# The Start, Propagation, and Spread Rate of Crown Fires

Miguel G. Cruz and Martin E. Alexander

In many respects, the most significant issue with regards to the prediction of crown fire behavior is first determining whether a surface fire will develop into a crown fire (that is, identifying the conditions favorable to the initiation or onset of crowning). The next concern is whether the crown fire can continue to perpetuate itself and, if so, what the rate of spread will be.

## Crown Fire Initiation

For a crown fire to start, a surface fire of sufficient intensity is first necessary. The distance between the heat source at the ground surface and the canopy-fuel layer will determine how much of the surface fire's energy is dissipated before reaching the fuels at the base of the canopy. The higher the canopy base, the lower the chance of crowning. Furthermore, if the moisture content of the canopy fuels is high, greater amounts of energy are required to raise the canopy tree foliage to ignition temperature.

Several empirical and semiphysical models have been developed over the past 35 years for predicting the initiation or onset of crowning. The simplest explanation of the general processes involved is offered by Van Wagner (1977a). Using physical reasoning and empirical observation, Van Wagner proposed that vertical fire spread (that is, the initiation of crowning) would begin to occur in a conifer forest stand when the surface fire's intensity (SFI) or energy release rate (taken from Byram 1959) attains or exceeds a certain critical value (CSFI). The former quantity (referred to as "fireline intensity") is equal to the product of the heat yield of the burned fuel, quantity of fuel consumed, and the rate of fire spread (figure 1A); flame size (figure 1B) is the main visual manifestation of fireline intensity (Alexander and Cruz 2012a, 2012b).

According to Van Wagner's (1977a) theory of crown fire initiation, the CSFI is dictated by the foliar moisture content and the canopy-base height (figure 2). If the SFI is greater than or equal to the CSFI, some form of crowning is presumed to be possible, but if the SFI is less than the CSFI value, a surface fire is expected to remain so. Nevertheless, crown scorch may occur, depending on the canopy-base height (figure 1B).

From figure 2A, it should be clear that the higher the canopy-base height and/or foliar moisture content, the more intense a surface fire must be to cause crowning. It is worth noting that the flames of a surface fire don't necessarily have to reach or extend into the lower tree crowns to initiate crowning (figure 2B).

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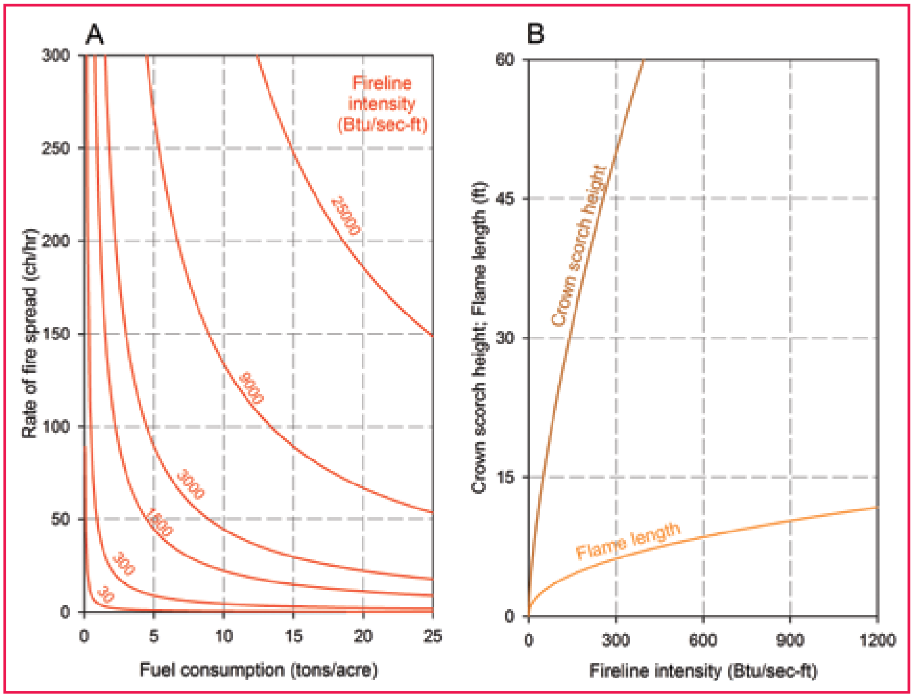


**Figure 1.**—*Graphical representation of (A) fireline intensity as a function of rate of fire spread and fuel consumption assuming a net low heat of combustion of 7740 British thermal units/lb (18 000 kJ/kg) (adapted from Alexander and Cruz 2012c) and (B) Byram's (1959) flame length-fireline intensity,y and Van Wagner's (1973) crown scorch height-fireline intensity relationships.*

## Crown Fire Propagation

Assuming that a given surface fire has sufficient intensity to initiate and sustain crown combustion from below, can a solid flame front develop and maintain itself within the canopy-fuel layer in order for horizontal crown fire spread to occur? Van Wagner (1977a) theorized that a minimum flow of fuel into the flaming zone of a crown fire is required for combustion of the canopy-fuel layer to continue.

