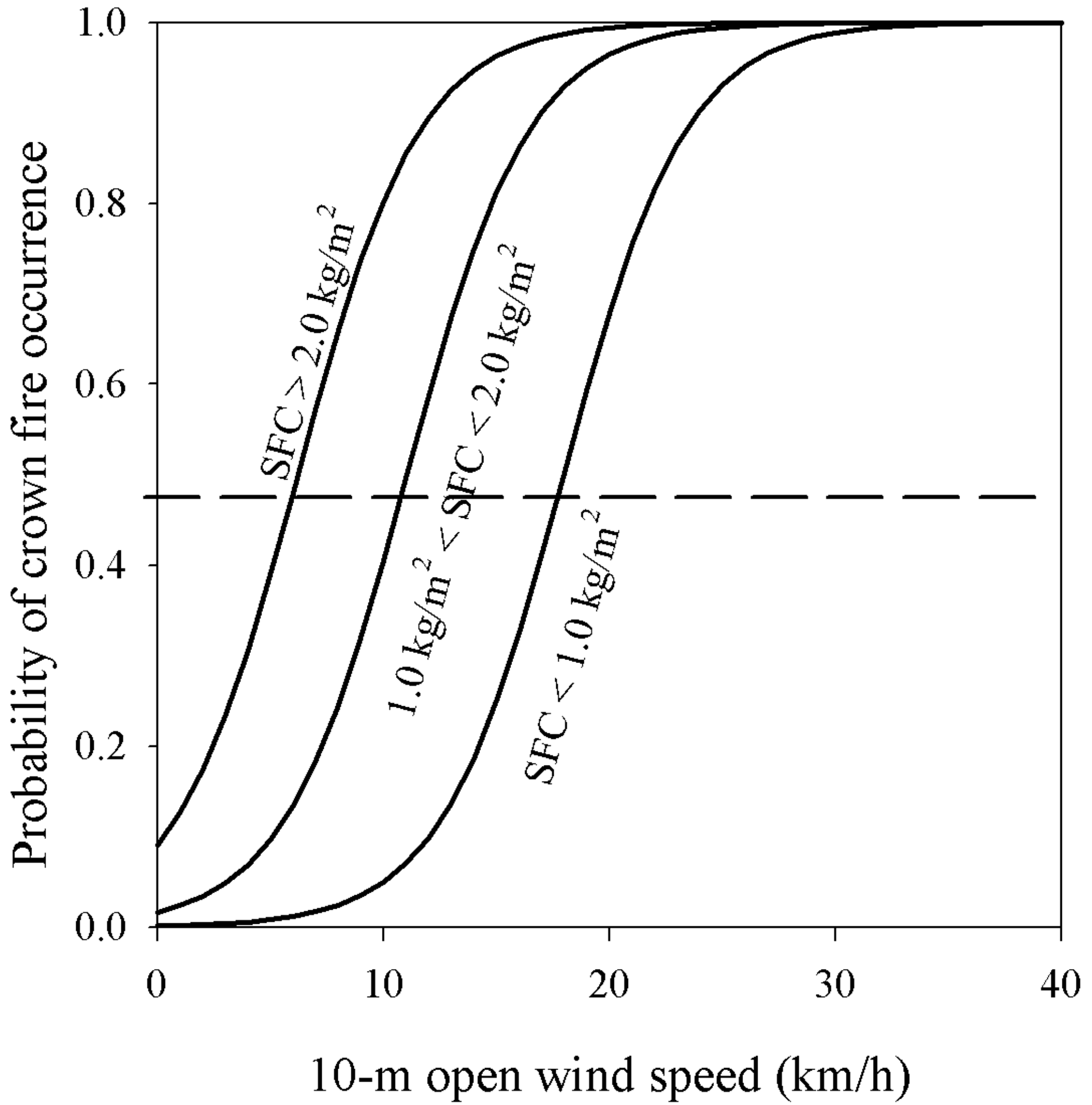
Effect of 10-m Open Wind Speed under variable Fuel Strata Gap (FSG)

Assume EFFM 6% and SFC 1-2 kg/m^2

Effect of Effective Fine Fuel Moisture under variable 10-m Open Wind Speeds (U_{10})



Assume SFC 1-2 kg/m²

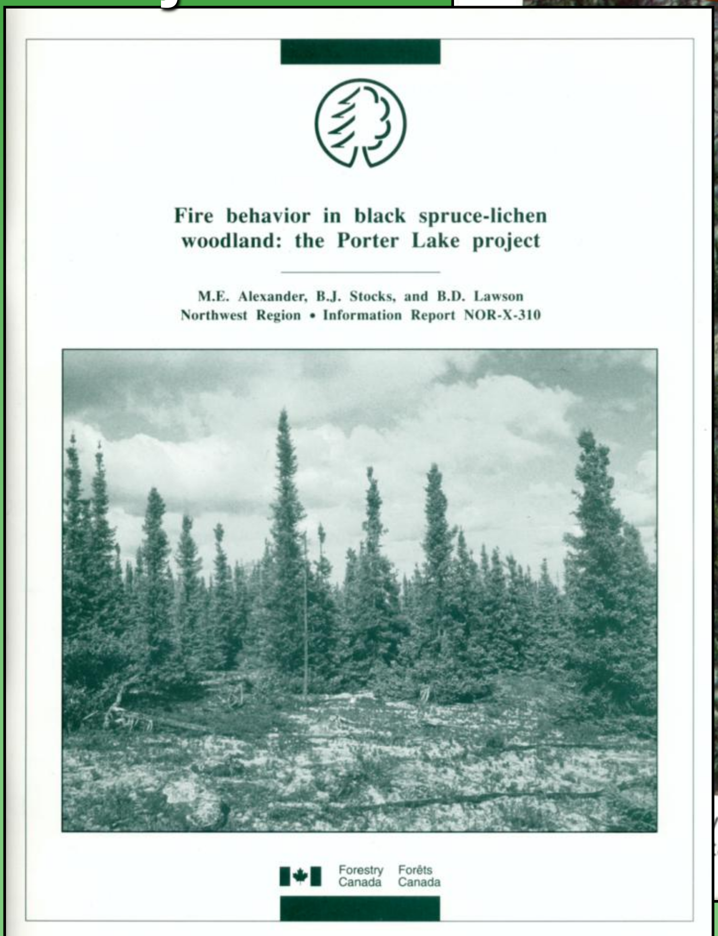


Effect of Surface Fuel Consumption (SFC) under variable 10-m Open Wind Speeds

Assume
EFFM 6%
FSG 6 m

Probability of Crown Fire Occurrence -- Evaluation

Porter Lake Project



Probability of Crown Fire Occurrence -- 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

Probability of Crown Fire Initiation

Assessing the probability of crown fire initiation based on fire danger indices

by Miguel G. Cruz[1], Martin E. Alexander[2] and Ronald H. Wakimoto[3]

The initiation of crown fires in conifer stands was modelled through logistic regression analysis by considering as independent variables a basic physical descriptor of the fuel complex structure and selected components of the Canadian Forest Fire Weather Index (FWI) System. The study was based on a fire behaviour research database consisting of 63 experimental fires covering a relatively wide range of burning conditions and fuel type characteristics. Four models were built with decreasing input needs. Significant predictors of crown fire initiation were: canopy base height, wind speed measured at a height of 10 m in the open, and four components of the FWI System (i.e., Fine Fuel Moisture Code, Drought Code, Initial Spread Index and Buildup Index). The models predicted correctly the type of fire (i.e., surface or crown) between 90% and 66% of the time. The C index, a statistical measure, varied from 0.94 to 0.71, revealing good concordance between predicted probabilities and observed events. A comparison between the logistic models and Canadian Forest Fire Behaviour Prediction System models did not show any conclusive differences. The results of a limited evaluation involving two independent experimental fire data sets for distinctly different fuel complexes were encouraging. The logistic models built may have applicability in fire management decision support systems, allowing for the estimation of the probability of crown fire initiation at small and large spatial scales from commonly available fire environment and fire danger rating information. The relationships presented are considered valid for free-burning fires on level terrain in coniferous forests that have reached a pseudo steady-state and are not deemed applicable to dead conifer forests (i.e., insect-killed stands).

Key words: Canadian Forest Fire Danger Rating System, crown fire initiation, fire behaviour, fire danger indices, logistic regression

L'amorce des feux de cime dans les peuplements résineux a été modélisée au moyen de l'analyse d'une régression logistique en considérant comme variables indépendantes un descripteur physique de base de la structure de l'ensemble formant le combustible et certains éléments choisis du Système canadien d'indice météorologique des feux de forêts (IMF). L'étude reposait sur une base de données de recherche sur le comportement du feu constituée de 63 feux expérimentaux rassemblant un assez grand éventail de conditions de brûlage et de caractéristiques du type de combustible. Quatre modèles ont été élaborés en fonction de la décroissance des intrants requis. Les prédicateurs significatifs de l'amorce des feux de cime étaient : la hauteur moyenne des cimes, la vitesse du vent mesurée à une hauteur de 10 m dans un espace ouvert, et quatre composantes du Système IMF (c'est-à-dire, le code d'humidité des particules fines de combustible, le code de sécheresse, l'indice de répartition initiale et l'indice d'accumulation). Les modèles ont prédit avec exactitude le type de feu (c'est-à-dire, de surface ou de cime) entre 90 % et 66 % du temps. L'indice C, une mesure statistique, a varié entre 0,94 et 0,71, démontrant une bonne concordance entre les probabilités prédites et les événements observés. Une comparaison entre les modèles logistiques et les modèles du Système canadien de prédiction du comportement des feux de forêts n'a révélé aucune différence significative. Les résultats de l'évaluation restreinte à deux ensembles de données sur des feux expérimentaux indépendants comportant des complexes de combustibles distinctement différents ont été encourageants. L'élaboration de modèles logistiques pourrait avoir une application dans les systèmes d'aide à la prise de décision pour la gestion des feux, permettant un estimé de la probabilité de l'amorce des feux de cime à petites et à grandes échelles dans le cas des situations courantes de feux et en fonction de l'information sur le niveau de danger associé aux feux. Les relations présentées dans cet article sont considérées être valides pour les feux non contrôlés en terrain plat dans des forêts de conifères qui ont atteint un pseudo état d'équilibre et ne sont pas utilisables pour les forêts de conifères mortes (par ex. les peuplements ravagés par des insectes).

Mots-clés: Système canadien de classification des feux de forêt, amorce des feux de cime, indices de danger relié aux feux, régression logistique

Introduction

The knowledge of fire behaviour is a fundamental component of any fire management system, allowing for the determination of the impact of fire on several ecosystem components, assessment of the effectiveness of fuel treatments, and support for decision-making in wildfire suppression planning and in forest management activities that

Miguel G. Cruz

Martin E. Alexander

Ronald H. Wakimoto

[1]Associação para o Desenvolvimento da Aerodinâmica Industrial, Apartado 10131, 3031 – 601 Coimbra, Portugal. Presently, Ph.D. Candidate, College of Forestry and Conservation, University of Montana, Missoula, Montana 59812. E-mail: miguel.gomesdacruz@umontana.edu
[2]Senior Fire Behaviour Research Officer, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre 5320–122 Street Edmonton, Alberta T6H 3S5. E-mail: malexand@nrcan.gc.ca
[3]Professor, College of Forestry and Conservation, University of Montana, Missoula, Montana 59812. E-mail: wakimoto@forestry.umt.edu

Four different logistic regression models that use crown base height (CBH) and/or 10-m open wind speed (U_{10}) and components of the Canadian Forest Fire Weather Index System:

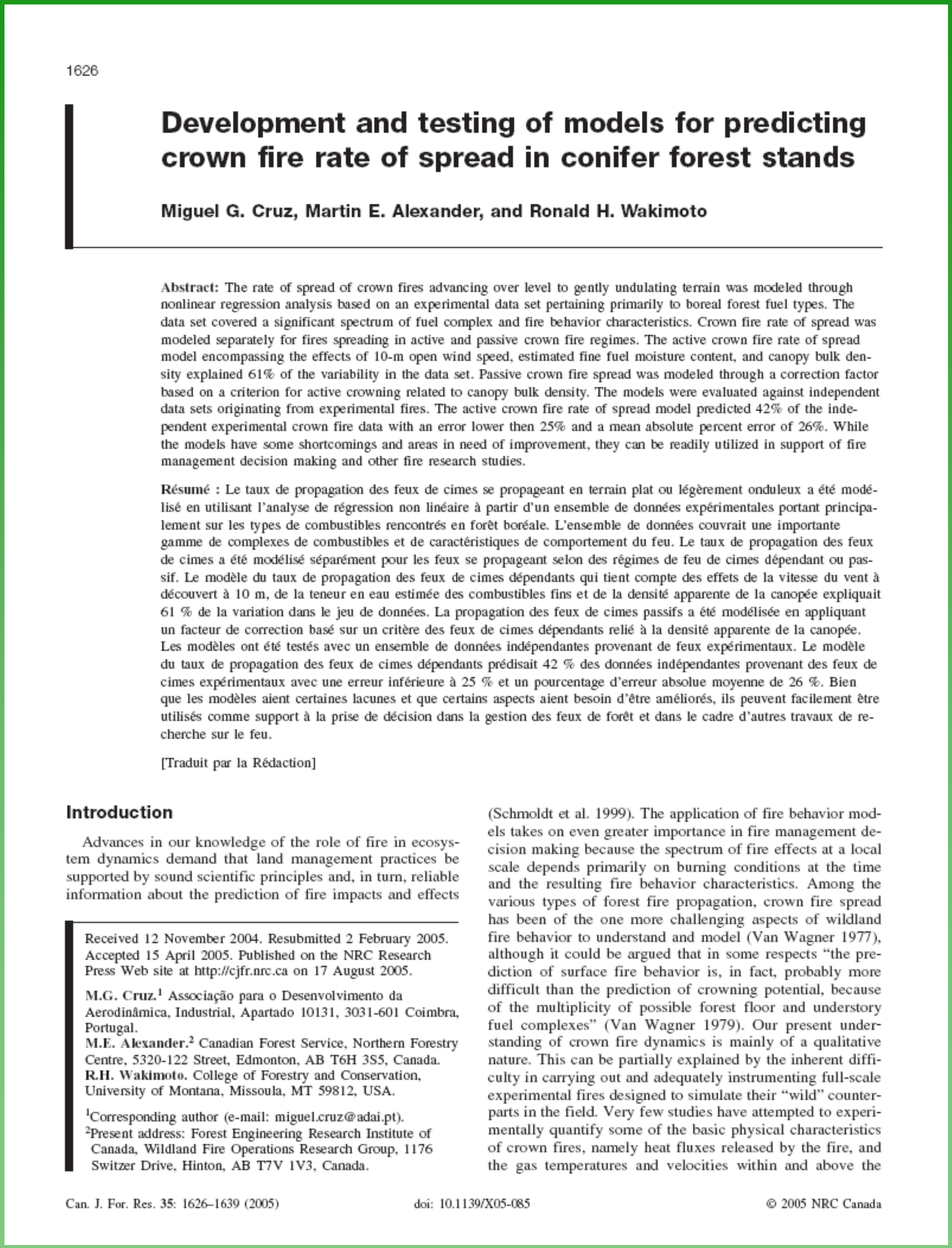
1: CBH, FFMC, WS, DC
2: CBH, ISI, DC
3: CBH, ISI, BUI
4: ISI, DC

