FOR 433

Fire Behavior Predictions Case Study

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During this lecture I am going to present a few of the many fire behavior models that are available, and then show you some of the studies that have attempted to evaluate or compare these models to actual events.

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Outline for this lecture

- Review of fire behavior models
  - Rothermel (1972) surface fire spread model
  - Van Wagner (1977) crown fire initiation model
  - Cruz (1999) crown fire initiation model
  - Rothermel (1991) crown fire spread model
  - Cruz (1999) crown fire spread model
- Review of validation studies
- Looking at the big picture: linking uncertainty with the prediction process

Let’s begin by going over what we will cover in this lecture. First, we will review several common fire behavior models used to predict surface fire rate of spread, fire transition and crown fire rate of spread. Then we will review a few studies which have compared these models and at the end I will attempt to bring all of this back together in terms of the prediction process.

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Looking at Rothermel (1972)

$$R_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

Input Variables:

- I_R is the reaction intensity
- ξ is the propagating flux ratio
- Φw is the wind coefficient
- Φs is the slope factor
- P_b is the oven-dry fuel bed bulk density
- ε is the effective heating number
- *Q_{ig} is the heat of preignition*

The most common method of predicting surface fire rate of spread was developed by Rothermel (1972) then modified by Albini (1976). This equation has been implemented in several very common fire behavior prediction systems such as BEHAVE, Nexus and Farsite. This equation predicts the head fire rate spread only.

This equation requires the user to gather data for many input factors, and its use has lead to the standard fire behavior prediction fuel models or to custom fuel models. Many authors have noted that the standard fuel models often do not accurately reflect both spread rate and fireline intensity. Therefore, depending upon the end goal of the model, a fuel model should be chosen to best predict one of these. For example, if prediction crown fire hazard is the end goal, then we should choose the fuel model which best represents fire line intensity.

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Van Wagner (1977) Crown Fire Initiation Model

$$I'_{initiation} = \left(\frac{CBH(460 + 25.9FMC)}{100} \right)^{3/2}$$

$I_{initiation}$ = surface fire line intensity required for fire transition

Input Variables

CBH - Canopy base height

FMC - Foliar moisture content

The theory behind the van Wagner model is fairly straightforward. This model assumes that canopy fuels will ignite when a surface fire provides a enough heat to raise the temperature of the fuel to the ignition temperature.

This equation can be reworked by converting the intensity to a spread rate by using Byrum (1959). This gives a critical rate of spread that allows crown fire to transition (similar to the Canadian Fire Behavior Prediction System).

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A note on Alexander (1998)

- This model is very similar to Van Wagner (1977) but includes additional input variables:
  - Flaming residence time
  - Plume angle
  - Fuel bed characteristics

The Alexander fire transition model is very similar to the Van Wagner model with the exception that it requires three additional input variables: flaming residence time, plume angle and fuel bed characteristics

Cruz et al. (1999) fire transition model

$$g(x) = \beta_0 + \beta_1 \mathrm{U}_{10} + \beta_2 \mathrm{FSG} + \sum_{u=1}^{k_j - 1} \beta_{ju} D_{ju} + \beta_5 \mathrm{EFFM}.$$

EFFM estimated fine fuel moisture content (% ovendry mass basis)

U_{10} 10-m open wind speed

$\beta_1, \ldots, \beta_4$ regression coefficients

FSG is the fuel stratum gap
(similar to canopy base height)

The Cruz et al fire (1999) transition model is a logistic model where the open wind speed, fine fuel moisture content and the fuel stratum gap are the primary variables involved. It should be noted that this model does not include a slope factor so that the predictions are limited to level terrain. In addition, this model was developed for free burning wildfires and not for point-source fires, such as those exhibited in some prescribed fire conditions.