This minimum flow of fuel being volatilized is a direct function of the speed of the fire and the fuel available per unit volume—the canopy-bulk density. For any given forest stand structure, there will be a critical or minimum threshold in rate of fire spread that will allow active crowning to be sustained relative to the canopy-bulk density (figure 3).

Active crowning is presumably not possible if a fire does not spread rapidly enough following initial crown combustion. Thus, if a fire's actual spread rate after the initial onset of crowning—a function largely of the prevailing wind speed and/or slope—is less than the critical rate of fire spread needed for active crowning, a passive crown fire is expected to occur (figure 3).

Any changes in forest stand structure that reduce the canopy-bulk density results in an increase in the critical rate of fire spread needed for active crowning. This is to say that, for lower canopy-bulk densities, more severe burning conditions (for example, higher wind speed and lower dead fuel moisture content) are required to maintain a self-sustaining active crown fire. High canopy-bulk densities are associated with dense stands, and low values are associated with open stands.

The validity of Van Wagner's (1977a) relation for active crown fire propagation has since been confirmed on the basis of a relatively large dataset of experimental crown fires (Cruz and Alexander 2010). Furthermore, canopy-bulk density levels of around 0.003 pounds/cubic foot (0.05 kg/m$^3$) and 0.006 pounds/cubic foot (0.1 kg/m$^3$), corresponding to critical minimum spread rates of 180

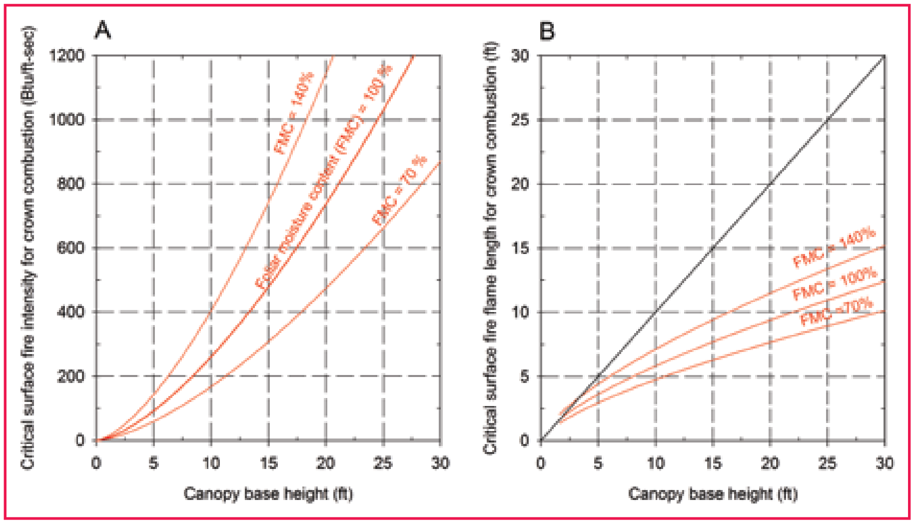


**Figure 2.**—*Graphical representations of (A) critical surface fire intensity for crown combustion in a conifer forest stand as a function of canopy-base height and foliar moisture content according to Van Wagner (1977a) and (B) the critical surface fire flame length for crown combustion in a conifer forest stand as a function of canopy-base height according to the flame length–fireline intensity model of Byram (1959); the diagonal line represents the boundary of exact agreement between flame length or height and canopy-base height.*

