# Operational Prediction of Crown Fire Behavior

Miguel G. Cruz and Martin E. Alexander

Operational guides for predicting various aspects of wildland fire behavior, including crowning, are generally dependent on mathematical models that can take a variety of forms. The degree of accuracy in predictions of crown fire behavior is dependent on the model's applicability to a given situation, the validity of the model variables' relationships, and the reliability of the model input data (Alexander and Cruz 2013).

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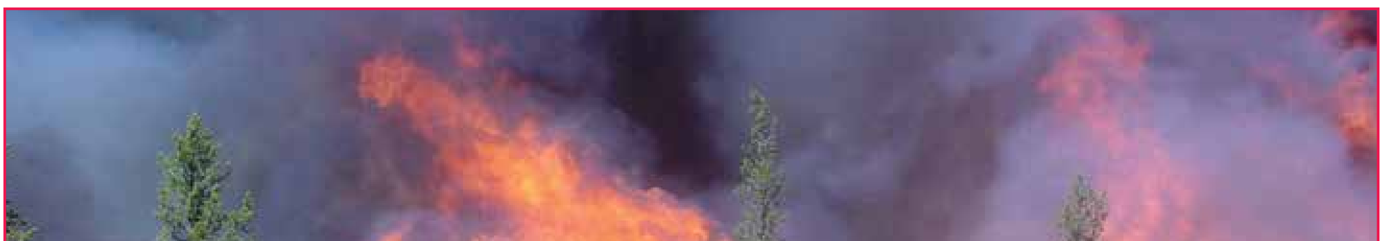
## Rothermel's Surface and Crown Fire Rate-of-Spread Models

Rothermel (1972) developed a model for predicting a surface fire's rate of spread and intensity that forms the basis for most of the decision aids used in predicting fire

## An Observation Regarding Surface Versus Crown Fires

"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)



*Flame front associated with experimental crown fire in a jack pine (Pinus banksiana)–black spruce (Picea mariana) forest, Plot S1, International Crown Fire Modelling Experiment, Northwest Territories Canada. Photo by M.G. Cruz.*

behavior today in the United States (Andrews 2013). Field application is dependent on either a stylized or custom-built fuel model, that is a simulated surface fuel complex for which all fuel descriptors required for the solution of the Rothermel (1972) mathematical rate of spread model are specified.

Favorable evaluations of observed versus predicted rate of surface fire spread have been obtained with the Rothermel model in a number of fuel complexes (Cruz and Alexander 2013). Rothermel acknowledged that his model was not applicable to predicting the behavior of crown fires because the nature and mechanisms of heat transfer between the two types of spread regimes were quite different. Later on, he did offer advice on judging whether crowning was possible or not based on the surface fire's predicted intensity or flame length (Rothermel 1983). In turn, crown fire spread rates were assumed to be two to four times the predicted surface fire rate of spread in the Anderson (1982) fire behavior fuel model in litter and understory.

Rothermel (1991) eventually produced a guide for predicting crown fire behavior in the northern Rocky Mountains of the United States and areas with similar fuels and climate. The core component of his method was a simple correlation derived from eight observations of crown fire rate of spread versus the corresponding predictions from his surface fire rate of spread model. He emphasized that his statistical model (incorporating a multiplier of 3.34) for predicting the spread rate of wind-driven crown fires was a first approximation and that more research was needed to strengthen the analysis.