***Forestry Chronicle* – September/October 2004 issue**

Results of evaluation of logistic models against two independent experimental fire data sets – Porter Lake and ICFME

Model	Type of fire	Porter Lake (Pred./Obs.)	ICFME (Pred./Obs.)
LOGIT1	Surface fires	0 / 0	1 / 0
	Crown fires	8 / 8	10 / 11
LOGIT2	Surface fires	0 / 0	2 / 0
	Crown fires	8 / 8	9 / 11
LOGIT3	Surface fires	0 / 0	3 / 0
	Crown fires	8 / 8	8 / 11
LOGIT4	Surface fires	0 / 0	2 / 0
	Crown fires	8 / 8	9 / 11

Active Crown Fire Rate of Spread



Development and testing of models for predicting crown fire rate of spread in conifer forest stands

Miguel G. Cruz, Martin E. Alexander, and Ronald H. Wakimoto

Abstract: The rate of spread of crown fires advancing over level to gently undulating terrain was modeled through nonlinear regression analysis based on an experimental data set pertaining primarily to boreal forest fuel types. The data set covered a significant spectrum of fuel complex and fire behavior characteristics. Crown fire rate of spread was modeled separately for fires spreading in active and passive crown fire regimes. The active crown fire rate of spread model encompassing the effects of 10-m open wind speed, estimated fine fuel moisture content, and canopy bulk density explained 61% of the variability in the data set. Passive crown fire spread was modeled through a correction factor based on a criterion for active crowning related to canopy bulk density. The models were evaluated against independent data sets originating from experimental fires. The active crown fire rate of spread model predicted 42% of the independent experimental crown fire data with an error lower then 25% and a mean absolute percent error of 26%. While the models have some shortcomings and areas in need of improvement, they can be readily utilized in support of fire management decision making and other fire research studies.

Résumé : Le taux de propagation des feux de cimes se propageant en terrain plat ou légèrement onduleux a été modélisé en utilisant l'analyse de régression non linéaire à partir d'un ensemble de données expérimentales portant principalement sur les types de combustibles rencontrés en forêt boréale. L'ensemble de données couvrait une importante gamme de complexes de combustibles et de caractéristiques de comportement du feu. Le taux de propagation des feux de cimes a été modélisé séparément pour les feux se propageant selon des régimes de feu de cimes dépendant ou passif. Le modèle du taux de propagation des feux de cimes dépendants qui tient compte des effets de la vitesse du vent à découvert à 10 m, de la teneur en eau estimée des combustibles fins et de la densité apparente de la canopée expliquait 61 % de la variation dans le jeu de données. La propagation des feux de cimes passifs a été modélisée en appliquant un facteur de correction basé sur un critère des feux de cimes dépendants relié à la densité apparente de la canopée. Les modèles ont été testés avec un ensemble de données indépendantes provenant de feux expérimentaux. Le modèle du taux de propagation des feux de cimes dépendants prédisait 42 % des données indépendantes provenant des feux de cimes expérimentaux avec une erreur inférieure à 25 % et un pourcentage d'erreur absolue moyenne de 26 %. Bien que les modèles aient certaines lacunes et que certains aspects aient besoin d'être améliorés, ils peuvent facilement être utilisés comme support à la prise de décision dans la gestion des feux de forêt et dans le cadre d'autres travaux de recherche sur le feu.

[Traduit par la Rédaction]

Introduction

Advances in our knowledge of the role of fire in ecosystem dynamics demand that land management practices be supported by sound scientific principles and, in turn, reliable information about the prediction of fire impacts and effects (Schmoldt et al. 1999). The application of fire behavior models takes on even greater importance in fire management decision making because the spectrum of fire effects at a local scale depends primarily on burning conditions at the time and the resulting fire behavior characteristics. Among the various types of forest fire propagation, crown fire spread has been of the one more challenging aspects of wildland fire behavior to understand and model (Van Wagner 1977), although it could be argued that in some respects "the prediction of surface fire behavior is, in fact, probably more difficult than the prediction of crowning potential, because of the multiplicity of possible forest floor and understory fuel complexes" (Van Wagner 1979). Our present understanding of crown fire dynamics is mainly of a qualitative nature. This can be partially explained by the inherent difficulty in carrying out and adequately instrumenting full-scale experimental fires designed to simulate their "wild" counterparts in the field. Very few studies have attempted to experimentally quantify some of the basic physical characteristics of crown fires, namely heat fluxes released by the fire, and the gas temperatures and velocities within and above the

Received 12 November 2004. Resubmitted 2 February 2005. Accepted 15 April 2005. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 17 August 2005.

M.G. Cruz.[1] Associação para o Desenvolvimento da Aerodinâmica, Industrial, Apartado 10131, 3031-601 Coimbra, Portugal.
M.E. Alexander.[2] Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB T6H 3S5, Canada.
R.H. Wakimoto. College of Forestry and Conservation, University of Montana, Missoula, MT 59812, USA.

[1]Corresponding author (e-mail: miguel.cruz@adai.pt).
[2]Present address: Forest Engineering Research Institute of Canada, Wildland Fire Operations Research Group, 1176 Switzer Drive, Hinton, AB T7V 1V3, Canada.

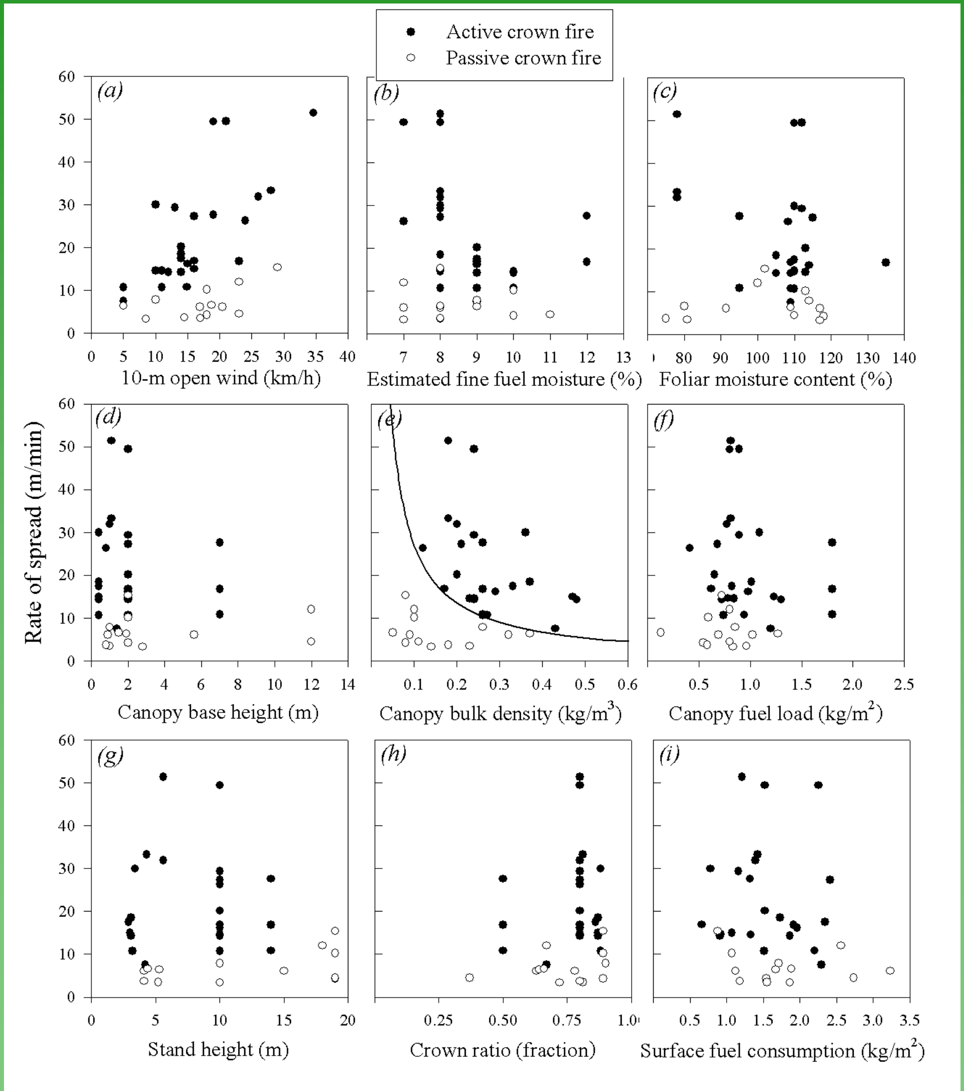
 doi: 10.1139/X05-085

Regression model for predicting active crown fire spread rates based on three environmental inputs:

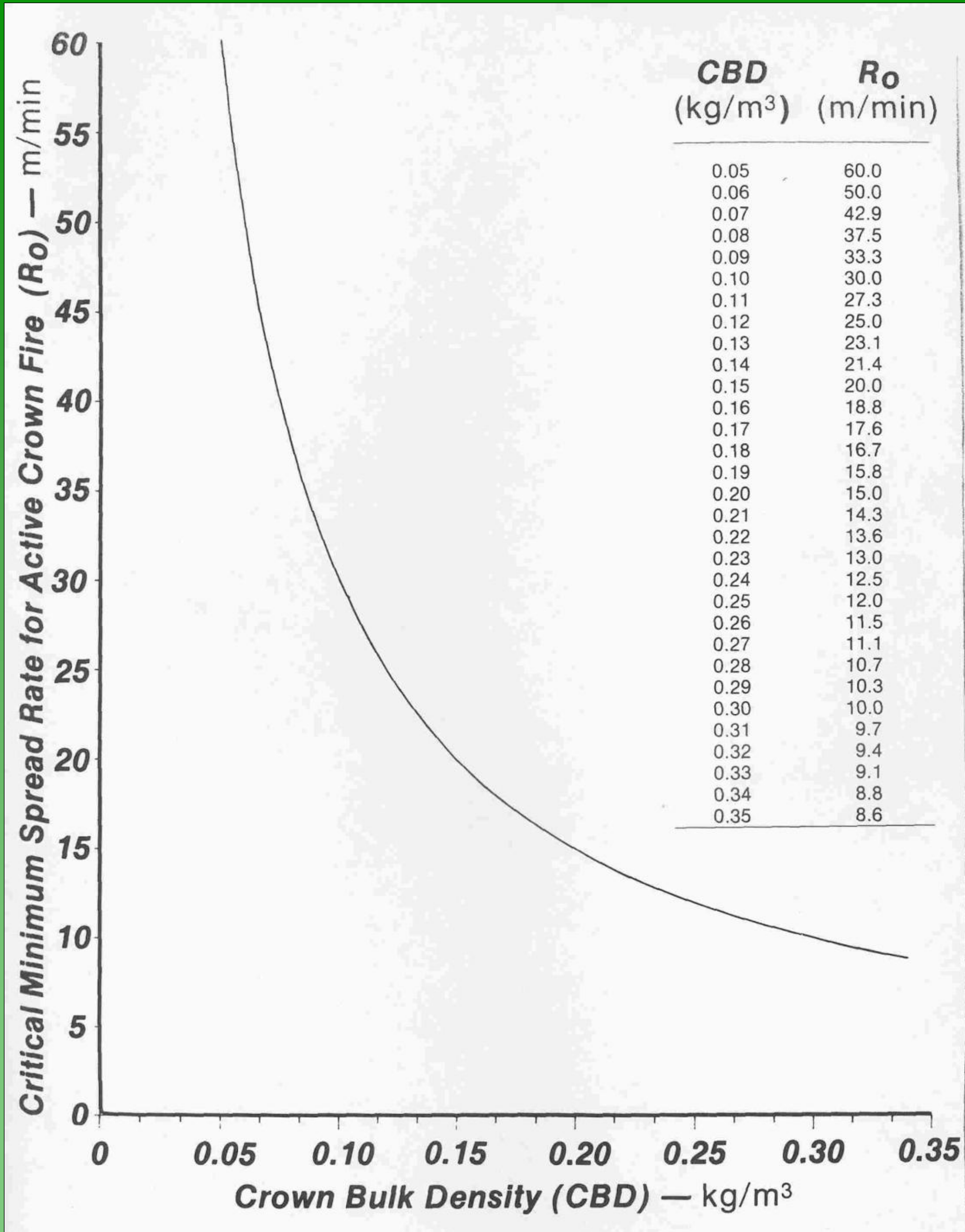
- 10-m open wind speed
- Canopy bulk density
- Effective fine
- fuel moisture