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Rothermel (1991) crown fire rate of spread

$$R_{active} = 3.34\left(R_{10}\right)_{40\%}$$

Where:

R_{active} is the crown fire rate of spread

R 10 is the surface fire rate of spread using the fuel characteristics for fuel model 10 and a midflame wind speed set at 40 % the 6.1-m windspeed

The Rothermel (1991) crown fire spread model is an empirical model which links the spread rate of a active crown fire to the spread rate of a surface fire. This model was originally intended for the northern Rocky Mountains and areas with similar fuel beds, climate and topography. The model assumes a linear regression between crown and surface fire rate of spread where the surface fire rate of spread is predicted using a fuel model number 10 and a 40% wind reduction factor.

This model has a few additional assumptions which are worth mentioning here:

First, it is assumed that this model estimates a full active crown fire

Second, this model does not account for increased spread rates due to spotting

Third, it gives the average spread rate, not the maximum

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Cruz et al. (2002) Crown Fire Spread Model

$$\mathrm{CROS_A} = \beta_1 U_{10}^{\beta_2} \times \mathrm{CBD}^{\beta_3} \times e^{(-\beta_4 \mathrm{EFFM})},$$

Where:

- EFFM estimated fine fuel moisture content (% ovendry mass basis)
- CBD canopy bulk density
- $\beta_1, \ldots, \beta_4$ regression coefficients
- U_{10} 10-m open wind speed

The Cruz et al (1999) model is a bit more complicated then the Rothermel (1991) rate of spread equation. In this equation the main input parameters are CBD, open wind speed and fine fuel moisture content.

A look at Rothermel (1972) Surface Fire Rate of Spread Model

Figures are from Weise and Biging (1997)

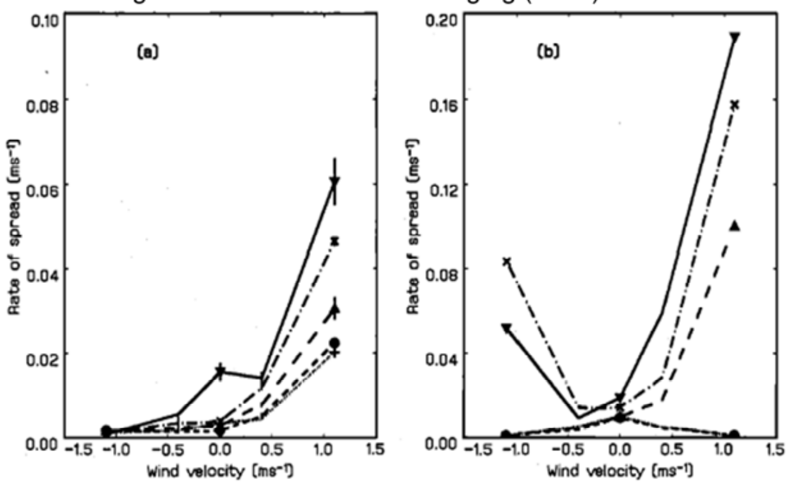

Figure 1. Mean observed rate of spread (a) as a function of wind velocity (ms^{-1}) and slope percent compared with predicted mean rate of spread from (b) Canadian FBP model, (c) original Rothermel model (ORTH), (d) Rothermel model with Albini method (ORTHA), and (e) Pagni and Peterson model (PAGNI). Negative wind velocity indicates fire spreading into wind (backfire). ▼ = 30% (upslope), ✖ = 15% (upslope), ▲ = 0% slope, ● = −15% (downslope), ✚ = −30% (downslope). Vertical bars indicate standard error for observed rate of spread only. Lines connect all points for a particular slope percentage together only and should not be used to interpolate.

In the left hand figure seen here you see the rate of spread of 5 test fires conducted in a wind tunnel under different slope conditions ranging from 30 % slope to -30% slope. On the right hand side you see the rate of spread predictions for the same conditions using the Rothermel equation. The conclusion of this study was that under the conditions of the tests the Rothermel equation predicted well except when an upslope backfire was occurring (negative wind velocities on the graph).

As you can see from this study, the Rothermel model has some given error despite the wind tunnel test and perfectly-controlled conditions of this experiment. Let’s review how this model handles uncertainty in terms of error propagation.