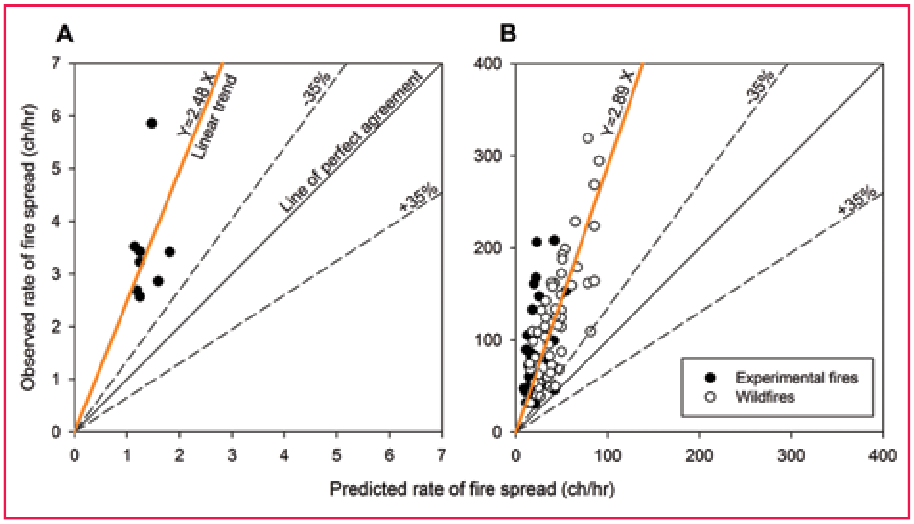



**Figure 1.**—*Observed head fire rates of spread associated with (A) experimental surface fires (n = 8) in lodgepole pine forests in central British Columbia by Lawson (1972) versus predictions based on the Rothermel (1972) surface fire rate of spread model and (B) a dataset of experimental crown fires (n = 34), and crowning wildfires (n = 54) in various conifer forest types compiled by Cruz and Alexander (2010) versus predictions based on the Rothermel (1991) crown fire rate of spread model. The dashed lines around the line of perfect agreement indicate the ±35 percent error interval.*

## Just How Predictable Is Wildland Rate of Fire Spread?

Cruz and Alexander (2013) examined the limits of predictability in surface and crown rate of fire spread from a compilation of 49 model evaluation datasets containing 1,278 observations in 7 different fuel type groups from various regions of the world. They reached the following conclusions:

- Only 3 percent of the predictions (35 out of 1,278) were considered to be "exact" predictions: undeniably, an elusive target.
- The mean percent error varied between 20 and 310 percent and was homogeneous across fuel type groups.
- Slightly more than half of the evaluation datasets had mean errors between 51 and 75 percent.
- Underprediction bias was prevalent in 75 percent of the 49 datasets analyzed.
- A case was made for suggesting that a ±35-percent error interval would constitute a reasonable standard for model performance in predicting a wildland fire's forward or heading rate of spread.
- Empirical-based fire behavior models developed from a solid foundation of field observations and well-accepted functional forms adequately predicted rates of fire spread far outside of the bounds of the original dataset used in their development.
- The prediction of surface fire rate of spread was found to be more difficult than predicting the rate of spread of crown fires, a result of the larger influence of fuel structure on low-intensity fire propagation.

## Point and Landscape-Scale Fire Behavior Modeling Systems in the United States

Since the late 1990s, a number of computerized decision-support systems—such as BehavePlus, NEXUS, the Fire and Fuels Extension to the Forest Vegetation Simulator, FARSITE, FlamMap, Fuel Management Analyst Plus, ArcFuels, and the Wildland Fire Decision Support System—either have been separately implemented or linked Rothermel's surface and crown rate of fire spread models (1972, 1991) with Van Wagner's (1977) crown fire transition and propagation criteria. These systems are extensively used for fire operations, planning, and research.

In spite of the popularity of these fire behavior modeling systems over the years, some user-oriented problems have emerged. Varner and Keyes (2009) have, for example, identified several commonly encountered errors in regards to the modeling inputs:

- Live and dead fuel moisture estimation,
- Wind adjustment factors,
- Fuel load estimates,
- Fuel model selection,
- Fuel decomposition rates, and
- Fuelbed patchiness.

They suggested that the errors "can often be tied to unsupported assumptions about actual conditions and overreliance on default values."

Cruz and Alexander (2010) have also pointed out that the operational fire behavior modeling systems currently used to simulate the onset of crowning and active crown fire rate of spread in conifer forests of the Western United States exhibit a significant underprediction bias related to several factors, including:

- Incompatible model linkages.
- Use of surface and crown fire rate of spread models that have inherent underprediction biases themselves (figure 1). The underprediction tendency with the Rothermel (1991) model was also found to occur with the Schaaf and others (2007) crown fire rate of spread model of the fuel characteristic classification system.
- A reduction in crown fire rate of spread based on the use of unsubstantiated functions for crown fraction burned (that is, a measure of the degree of crown fuel consumption expressed as a percentage of the total number of tree crowns and, as such, constituting an indication of the probable type of fire activity to be expressed over a burned area for fuel types that are susceptible to crowning).

The use of uncalibrated custom fuel models to represent surface fuelbeds was considered as a fourth potential source of bias. Ager and others (2011) claim that such limitations "are well known by the user community" but offered no empirical evidence to substantiate their statement.