***Canadian Journal of Forest Research* – August 2005 issue**

Crown Fire Rate of Spread – Analysis & Model Development



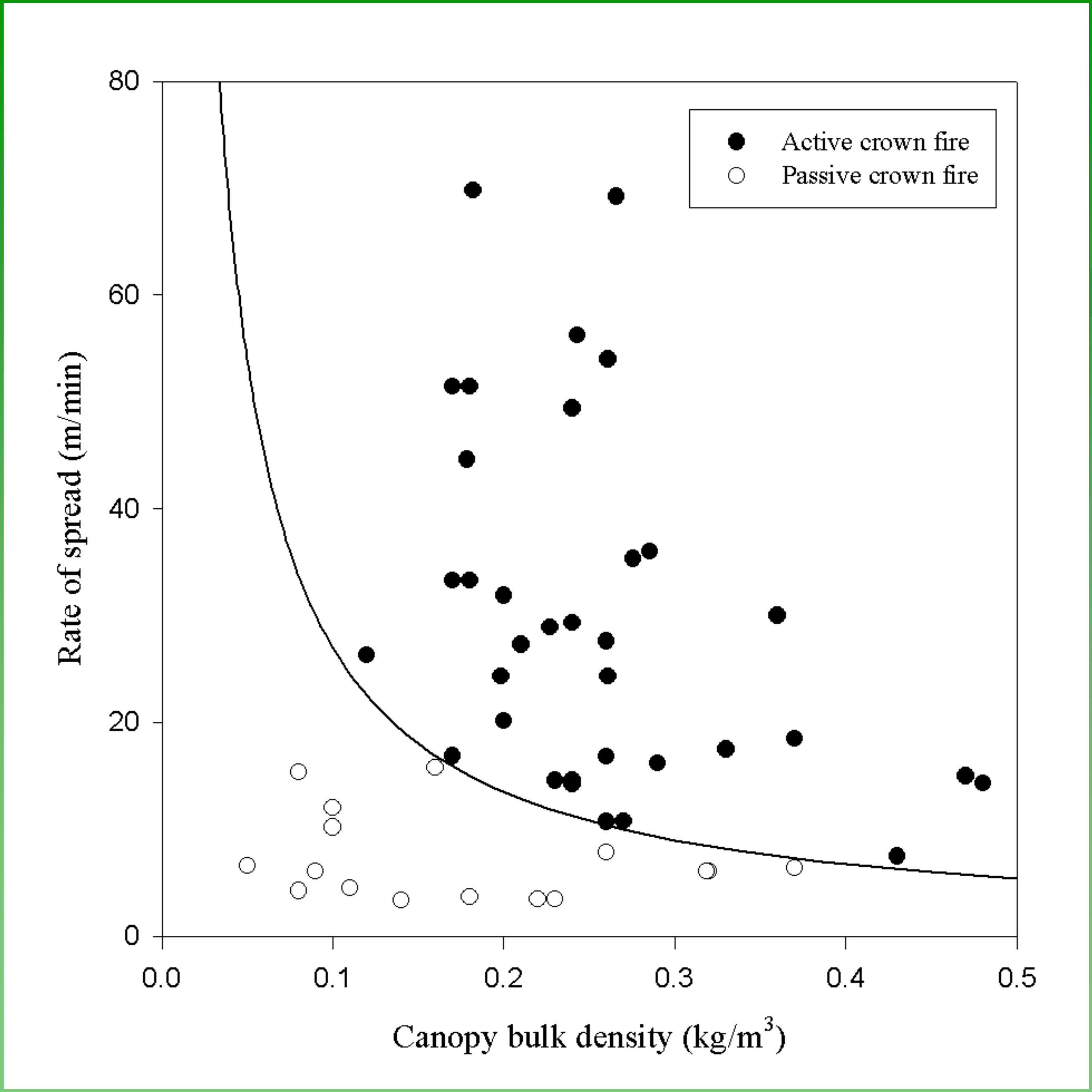
- Comprehensive review of the literature
- Number of variables examined
- Data available for 24 active crown fires and 13 passive crown fires



CBD (kg/m³)	R_O (m/min)
0.05	60.0
0.06	50.0
0.07	42.9
0.08	37.5
0.09	33.3
0.10	30.0
0.11	27.3
0.12	25.0
0.13	23.1
0.14	21.4
0.15	20.0
0.16	18.8
0.17	17.6
0.18	16.7
0.19	15.8
0.20	15.0
0.21	14.3
0.22	13.6
0.23	13.0
0.24	12.5
0.25	12.0
0.26	11.5
0.27	11.1
0.28	10.7
0.29	10.3
0.30	10.0
0.31	9.7
0.32	9.4
0.33	9.1
0.34	8.8
0.35	8.6

Passive crown fire rate of spread was modelled through a correction factor based on the criterion for active crowning related to canopy bulk density as suggested by C.E. Van Wagner.*

*1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7: 23-34.



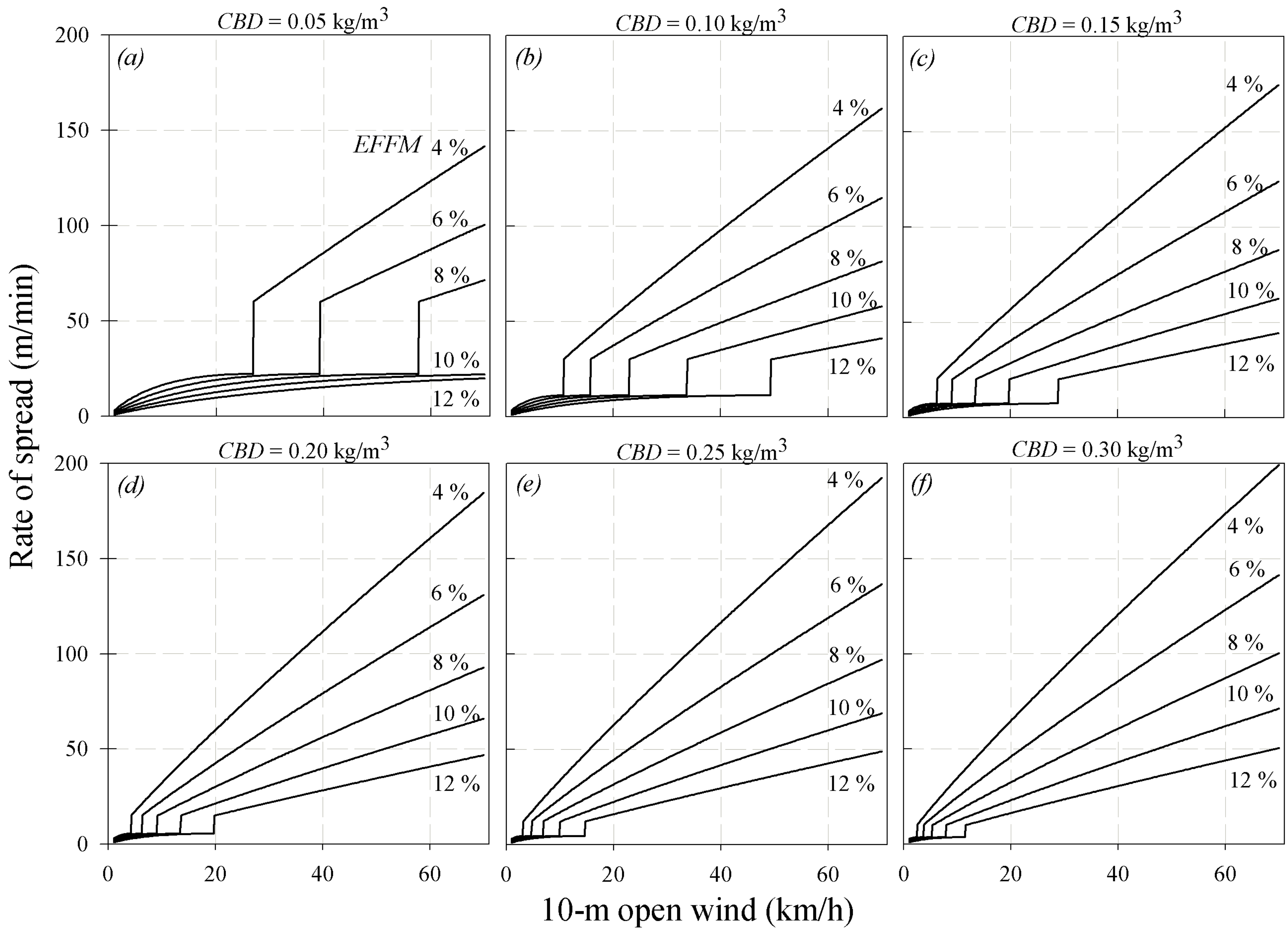
Van Wagner's (1977) criterion represented by curve

Crown Fire Rate of Spread – Analysis & Model Development

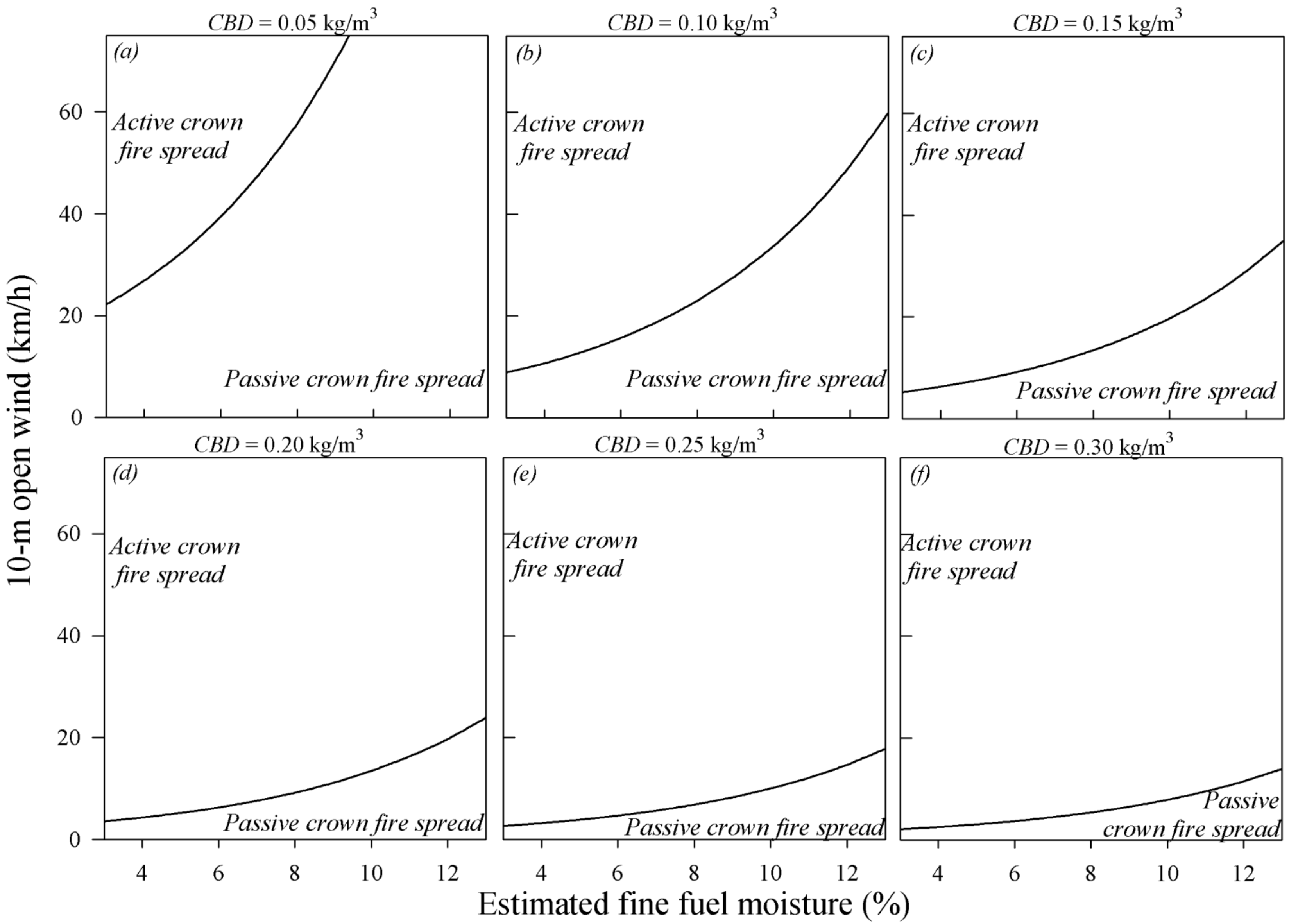
Statistics on Assembled Database

	Active crown fires (n = 24)				Passive crown fires (n = 13)			
Variable	Min.	Max.	Mean	Std. dev.	Min.	Max.	Mean	Std. dev.
Stand basal area ($m^2 \cdot ha^{-1}$)	3.35	50	26.8	16.3	4.14	35.2	18.4	10.4
Stand density ($trees \cdot ha^{-1}$)	887	6750	3561	1454	597	9276	3656	3481
Stand height (m)	2.9	14	7.9	3.8	4.1	19	11.7	6.6
Crown ratio (fraction)	0.5	0.88	0.78	0.12	0.37	0.9	0.74	0.15
Canopy base height (m)	0.4	7	2.1	2	0.8	12	3	3.2
Canopy bulk density ($kg \cdot m^{-3}$)	0.12	0.48	0.27	0.09	0.05	0.37	0.16	0.1
10-m open wind speed ($km \cdot h^{-1}$)	5	32.1	15.8	6.7	5	29	16.3	6.3
Estimated fine fuel moisture content (%)	7	12	8.8	1.3	7	11	8.6	1.2
Surface fuel consumption ($kg \cdot m^{-2}$)	0.66	2.4	1.6	0.5	0.9	3.2	1.7	0.7
Foliar moisture content (%)	78	135	107	11.5	75	118	102	15.4
Rate of fire spread ($m \cdot min^{-1}$)	7.5	51.4	22.6	12.6	3.35	15.4	7.1	4
Fireline intensity ($kW \cdot m^{-1}$)	4230	45 200	16 918	10 746	1698	17 000	5127	4239