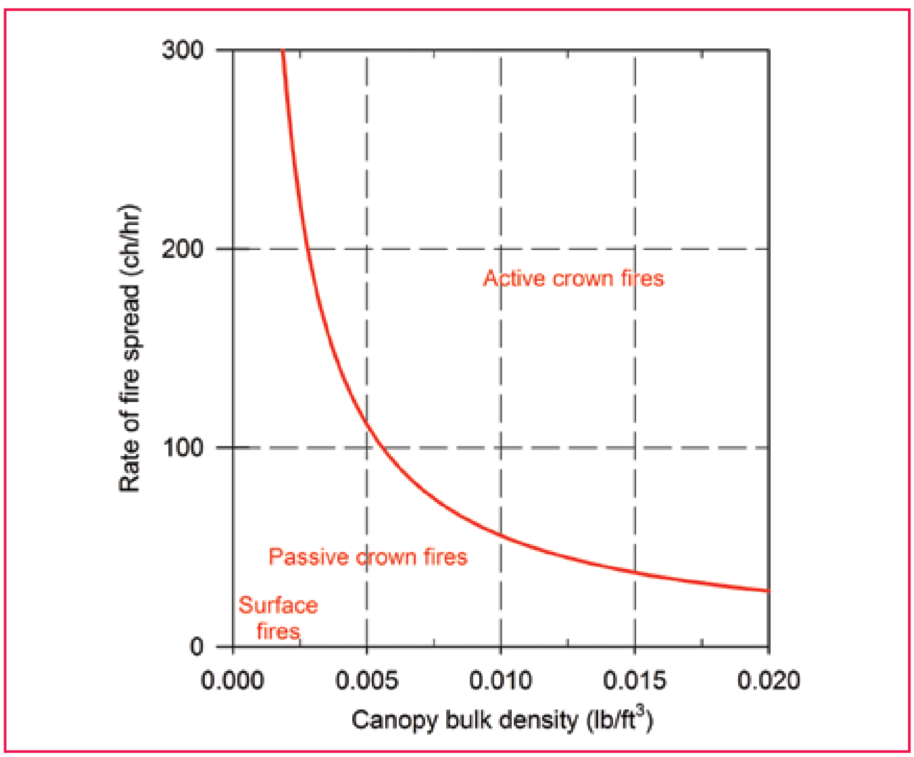


**Figure 3.**—*Critical minimum spread rate for active crowning in a conifer forest stand as a function of canopy-bulk density according to Van Wagner (1977a).*

to 90 chains/hour (60 and 30 m/min), respectively, have come to represent thresholds for passive and active crown fire development.

A passive crown fire is not a benevolent form of crown fire activity. Passive crown fires can spread at very high rates and release large amounts of energy in a very short period of time, thus creating hazardous and potentially life-threatening situations. This typically occurs in fires spreading through open stands with a low canopy-bulk density or closed-canopied stands exhibiting a very high canopy-base height; in such a case, spread rates might reach as high as 75 chains/hour (25 m/min) with associated fireline intensities of 2,900 British thermal units/second-foot (10,000 kW/m) and flame lengths of around 18 feet (5.5 m).

According to Van Wagner's (1977a) theories of crown fire initiation and propagation, it can now be seen why some conifer fuel complexes are far more prone to or have a greater propensity for crowning than others simply because of their intrinsic fuel properties. For example, many of the black spruce forest types found in Alaska and the Lake States, as well as Canada, are known to be notoriously flammable. This occurs as a result of a combination of low canopy-base height typical of this tree species, the abundance of ladder or bridge fuels (that is, bark flakes, lichens, and dead branches on the lower tree boles), low foliar moisture content levels, moderately high canopy-bulk densities, and potentially other fuel properties (for example, cones as firebrand material and high live-to-dead ratios of available fuel within the tree crowns).

## Crown Fire Rate of Spread

Surface fires spreading beneath conifer forest canopies seldom exceed 15 to 30 chains/hour (5 to 10 m/min) without the onset of crowning in some form or another. General observations of wildfires and documentation of experimental crown fires indicate that a rather abrupt transition between surface and crown fire spread regimes (in both directions) is far more commonplace than a gradual transition. With the onset of crowning, a fire typically doubles or triples its spread rate in comparison to its previous state on the ground surface (figure 4). This sudden jump in the fire's rate of spread occurs as a result of the fact that the wind speeds just above the tree canopy are about 2.5 to 6 times higher than understory winds, there is an increased efficiency of heat transfer into a tall and porous fuel layer, and there is a possible increase in spotting density just beyond the fire's leading edge.

Once crowning has commenced, a fire's forward rate of spread on level terrain is influenced largely by wind velocity (figure 4) and, to a lesser extent, by physical fuel properties. If ground and surface fuels are dry and plentiful and ladder fuels or bridge fuels are abundant, crown fires can still propagate in closed-canopied forests even if winds are not especially strong, although spread rates may not be particularly high.