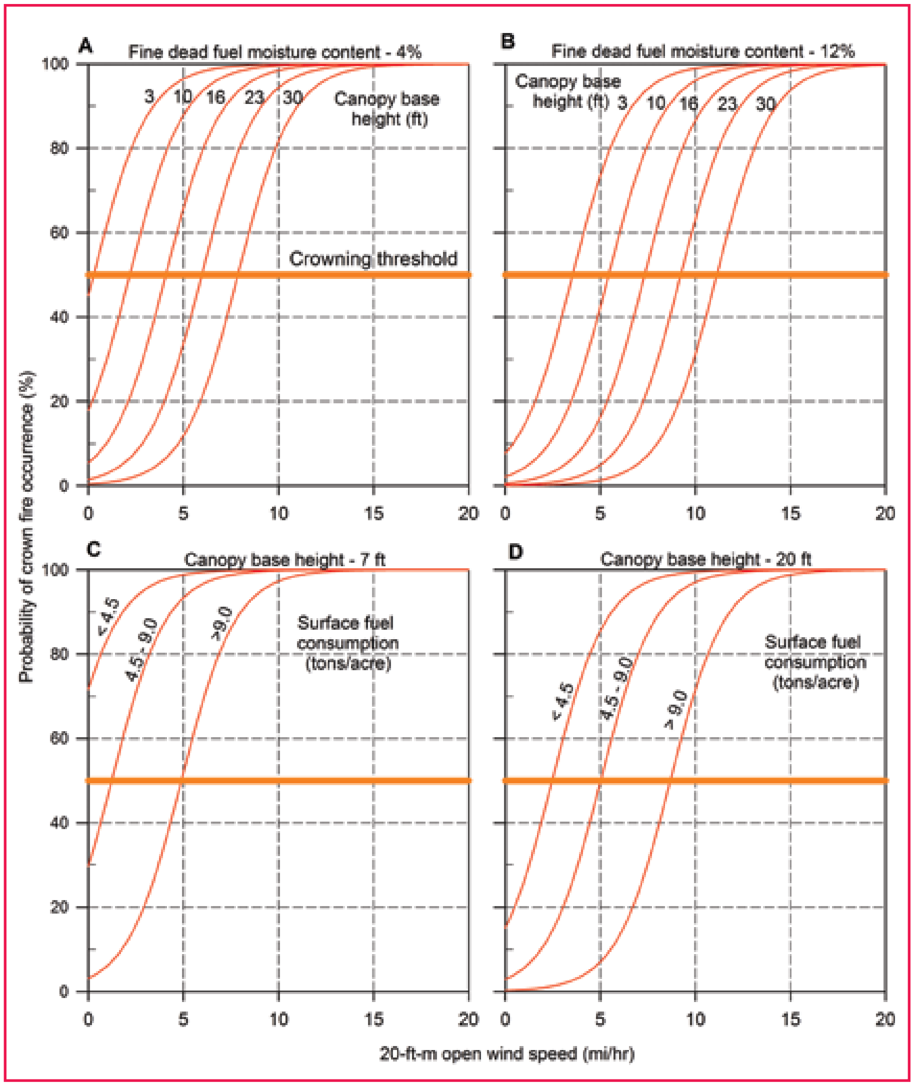



**Figure 2.**—*The likelihood of crown fire occurrence as (A-B) a function of canopy base height and wind speed for two fine dead fuel moisture levels assuming a surface fuel consumption of 4.5 to 9.0 tons/acre, and (C-D) as a function of surface fuel consumption and wind speed assuming a fine dead fuel moisture of 4 percent (after Alexander and Cruz 2013). The solid horizontal line in each graph represents the approximate threshold value for the onset of crowning (0.5 probability of crown fire occurrence).*