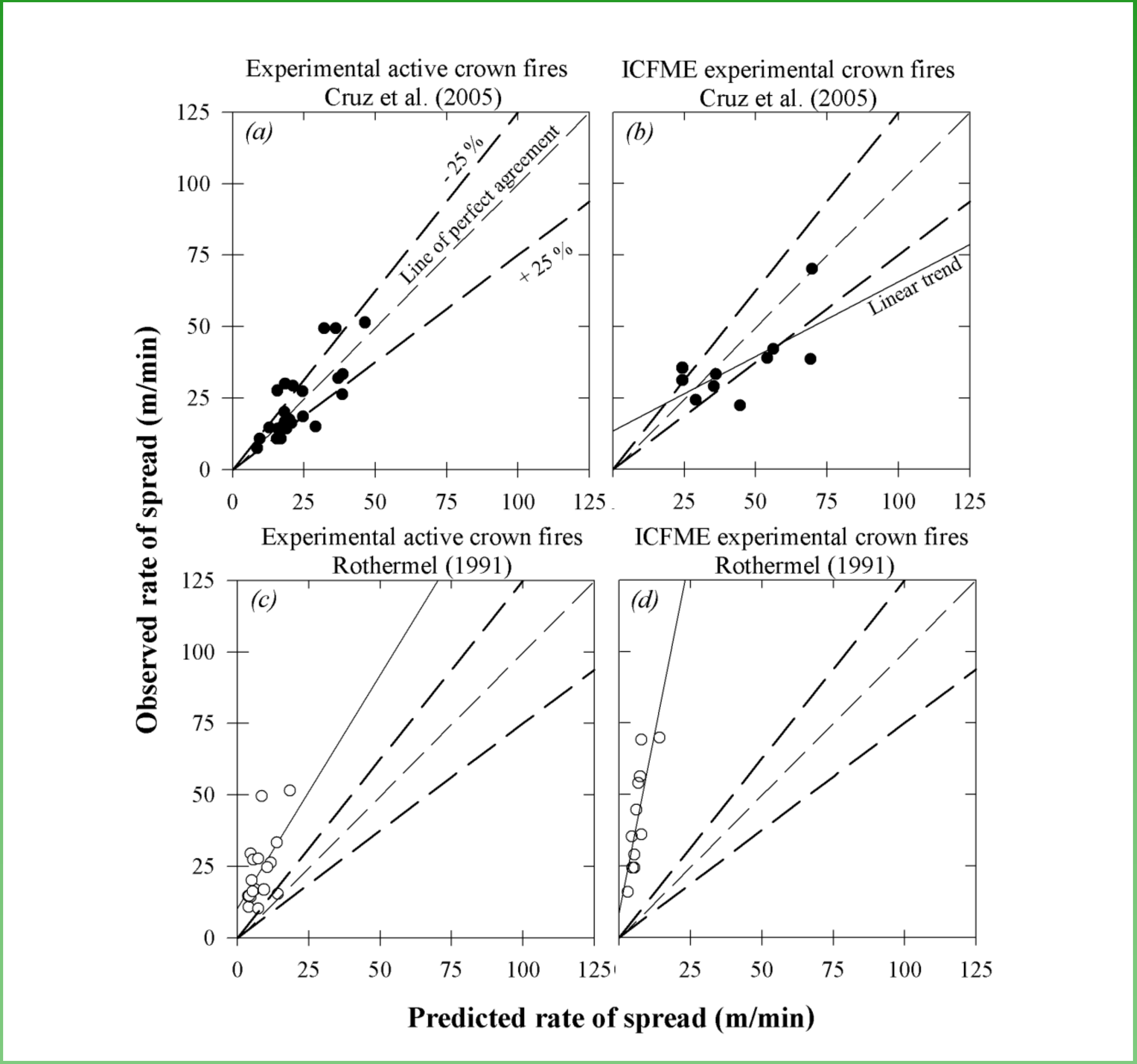
Crown Fire Rate of Spread

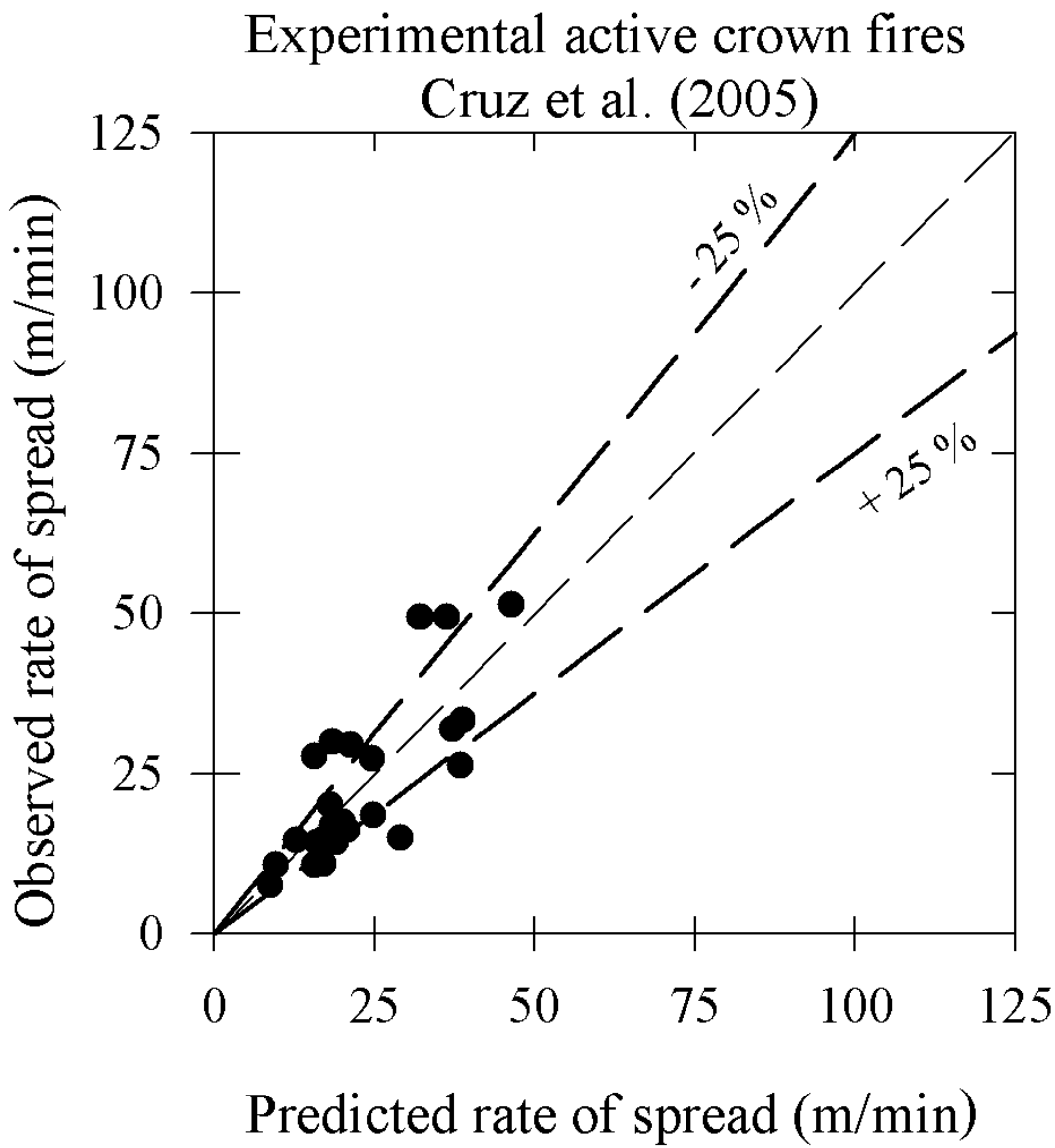


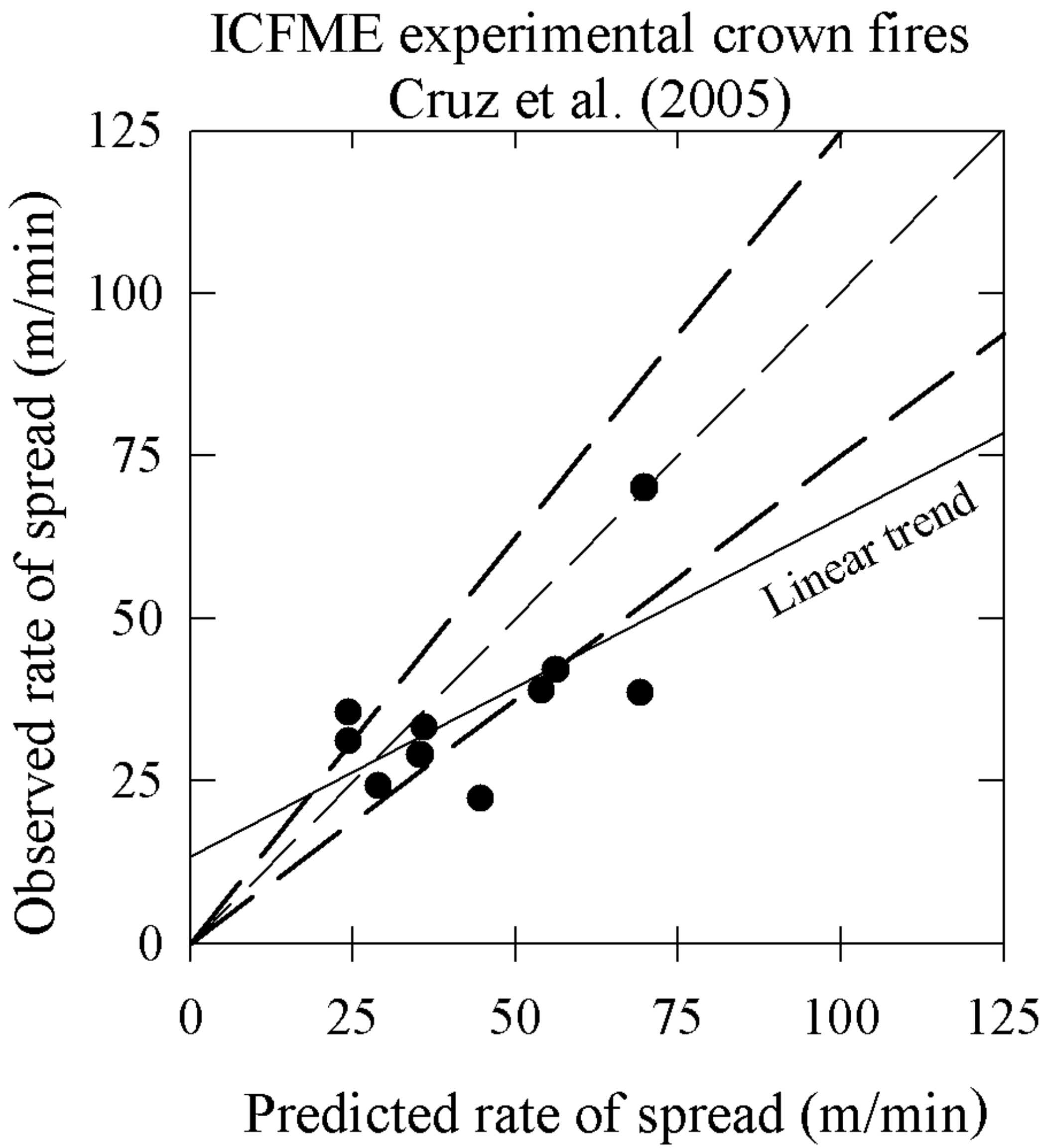
Crown Fire Rate of Spread

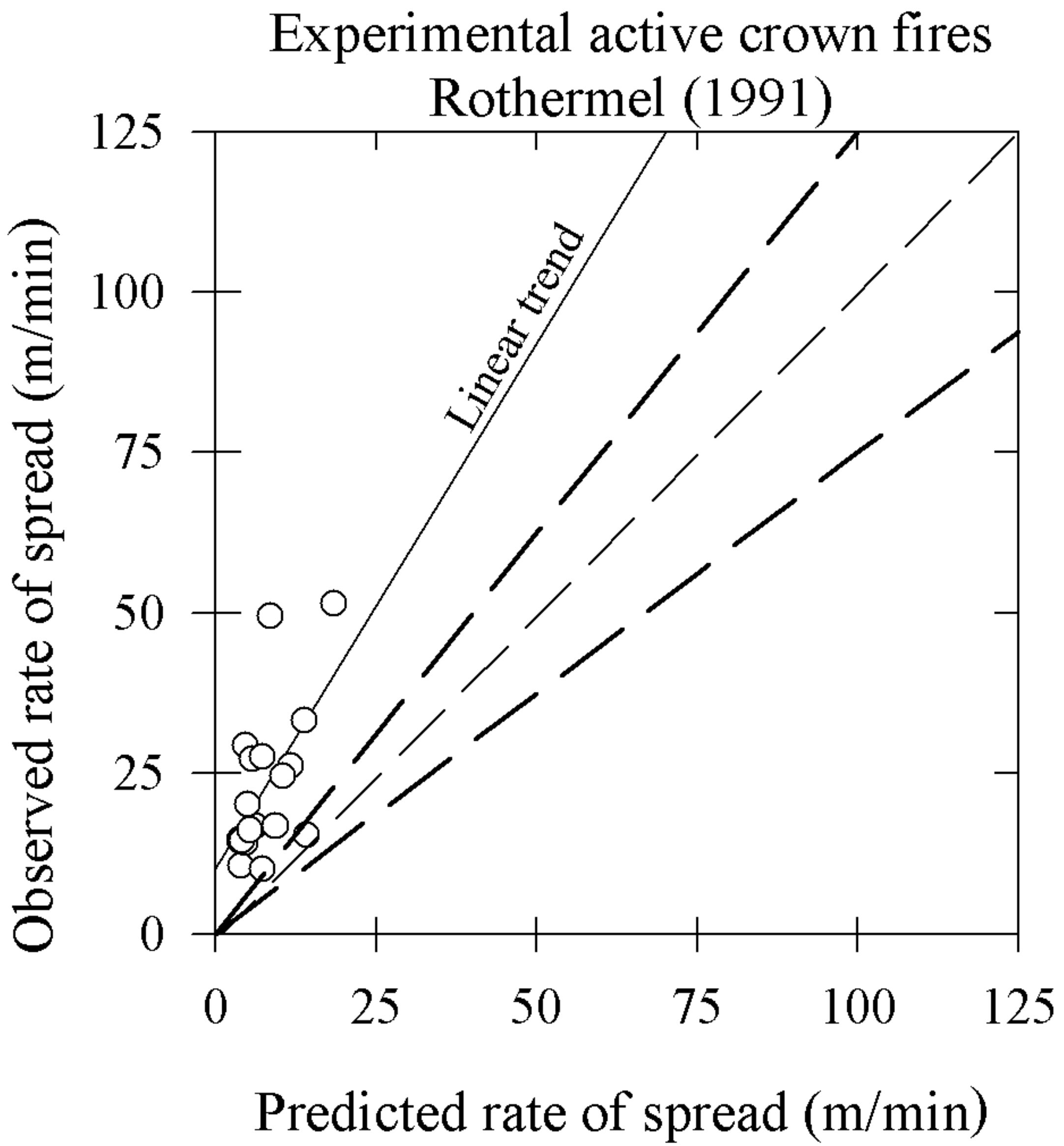


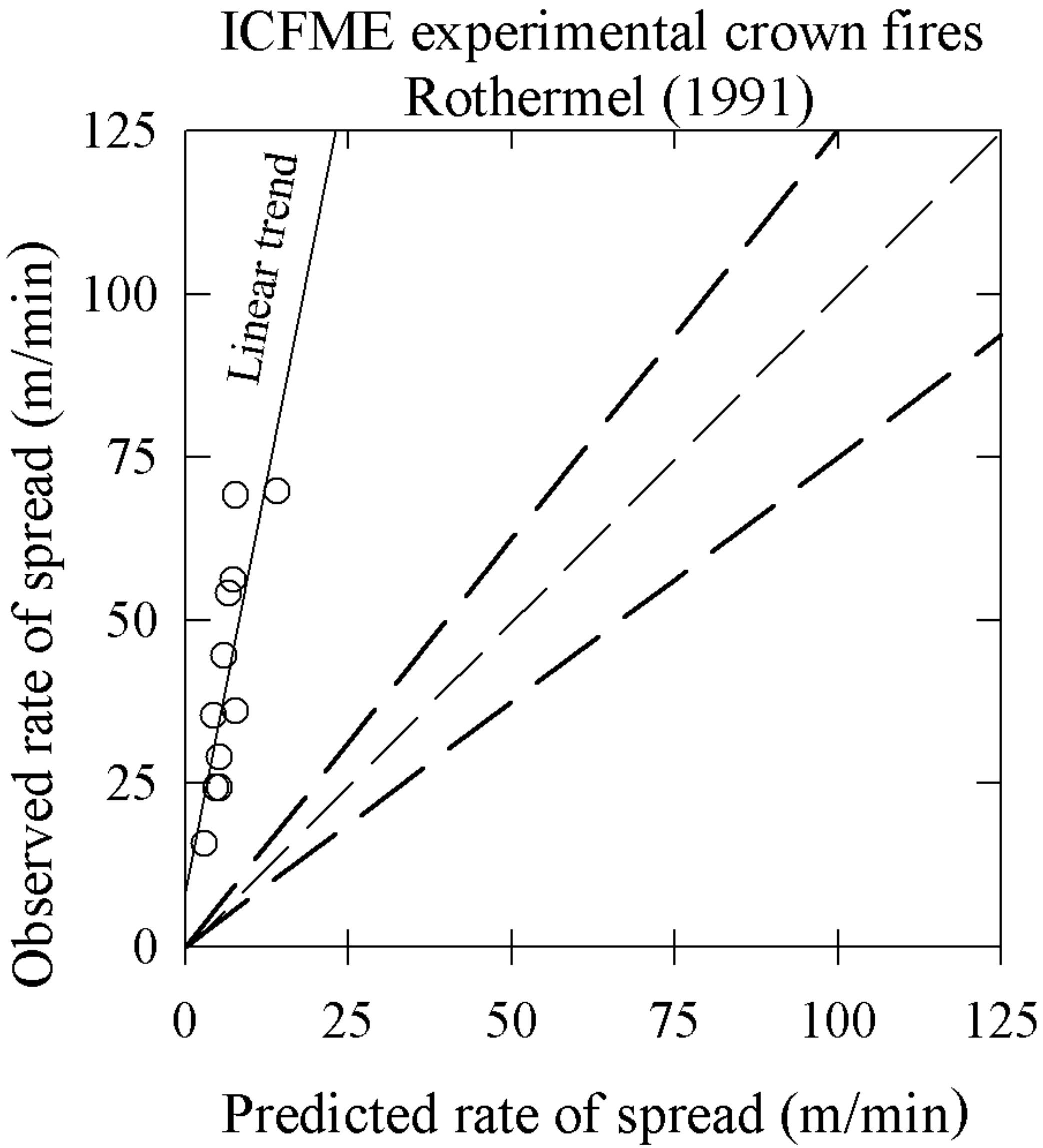
Active Crown Fire Rate of Spread -- Evaluation Results from Experimental Fires




Experimental active crown fires
Cruz et al. (2005)
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
-25 %
+ 25 %
0
25
50
75
100
125