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A look at Rothermel (1972) Surface Fire Rate of Spread Model

Table 1. Fuel model properties.

Particle properties					
Particle classes		Fuel Load [kg m^{-2}]		Surface to volume [m^{-2} m^{-3}]	
	0.0–0.6 cm	$w0_{d1}$	measured	sv_{d1}	measured
Dead	0.6–2.5 cm	$w0_{d2}$	measured	sv_{d2}	constant
	2.5–7.6 cm	$w0_{d3}$	measured	sv_{d3}	constant
Live	Herbs	$w0_{lh}$	measured	sv_{lh}	constant
	Woody	$w0_{lw}$	measured	sv_{lw}	constant
Fuel bed properties					
	Depth [m]	d	measured		
	Moisture of Extinction [%]	mx	measured		
	Particle density [kg m^{-3}]	ρ	constant		
	Total mineral content [%]	s_t	constant		
	Eff. mineral content [%]	s_e	constant		
	Heat content [kJ kg^{-1}]	$heat$	constant		

Table from Bachmann and Allgower 2002

The initial reaction most people have when we talk about the Rothermel model predictions is that we overly simplify the fuel characteristics as a fuel model. This table shows a list of the fuel input parameters needed in the Rothermel model. You can also see that there are several parameters which are measured and several more which are assumed constant. In addition to these variables, we will need to estimate the slope, aspect, wind speed and wind direction at mid-flame height. Altogether the Rothermel equation consists of 17 input variables.

In their study, they found that of all the input variables of the Rothermel model, very few contributed to a significant part of the error. The three key variables in this study were fuel bed depth, wind speed and the surface area to volume ratio, which accounted for 28%, 16% and 41% of the errors, respectively. Thus, if we are to apply this model, we must realize that these three input parameters are important, and care should be taken to gather adequate information about these before the model is run.

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Crown Fire Initiation Models

Table 1—Input requirements for the crown fire initiation models being evaluated[1].

Model	Fireline intensity	FMC	Wind speed	Residence time	CBH/FSG	EFFM	SFC
Van Wagner (1977)	X	X			X		
Alexander (1998)	X	X	X	X	X		
Cruz (1999)			X		X	X	X

[1]FMC= foliar moisture content; CBH= canopy base height; FSG = fuel strata gap; EFFM = estimated fine dead fuel moisture content; and SFC = surface fuel consumption.

Table from Cruz et al. 2003

Let’s now shift focus to fire transition models. In the table you see here there are three models listed: the Van Wagner, Alexander and Cruz models, and their required input parameters. From this table it’s evident that the only parameter all three models have in common is canopy base height. The Van Wagner model also requires fireline intensity and foliar moisture content, the Alexander model requires fireline intensity, foliar moisture content, wind speed, and residence time, and the Cruz model requires wind speed, fine fuel moisture content and surface fuel consumption.

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Crown Fire Initiation Models

Table 3—Relative sensitivity (RS) values associated with the crown fire initiation model outputs for the major input parameters.

Input parameters	Fire environment severity: High	Fire environment severity: Very high
Van Wagner (1977)		
CBH	1.5	1.5
FMC	1.3	1.3
Alexander (1998)		
CBH	1.5	1.5
FMC	1	0.4
Within stand wind speed	0.6	1.4
Flame front residence time	- 0.5	- 1.1
Cruz (1999)		
FSG	- 2.8	- 0.2
Fine dead fuel moisture	- 2.4	- 0.1
10-m open wind speed	2.6	0.1

Table adapted from Cruz et al 2003

Now that we have viewed the input parameters to these three models, let's look at the relative sensitivity of the inputs for each model. Ignoring the signage, scores less than 0.5 indicate that the model is insensitive to changes in this input, scores between 0.5 and 1 indicate that the model is slightly sensitive, and values over 1 indicate the model is most sensitive to the input.

You can see that the Van Wagner model is sensitive to both its inputs under high and very high fire severity conditions. This is due to the non-dynamic nature of this model. The Alexander model is sensitive to CBH under both conditions and the other variables have different sensitivities under different conditions.