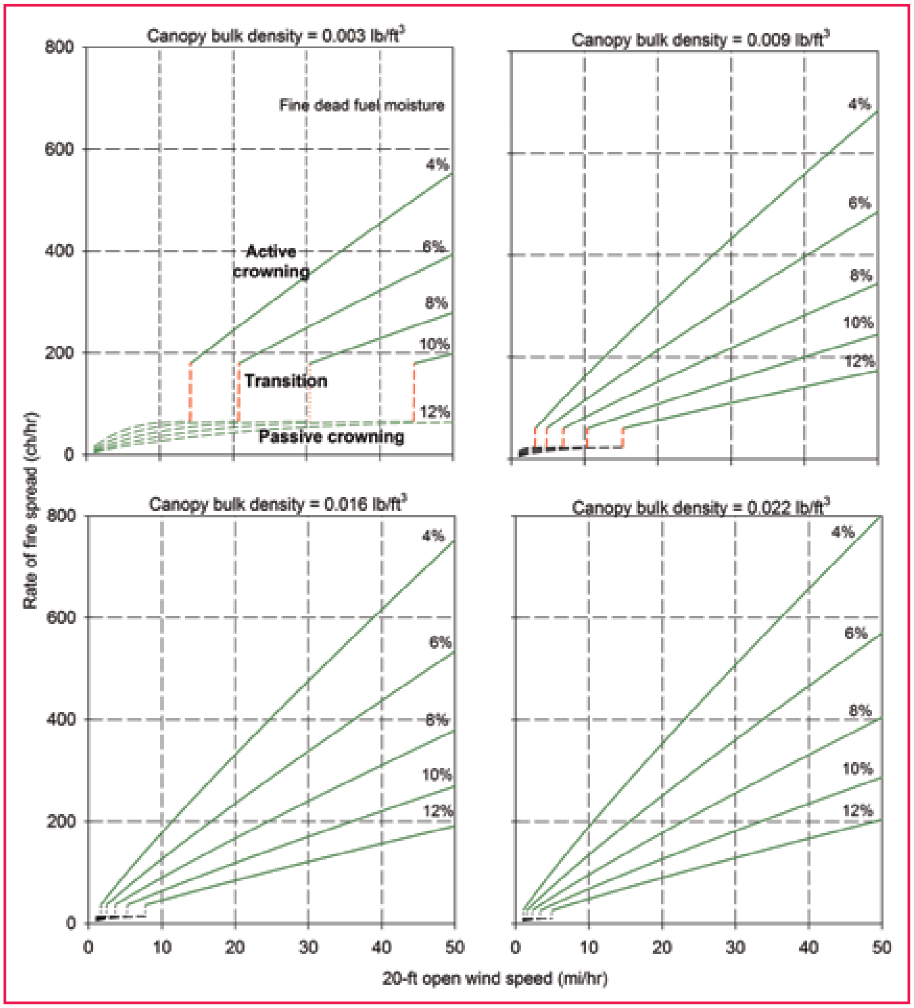



**Figure 3.**—*Passive and active crown fire spread rates as a function of wind speed and fine dead fuel moisture for four canopy bulk density levels (after Alexander and Cruz 2013). The vertical "kinks" in the fine dead fuel moisture curves are considered to represent the wind speed thresholds between passive and active crowning.*

## The Canadian System of Fire Behavior Prediction

The Canadian Forest Fire Behavior Prediction system (FBP) (Wotton and others 2009) is a module of the larger Canadian forest fire danger rating system (<http://www.frames.gov/cffdrs>), which also includes the Canadian Forest Fire Weather Index (FWI). The FBP is used in parts of the United States—specifically, in the Lake States and Alaska, where conifer forests are structurally similar to those found in Canada. Eleven of the 16 fuel types included in the FBP are subject to crowning (seven coniferous and four mixed-wood forest stand types). Parts of the system are also used outside of North American—for example, in New Zealand (Pearce and others 2012).

The FBP is similar in many respects to the fire behavior modeling systems currently used in the United States. The principal difference lies in its technical basis. While the Rothermel (1972) surface fire model is based largely on laboratory fires and physical theory, the FBP system is empirical in nature, based on the analysis of experimental fires and observations of wildfires dating back about 50 years (Stocks and others 2004).

## The Crown Fire Initiation and Spread System

The Crown Fire Initiation and Spread (CFIS) software system is a suite of empirically based models for predicting crown fire behavior (Alexander and others 2006) based largely on a reanalysis of the experimental fires carried out in conifer forest fuel types used in the development of the Canadian FBP System.