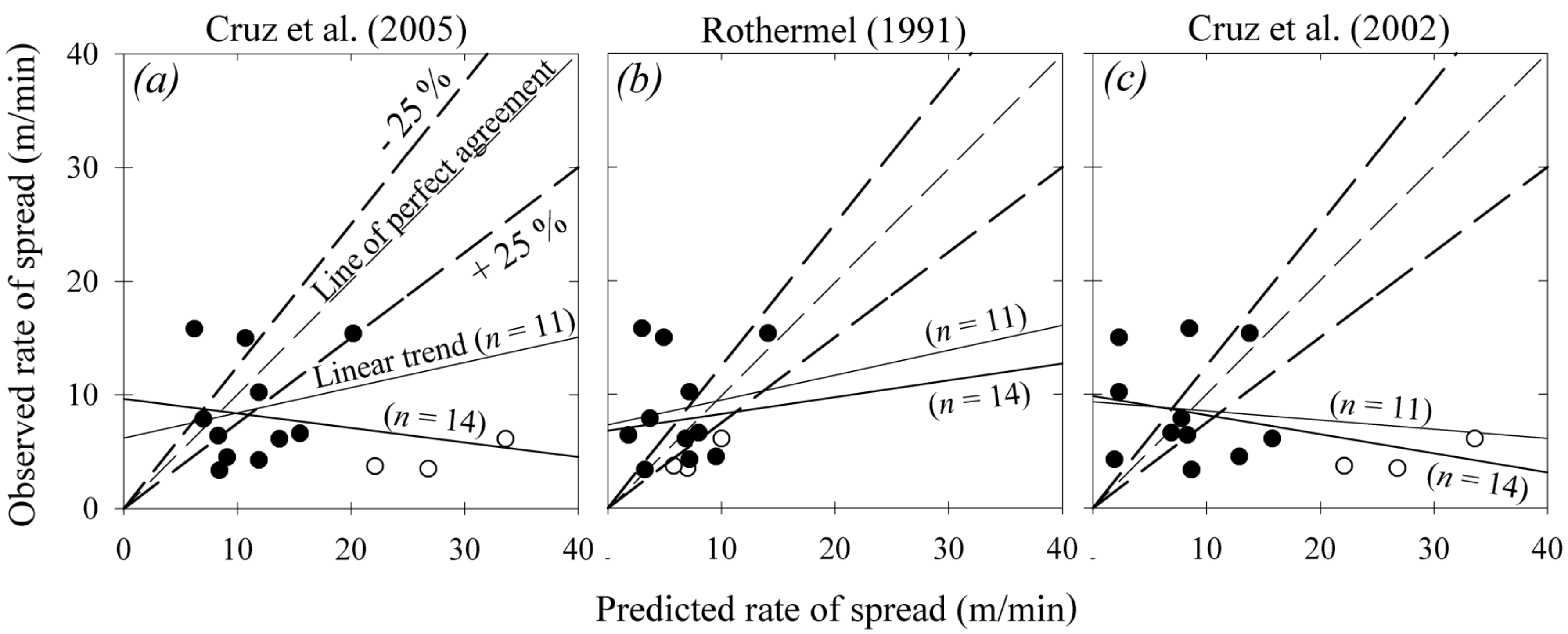

ICFME experimental crown fires
Cruz et al. (2005)
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
Linear trend
0
25
50
75
100
125
0
25
50
75
100
125


Experimental active crown fires
Rothermel (1991)
Linear trend
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
0
25
50
75
100
125

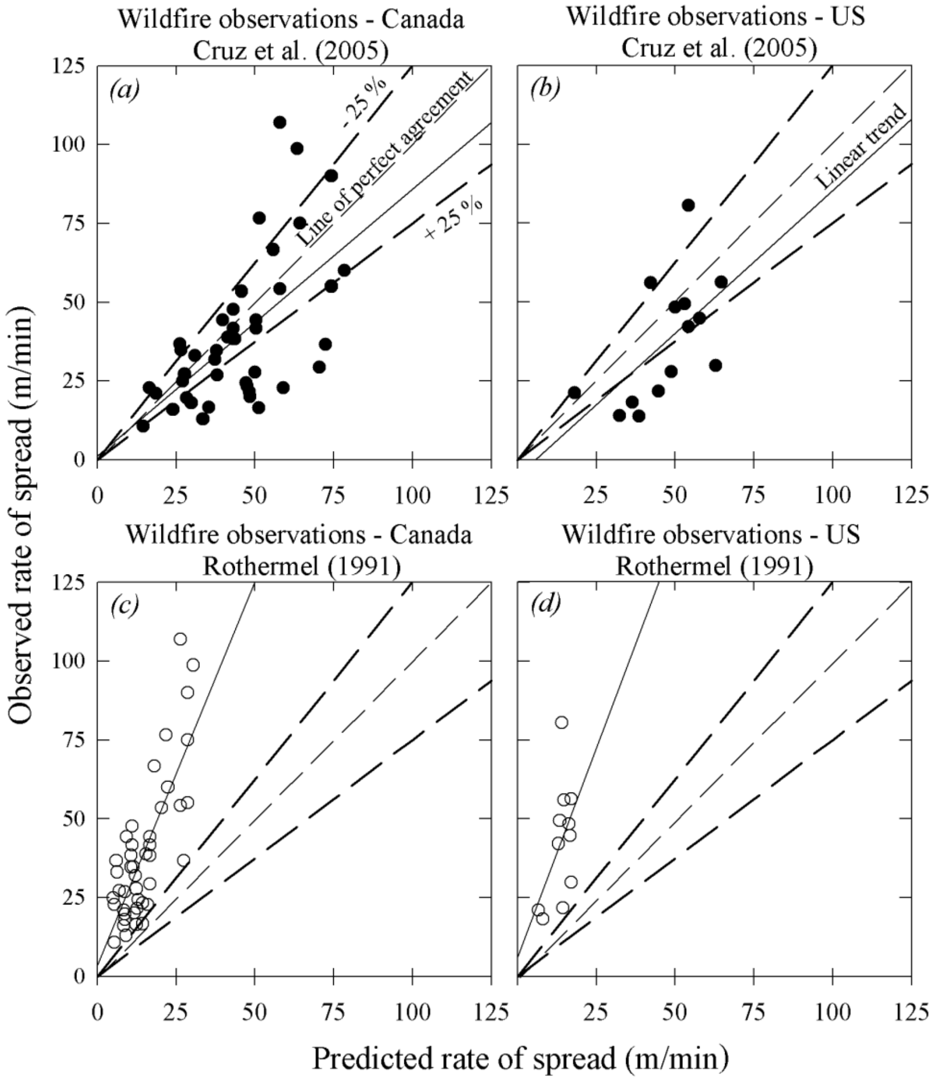


ICFME experimental crown fires
Rothermel (1991)
Linear trend
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
0
25
50
75
100
125