A note of the Cruz model is that the high sensitivity scores suggest that errors in estimating these variables make it very prone to error propagation.

Crown Fire Initiation Models

Table 5. Classification table comparing observed and predicted type of fire through the application of the logistic model to the data set used in its development and two independent experimental fire data sets.

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

Table adapted from Cruz et al 2003

This table shows the predictive capacity of the Cruz et al model versus the original data set and two experimental fire data sets. You will notice that the Cruz model predicted crown fires in the two independent data sets very well.

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Crown Fire Rate of Spread Models

Table 4—Relative sensitivity (RS) values associated with crown fire rate of spread model outputs for the major input parameters.

Input parameters	Fire environment severity: High	Very high
Rothermel (1991)		
Fine dead fuel moisture	- 0.2	- 0.2
10-m open wind speed [1]	1.4	1.3
Forestry Canada Fire Danger Group (1992)		
FFMC[2]	- 5.6 / - 2.3	- 0.6 / - 0.2
10-m open wind speed	5.4 / 2.2	1.4 / 0.3
FMC	- 3.6	- 1.7
Cruz (1999)		
Canopy bulk density	0.2	0.2
10-m open wind speed	0.9	0.9
Fine dead fuel moisture	- 1.4	- 0.9

[1] 10-m open wind speed was converted into 6-m (20 ft) wind speed by the 15 % adjustment factor as determined by Turner and Lawson (1978).
[2] FFMC = Fine fuel moisture code.

Table adapted from Cruz et al 2003

Let’s move on and look at some crown fire rate of spread models. This table shows the relative sensitivity score for the Rothermel models, the Forestry Canada Fire Danger Group model and the Cruz (1999) model.

The Rothermel model shows little sensitivity to fine dead fuel moisture and a moderate sensitivity to 10 meter open wind speed. The Canadian model is fuel type-specific and is extremely sensitive to changes in input parameters during fire transition and less sensitive to these changes during very high conditions. The Cruz model shows low to moderate sensitivity to changes in canopy bulk density and fine dead fuel moisture. It should be noted that wind speed has a proportional effect in the Cruz (1999) model.

Crown Fire Rate of Spread Models

Figure 1—Plot of observed versus predicted rate of spread of crown fires in the Rothermel (1991) and Cruz (1999) crown fire spread models.