## Words of Wisdom†

*"Anyone can tell what a fire has done, and most can look at a fire and tell what it is doing—but your challenge to be successful and survive in fighting wildfire is to be able to correctly predict what the fire will do, well before it does it.… Pay attention to the signs the smoke is always giving: color, intensity, pulsing or steady, and direction of drift. Pay special attention to the fuels it's getting into and the topography that will influence its behavior. Constantly monitor the weather's relative humidity, temperature, and especially the winds."—*
Earl Cooley (1967)

†From Trembath (2011), describing the advice offered by a veteran smokejumper regarding fire behavior during a training session in his first season of wildland firefighting as a member of the Flathead Hotshots based out of northwestern Montana.

**Table 1.**—*Predicted fine dead fuel moisture content as a function of ambient air temperature and relative humidity assuming >50 percent shading at between 1200–1600 hours during May–July on level terrain (adapted from Rothermel 1983).*

| Relative humidity (%) | Air temperature (°F) | | | | |
|---|---|---|---|---|---|
| | 32 – 49 | 50 – 68 | 69 – 88 | 89 – 108 | >109 |
| | Fine dead fuel moisture (%) | | | | |
| 0 – 4 | 4 | 4 | 4 | 4 | 4 |
| 5 – 9 | 5 | 5 | 4 | 4 | 4 |
| 10 – 14 | 5 | 5 | 5 | 5 | 5 |
| 15 – 19 | 6 | 6 | 5 | 5 | 5 |
| 20 – 24 | 7 | 7 | 6 | 6 | 6 |
| 25 – 29 | 8 | 8 | 7 | 7 | 7 |
| 30 – 34 | 8 | 8 | 8 | 7 | 7 |
| 35 – 39 | 9 | 9 | 8 | 8 | 8 |
| 40 – 44 | 10 | 9 | 9 | 9 | 9 |
| 45 – 49 | 10 | 10 | 10 | 10 | 10 |
| 50 – 54 | 10 | 10 | 10 | 10 | 10 |
| 55 – 59 | 11 | 11 | 11 | 11 | 11 |
| 60 – 64 | 12 | 11 | 11 | 11 | 11 |
| 65 – 69 | 12 | 12 | 11 | 11 | 11 |
| 70 – 74 | 13 | 12 | 12 | 12 | 12 |
| 75 – 79 | 14 | 13 | 13 | 13 | 13 |

The primary models incorporated into CFIS have been evaluated against both outdoor experimental fires and wildfire observations and shown to be reasonably reliable. The two main outputs of CFIS are:

- Likelihood of crown fire initiation or occurrence based on two distinct approaches: the canopy base height and/or certain components of the Canadian FWI or the fine dead fuel moisture, canopy base height or fuel strata gap, wind speed, and an estimate of surface fuel consumption (figure 2).
- Type of crown fire (passive crown fire or active crown fire) according to Van Wagner's (1977) criterion for active crowning and its associated rate of spread based on fine dead fuel moisture, canopy bulk density, and wind speed (figure 3).

The estimation of the fine dead fuel moisture input in CFIS follows Rothermel's (1983) tabular method (table 1). In lieu of a weather station measurement or a forecasted value, the 20-foot (6.1 m) open wind speed input can be estimated in the field using the Beaufort wind scale (see figure 4). CFIS is available for downloading free at <http://www.frames.gov/partner-sites/applied-fire-behavior/cfis/>.

## Final Thoughts on Predicting Crown Fire Behavior

Models or guides that have a good fundamental framework and a solid empirical basis presumably predict fire behavior well when used for conditions that are within the database parameters used in their development. An understanding of the uncertainty inherent in fire behavior predictions should always accompany the process of conducting and communicating fire simulations. An overestimate can easily be readjusted without serious repercussions; however, an underestimate of fire behavior can be disastrous both for fire operations and the credibility of the person making the prediction (Cheney 1981). The underprediction trends in both surface and crown fire behavior noted earlier on with respect to the U.S. fire behavior models and modeling systems should be of concern to users.