Passive Crown Fire Rate of Spread -- Evaluation Results from Experimental Fires

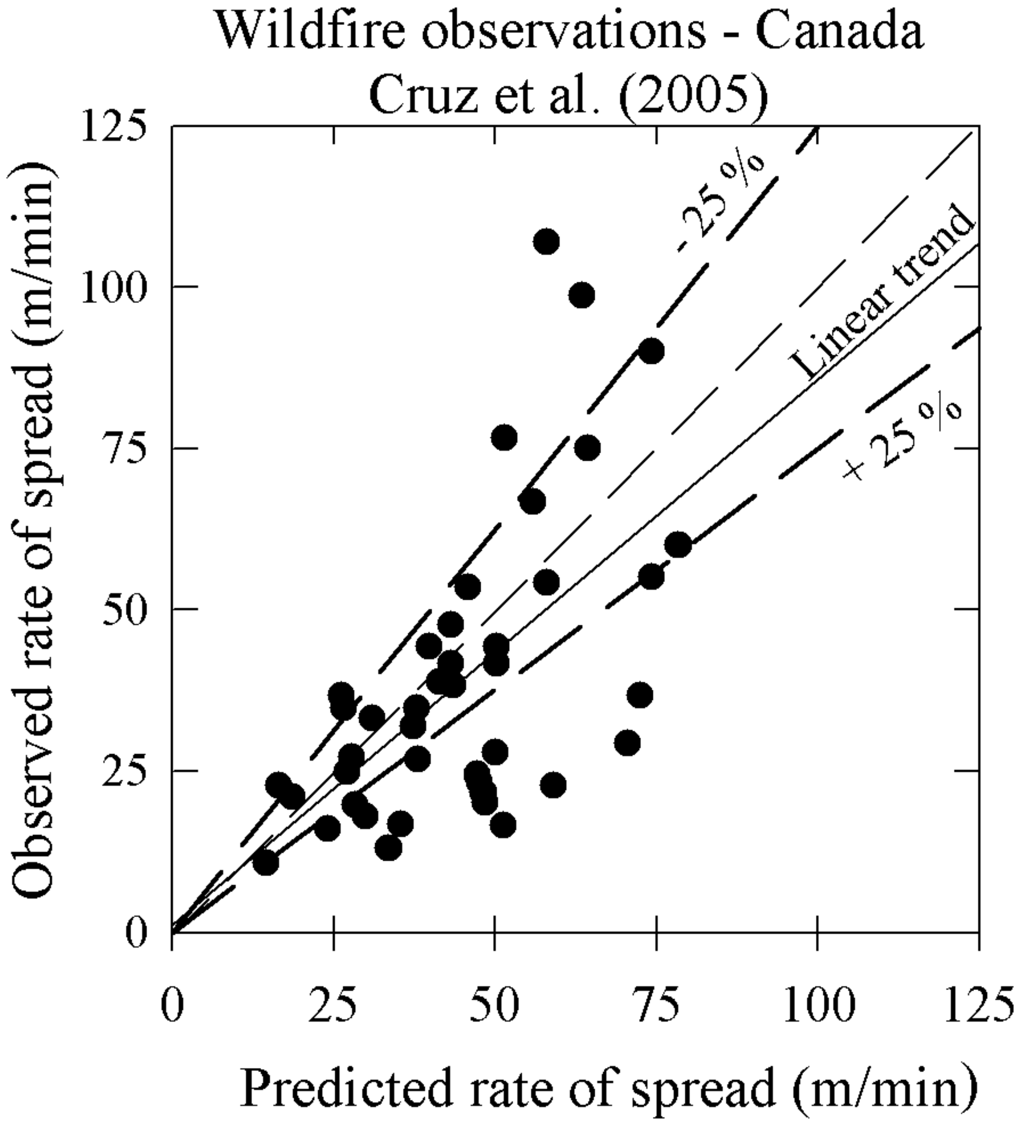


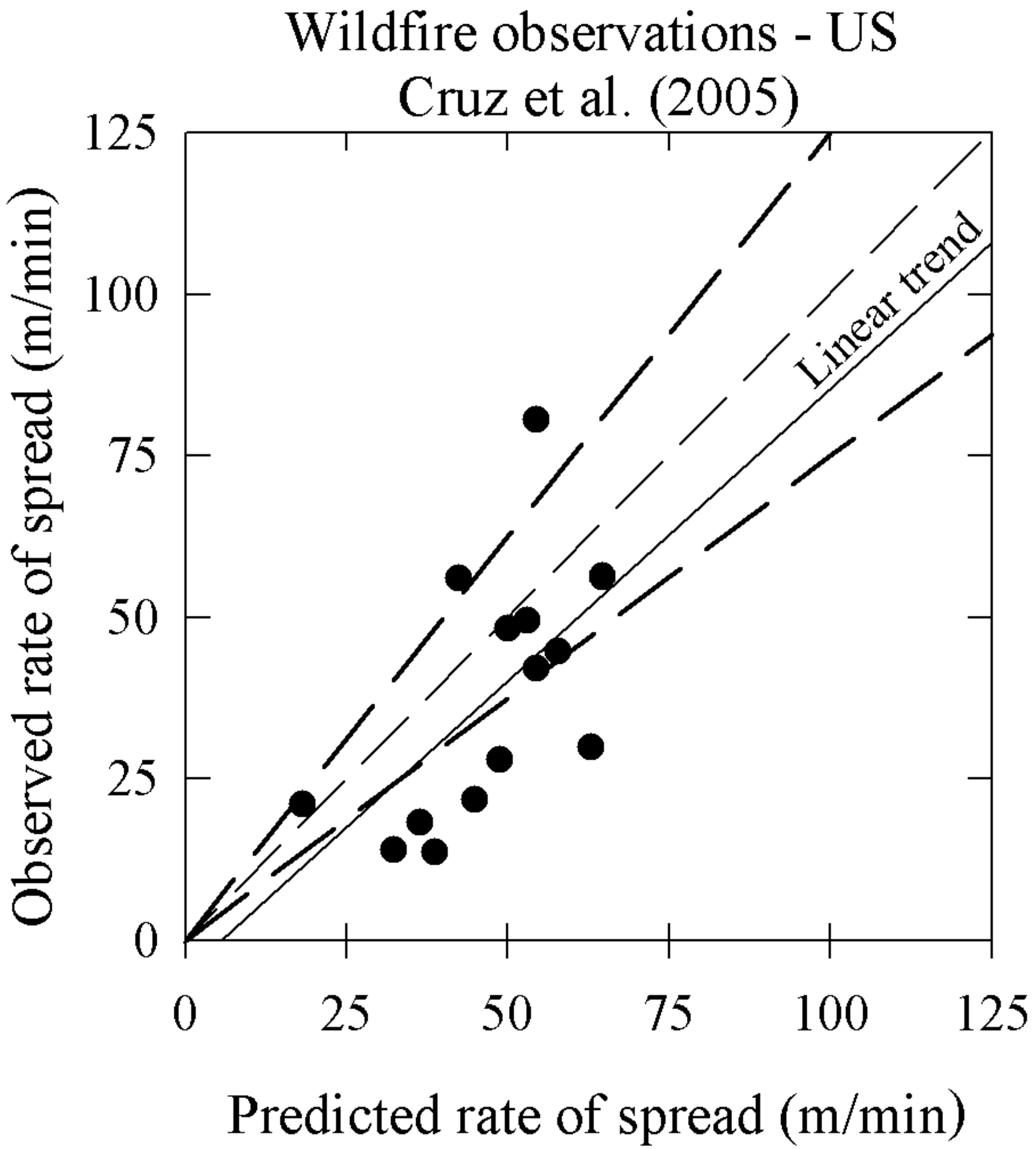
Active Crown Fire Rate of Spread -- Evaluation Results from Wildfires



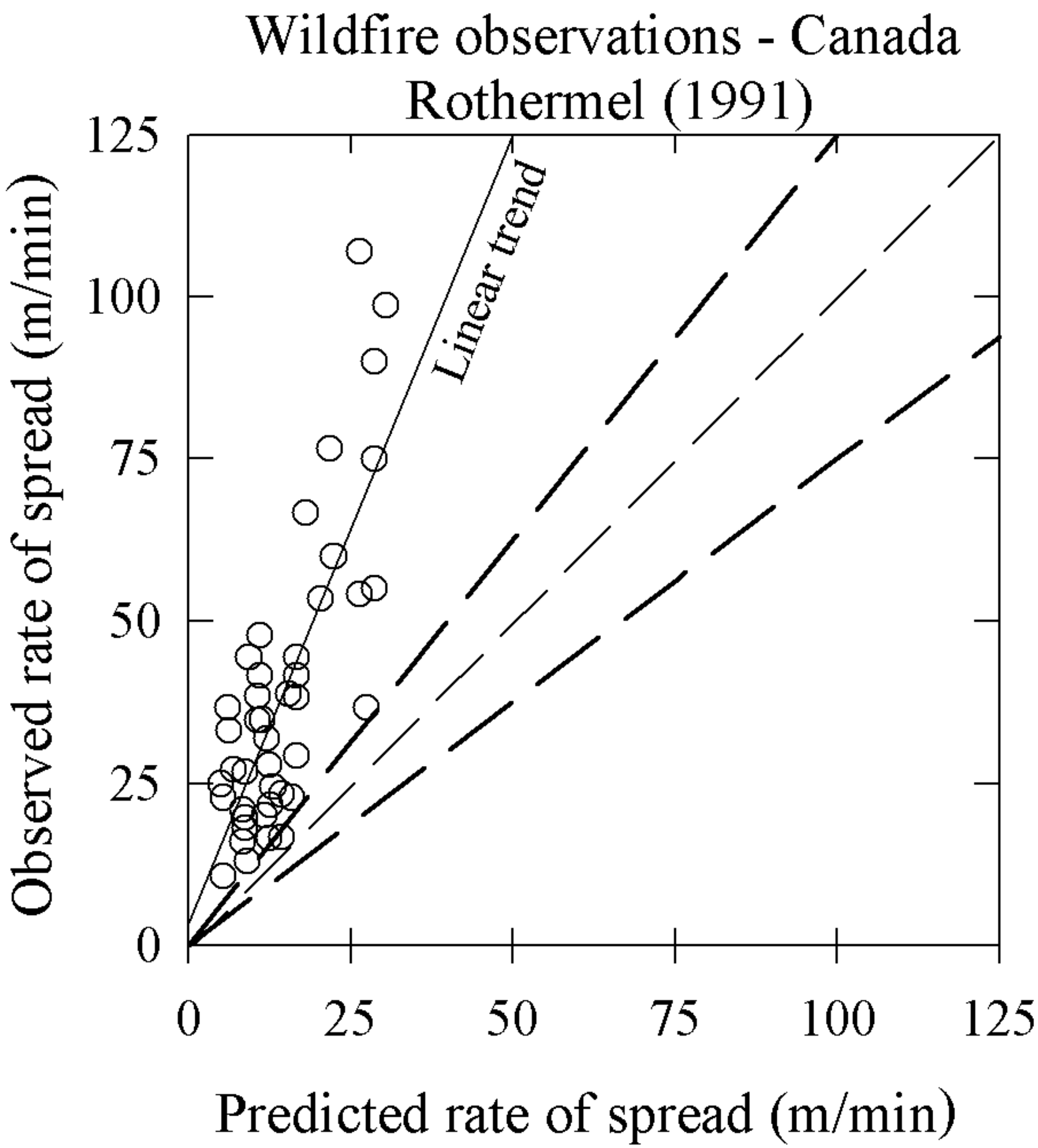
57 Wildfires:

- **43 Canadian Wildfires**
- **14 U.S. Wildfires**

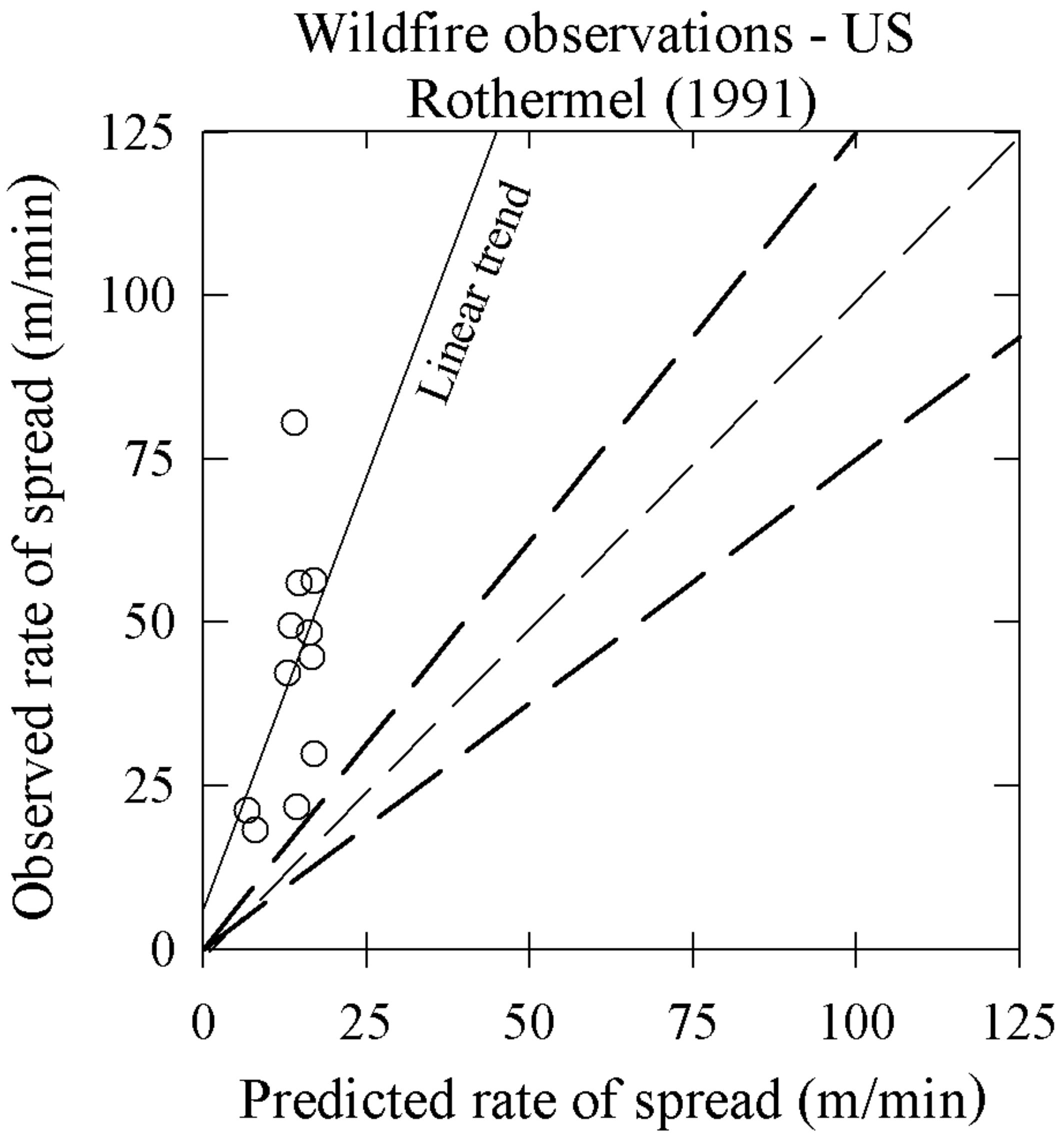

Wildfire observations - Canada
Cruz et al. (2005)
-25 %
Linear trend
+ 25 %
0
25
50
75
100
125
Predicted rate of spread (m/min)
Observed rate of spread (m/min)