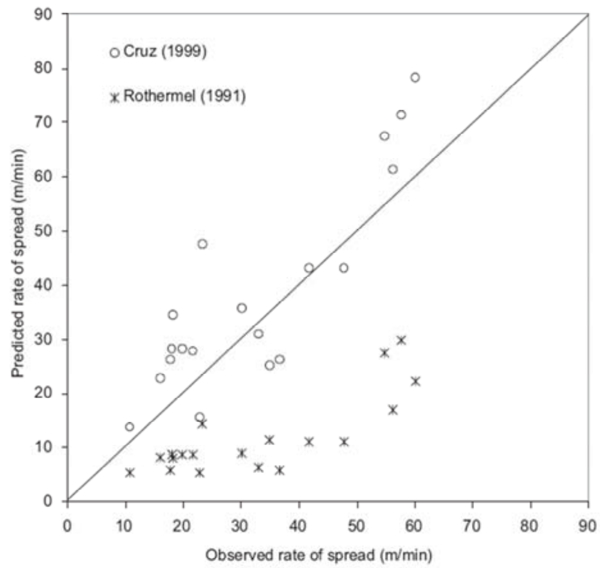
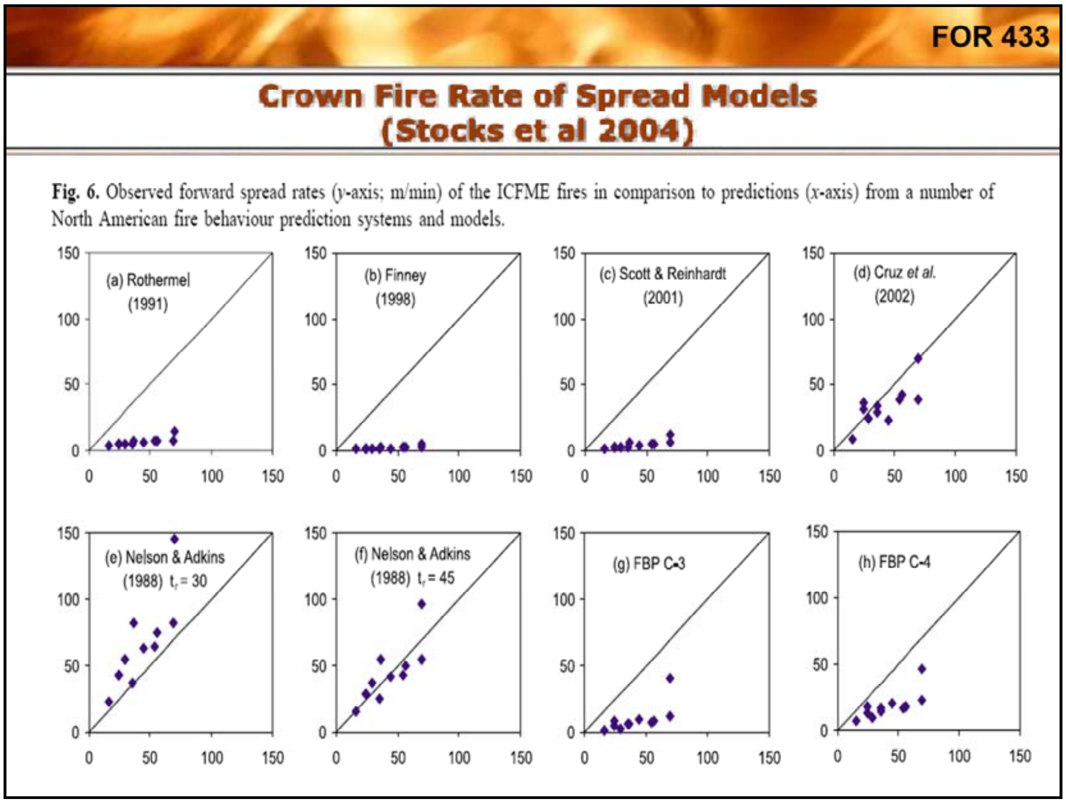