## Acknowledgment

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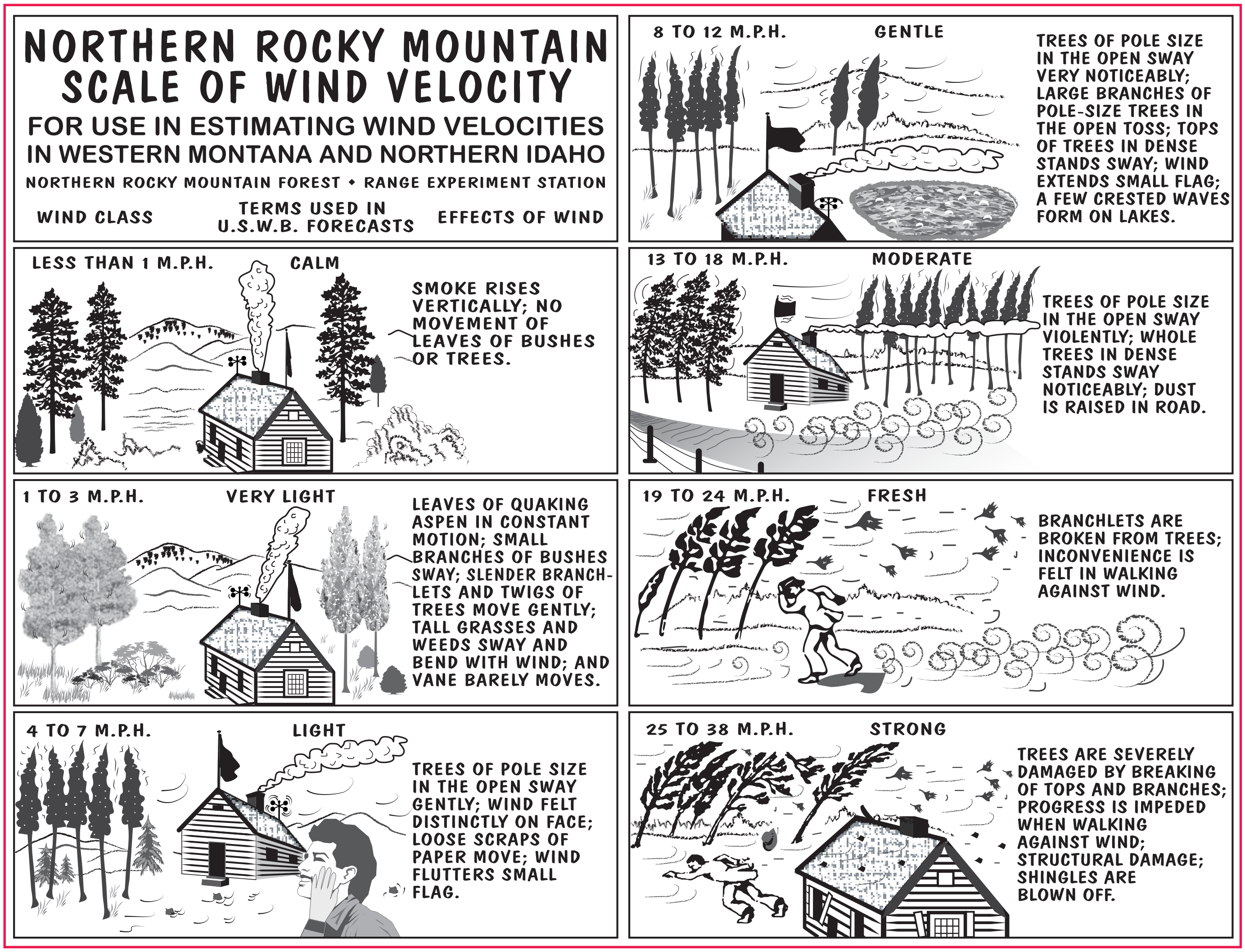


*The Beaufort scale for estimating 20-foot (6.1 m) open wind speeds when instruments are not available or appropriate for measurement (from Gisborne 1941).*

## Can Crown Fire Behavior in Mountain Pine Beetle-Attacked Stands Be Modeled Using Operational Models?

Assessing crown fire potential in mountain pine beetle (MPB)-attacked conifer forests is a topical subject (Page and others 2013a). Several authors applied operational fire behavior modeling systems (such as BehavePlus, the Fire and Fuels Extension to the Forest Vegetation Simulator, and NEXUS) to lodgepole pine forests attacked by MPB in the past couple of years (Page and others, in review). It is unknown how appropriate the crown fire behavior components of these systems are to the "red" and "gray" stages of MPB-attacked forests. Page and others (2013b) recently documented foliar moisture contents as low as ~7 percent in the red stage of MPB attack on lodgepole pine trees.

Given the empirical basis of Van Wagner's (1977) criteria for crown fire initiation (that is, live conifer forests with foliar moisture contents in and around 95 to 135 percent), this is a situation for which the operational fire behavior modeling systems never were designed (Page and others in review) and could possibly result in erroneous outcomes.