Wildfire observations - US
Cruz et al. (2005)
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
Linear trend
0
25
50
75
100
125



Wildfire observations - Canada
Rothermel (1991)
Linear trend
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
0
25
50
75
100
125


Wildfire observations - US
Rothermel (1991)
Linear trend
Observed rate of spread (m/min)
Predicted rate of spread (m/min)
0
25
50
75
100
125

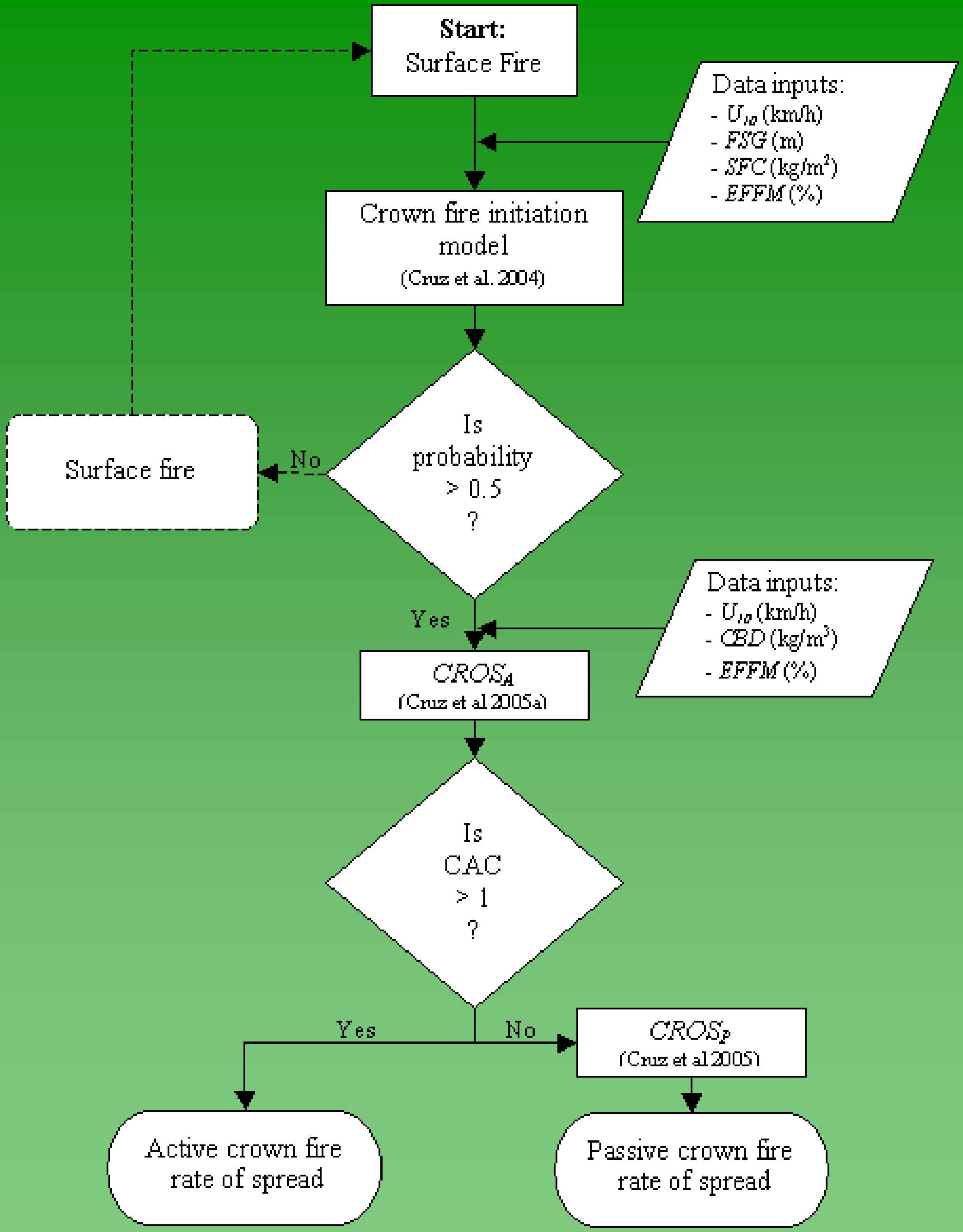
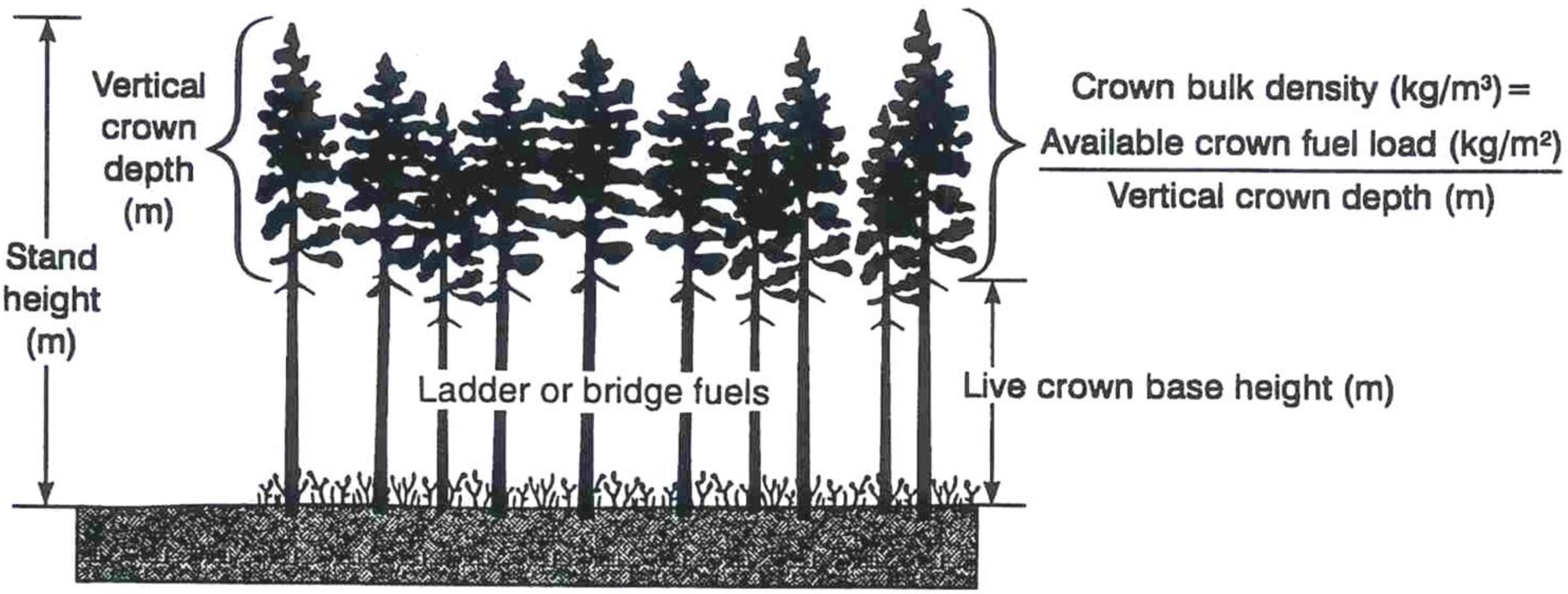
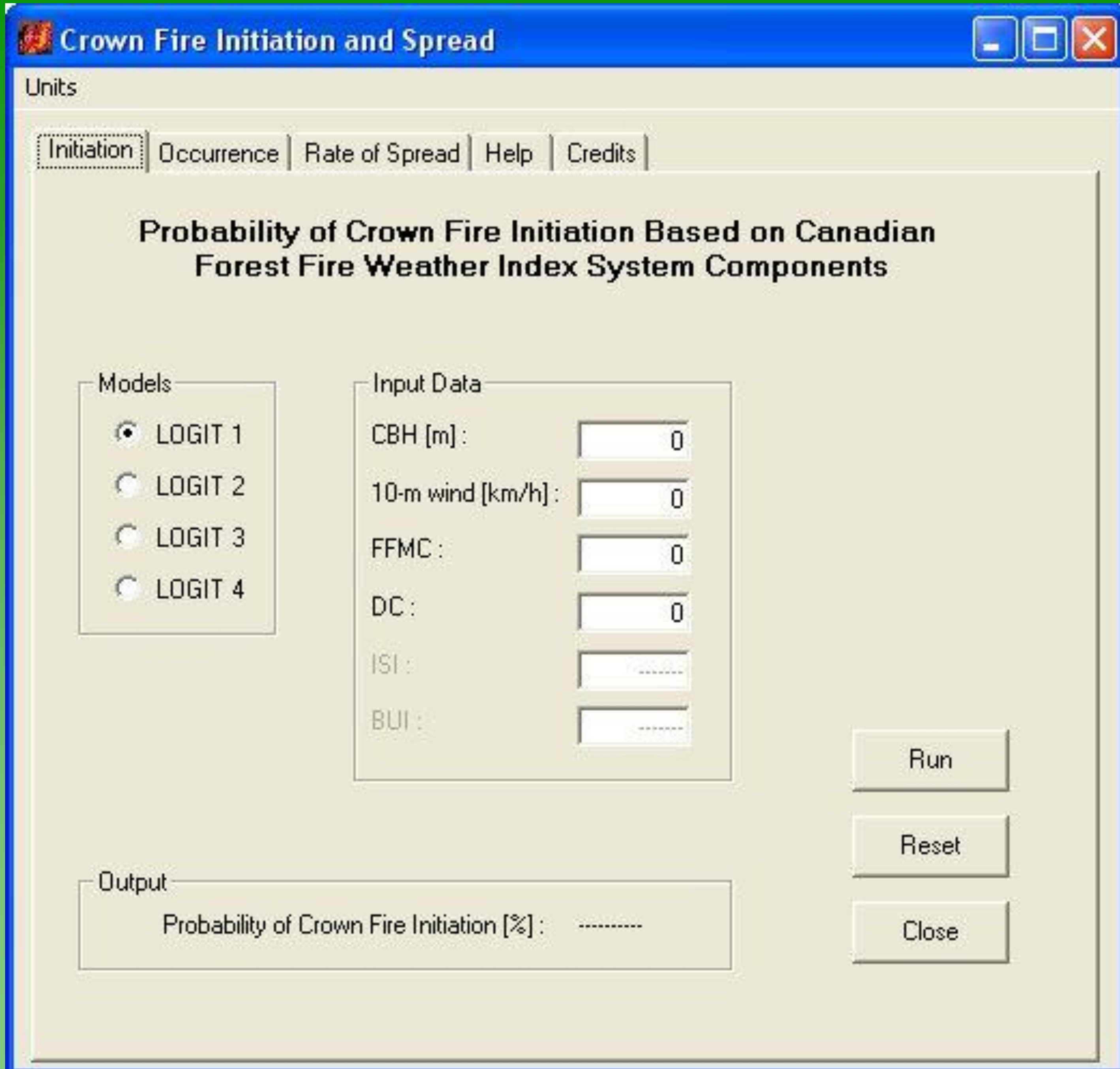