Figure form Cruz et al. 2003

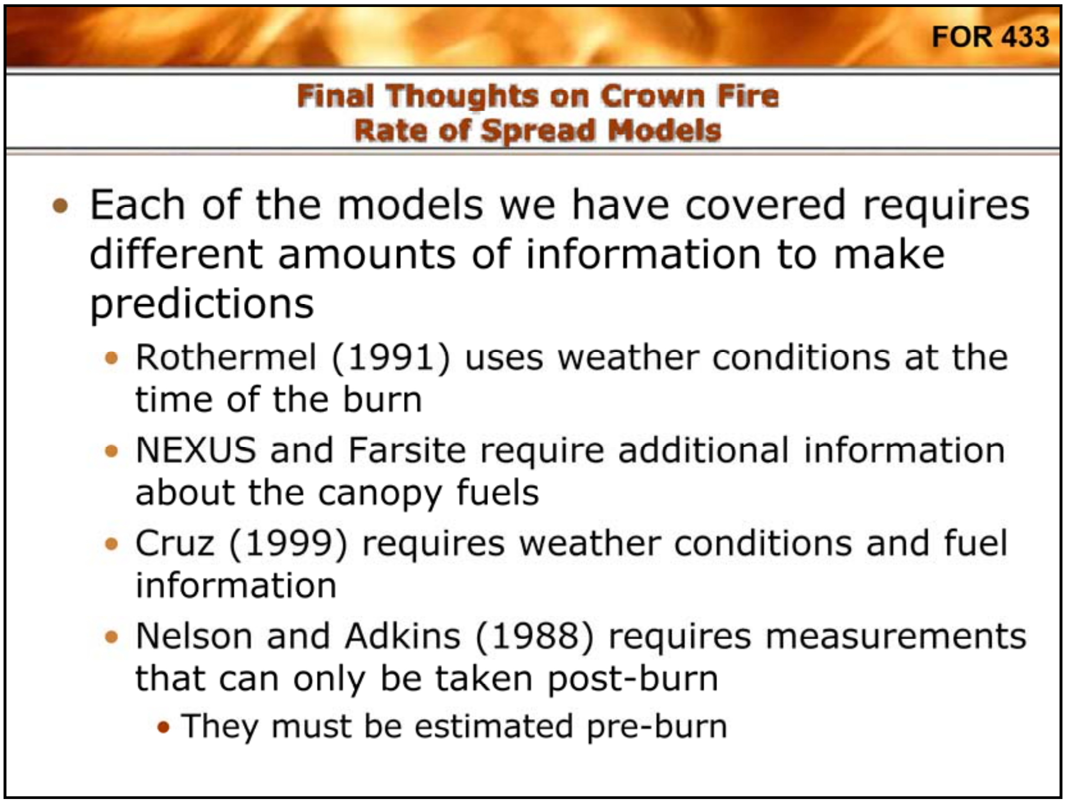
This plot shows the predicted versus observed spread rates for the Cruz and Rothermel models. From this data set you can see that the Rothermel model tends to under-predict crown fire spread rates, especially at high rates of spread. The Cruz model shows a better fit; however, you can see that it often over-predicts crown fire rate of spread.



This graph shows 4 different crown fire spread models compared to the international crown fire modeling experiments. The Rothermel 1991 model is represented in panels a, b, and c. Panel a is the typical Rothermel equation, Panel B is the Rothermel equation as implemented in FARSITE and Panel C is the Rothermel equation as implemented in NEXUS. Given the conditions under which the fires were conducted, the Rothermel model and consequently FARSITE and NEXUS all severely under-predicted crown fire rate of spread.

The Cruz model represented in Panel d produced a good fit to the data set. In addition, a model proposed by Nelson and Adkins also provided a good fit. However, this model is based on fuel consumed, wind speed and flame residence time, all of which were measured post-burn, so the high accuracy of the model "predictions" is somewhat misleading. Two different flame residence times were used in the simulations: 30 seconds and 45 seconds. You can see that using a flame residence time of 30 seconds tended to over-predict (although not by much) while the 45 second residence time provided a nice fit.

The last model tested was the Canadian FBP models for mature jack pine and lodgepole pine and immature jack pine and lodgepole pine. Like the Rothermel models these models also tend to under-predict the crown fire rate of spread but showed an improvement over the Rothermel model.



Each model we have looked at requires different amounts of information to make an prediction. In the case of the Rothermel model, only weather conditions at the time of the burn is required, this model does not use specific fuel information for the prediction. Two of the Rothermel based programs (FARSITE and NEXUS) require additional information about the canopy fuels.

The Cruz and Nelson and Adkins models both provided a good prediction for the test fires; however, the Nelson and Adkins model uses post-burn data, therefore making it unreliable at best to predict future events.

Back to the prediction process

- The information in this lecture should not be used as a context for not using any of these models; instead, it represents additional information which can assist in successfully using these models within the prediction process

To end this lecture I would like to modify a statement from the Bachmann and Allgower paper.

The information in this lecture should not be used as a context for not using any of these models, instead it represents additional information which can assist in successfully using these models within the prediction process

Specifically I feel that this information provides some useful tools in communicating the uncertainties within these models, and allows us to better interpret the results of their use. You can see how understanding the uncertainties and predictive ability of the models might allow us to make better decisions. For example, the Rothermel crown fire rate of spread model often under-predicted actual rate of spread. Therefore, as a manager, instead of just relying on the prediction, we can incorporate the uncertainty information as well. So we might expect a crown fire to move faster than the model predicted and we can account for this when making a decision.