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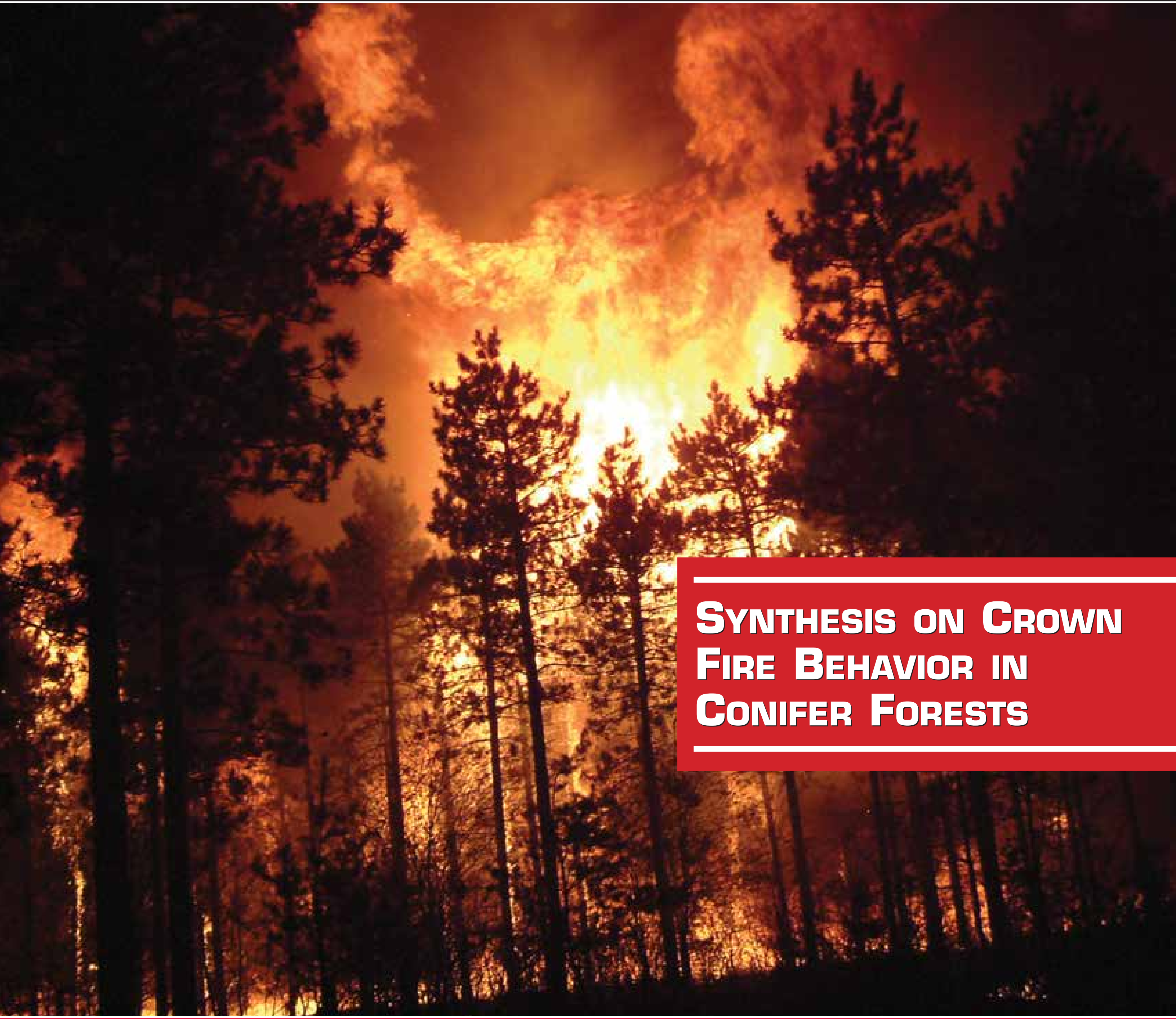

## Synthesis on Crown Fire Behavior in Conifer Forests

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## On the Cover:

*Crowning associated with the major run of the Cottonville Fire in central Wisconsin at 5:11 p.m. CDT on May 5, 2005, in a red pine plantation. Photo taken by Mike Lehman, Wisconsin Department of Natural Resources.*

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