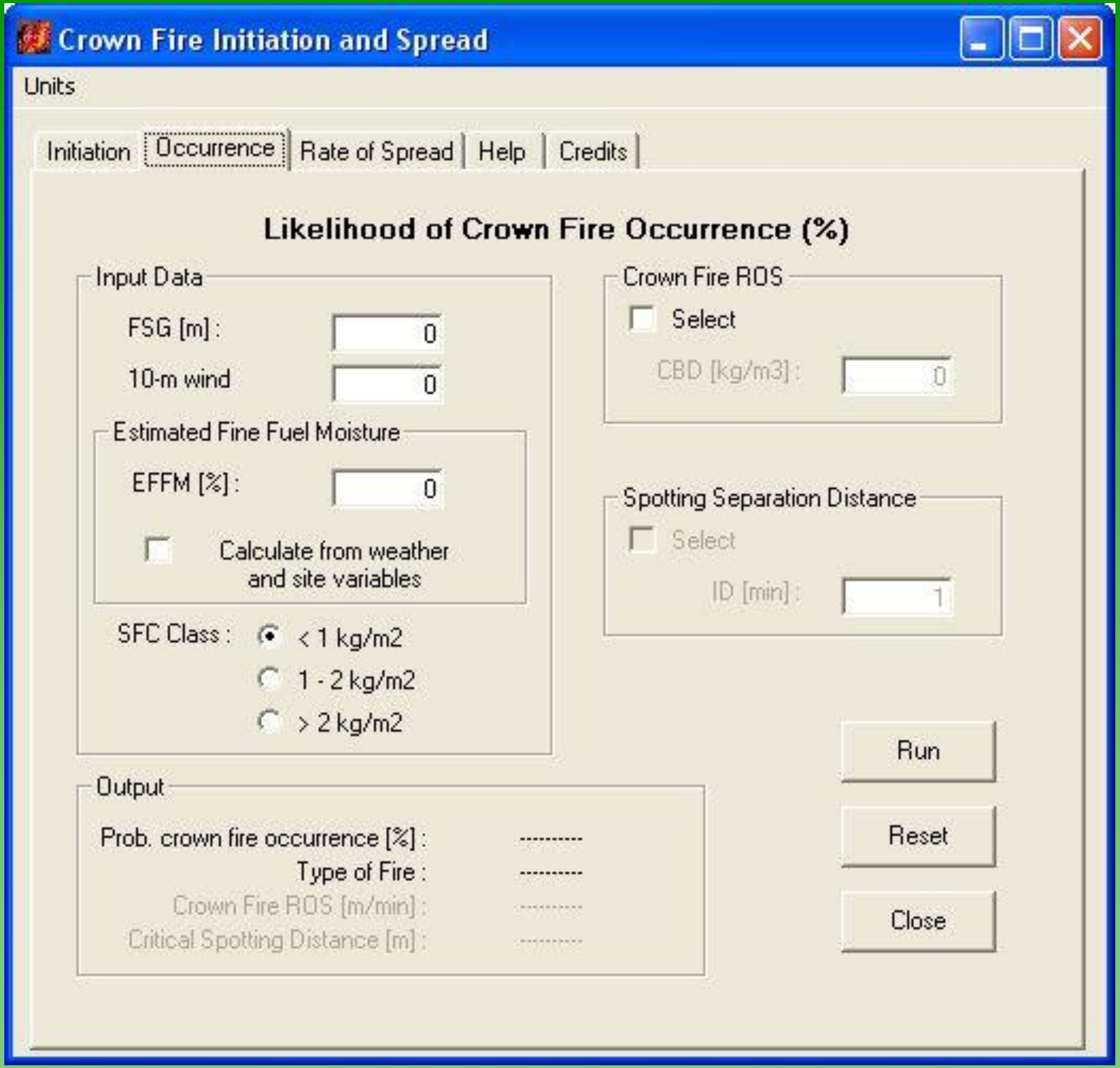
Diagram of information flow for predicting crown fire behavior potential based on the models developed by Cruz, Alexander and Wakimoto (2004, 2005).

Canopy or Crown Bulk Density




Crown Fire Initiation and Spread
Units
Initiation
Occurrence
Rate of Spread
Help
Credits
CFIS
Simulation of Crown Fire Initiation and Spread
Developed by :
Miguel G. Cruz - ADAI
António M.G. Lopes - ADAI
Martin E. Alexander - FERIC
Associação para o Desenvolvimento
da Aerodinâmica Industrial
FERIC
Forest Engineering
Research Institute of Canada

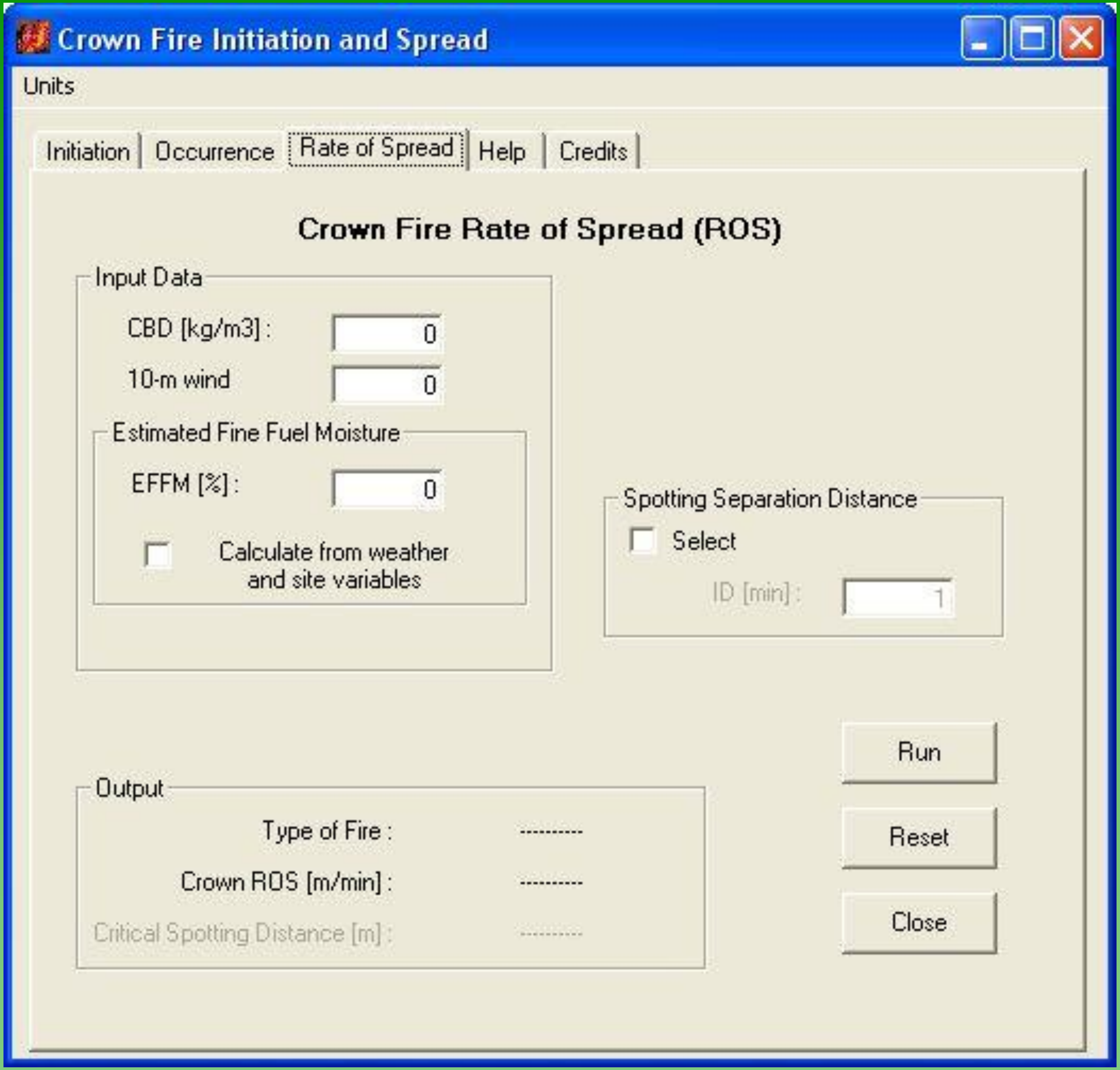

Crown Fire Initiation and Spread
Units
Initiation
Occurrence
Rate of Spread
Help
Credits
Probability of Crown Fire Initiation Based on Canadian Forest Fire Weather Index System Components
Models
LOGIT 1
LOGIT 2
LOGIT 3
LOGIT 4
Input Data
CBH [m] :
0
10-m wind [km/h] :
0
FFMC :
0
DC :
0
ISI :
BUI :
Run
Reset
Close
Output
Probability of Crown Fire Initiation [%] :


Crown Fire Initiation and Spread
Units
Initiation
Occurrence
Rate of Spread
Help
Credits
Likelihood of Crown Fire Occurrence (%)
Input Data
FSG [m] :
0
10-m wind
0
Estimated Fine Fuel Moisture
EFFM [%] :
0
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] :
0
Spotting Separation Distance
Select
ID [min] :
1
Run
Reset
Close
Output
Prob. crown fire occurrence [%] :

Type of 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] :
0
10-m wind
0
Estimated Fine Fuel Moisture
EFFM [%] :
0
Calculate from weather and site variables
Spotting Separation Distance
Select
ID [min] :
1
Run
Reset
Close
Output
Type of Fire :

Crown ROS [m/min] :

Critical Spotting Distance [m] :

Crown Fire Initiation and Spread

Units

Initiation | Occurrence | Rate of Spread | Help | Credits

Quick help and useful references

QUICK HELP

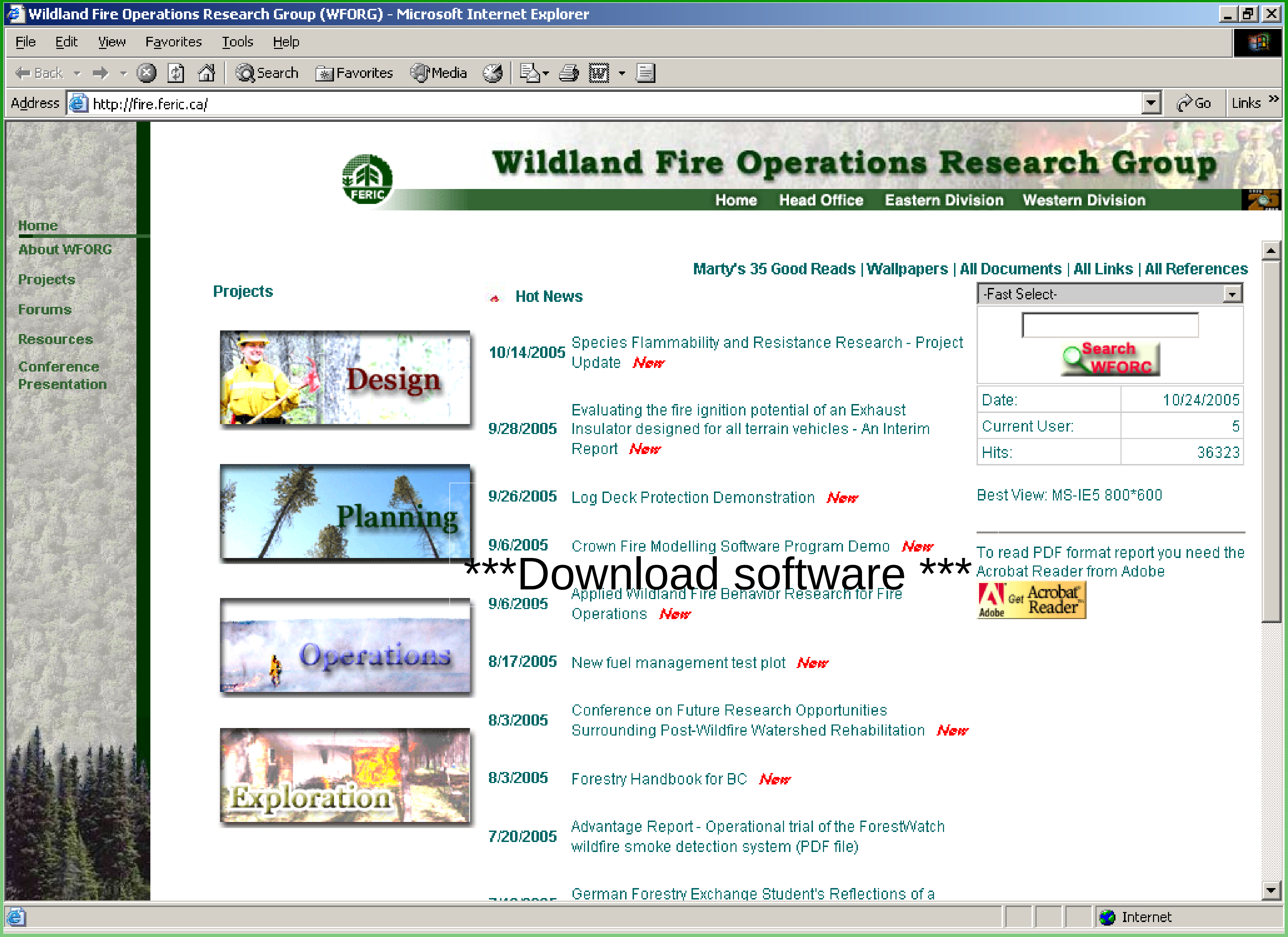
This program allows the estimation of the likelihood of crown fire initiation and the spread rate of crown fires from the knowledge of Canadian Forest Fire Danger Rating System (CFFDRS) components, weather and fuel complex variables.

The Tab - Initiation - incorporates four distinct models that predict the likelihood of crown fire occurence from Canadian Forest Fire Danger Rating System components (Cruz, Alexander and Wakimoto 2003, 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



***Download software ***

http://fire.feric.ca

Concluding Remarks

- **M. Cruz – PhD (2004) & Australia (2005)**
- **Better than the FBP System???**
- **FIRE BEHAVIOR PREDICTION PARADOX --**

  The models and systems aren't accurate enough.

  The models and systems are too complicated.

  Presumably, crude but reliable decision aids are needed at the field level.

- **Fuel Treatments – Future Experimental Fires**

THE END – THANK YOU

Questions or comments?