Van Wagner (1998) also believed that the natural variation in foliar moisture content would presumably have an effect on the rate of spread of a crown fire in addition to being a factor influencing the onset of crowning in conifer forest

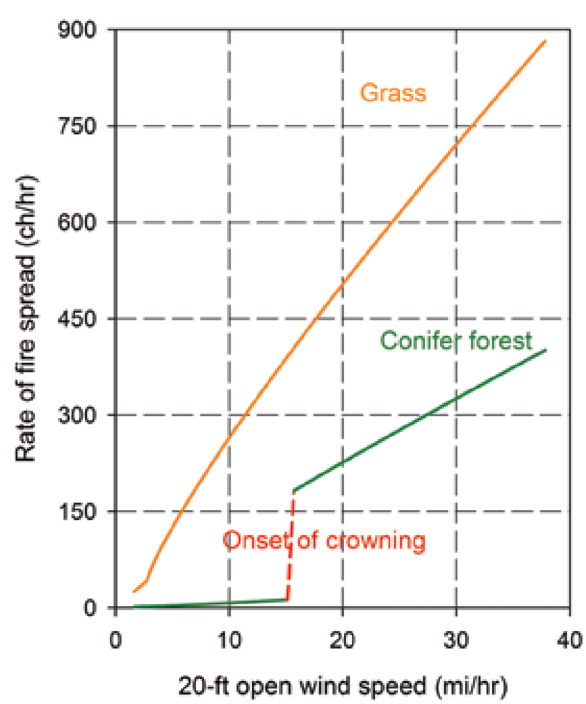


**Figure 4.**—*The variation in rate of fire spread in relation to wind speed for a conifer forest stand compared to a grassland fuel complex (after Alexander and Cruz 2011). The "kink" in the curve associated with the conifer forest represents the point of surface-to-crown fire transition.*

stands. Alexander and Cruz (2013) reviewed the literature related to this topic and concluded that the evidence from outdoor experimental fires did not necessarily support this conclusion.

Continuous active crowning generally takes place at spread rates between about 45 and 90 chains/hour (15 and 30 m/min). A “mile an hour”—80 chains/hour (1.6 km/hr or 27 m/min)—has been suggested by some authors as a rough rule of thumb for crown fire rate of spread (see Van Wagner 1968). This appears to be somewhat of an underestimate according to the work of Alexander and Cruz (2006), who found from a review of wildfire case studies an average crown fire rate of spread of about 1.5 miles/hour or 115 chains/hour (39 m/min or 2.3 km/hr) (figure 5).

Crowning wildfires have been known to make sustained runs of 18.5 to 40 miles (30 to 65 km) over flat and rolling to gently undulating ground during a single burning period and over multiple days. For example, the Lesser Slave Fire in central Alberta advanced 40 miles (64 km) through a variety of boreal forest fuel types in a period of 10 hours on May 23, 1968 (Kiil and Grigel 1969), resulting in an average rate of spread of 320 chains/hour (107 m/min). Peak spread rates in crowning wildfires associated with short bursts of fire activity have been reported to reach 695 chains/hour (235 m/min) (Keeves and Douglas 1983).

In some conifer forest fuel types exhibiting discontinuous or very low quantities of surface fuels, surface fire spread is nearly nonexistent even under moderately strong winds. However, once a certain wind speed threshold is reached with respect to given level of fuel dryness, a dramatic change to crown fire spread can suddenly occur (Bruner and Klebenow 1979, Hough 1973).

Slope steepness dramatically increases the uphill rate of spread and intensity of wildland fires by exposing the fuel ahead of the advancing flame front to additional convective and radiant heat. As slope steepness increases, the flames tend to lean more and more toward the slope surface, gradually becoming attached, the result being a sheet of flame moving roughly parallel to the slope. Fires advancing upslope are thus capable of making exceedingly fast runs compared to those on level topography. A crown fire burning on to a 35-percent slope can be expected to spread about 2.5 times as fast as one on level terrain for the same fuel and weather conditions (figure 6).

The overall advance of crown fires in mountainous terrain tends to be well below what would be expected on flat ground, even under extreme fire weather conditions. This is most likely due to major topographical barriers to fire spread, differences in fuel moisture according to slope aspect, and the degree of terrain exposure to the prevailing winds, which limits the full effectiveness of wind speed on fire spread (Chandler and others 1963, Schroeder and Buck 1970). When wind and topography become favorably aligned, exceedingly rapid fire growth can be expected for brief periods over short distances.

It is worth highlighting the fact that crown fire runs in mountainous terrain are not strictly limited to upslope situations. Cases of crown fires burning downslope or cross-slope under the influence of strong winds have occurred (Goens and Andrews 1998).

## Caution in the Use of Fire Behavior Models To Judge Fuel Treatment Effectiveness

Cruz and Alexander (2014) explored the relative variation in predicted

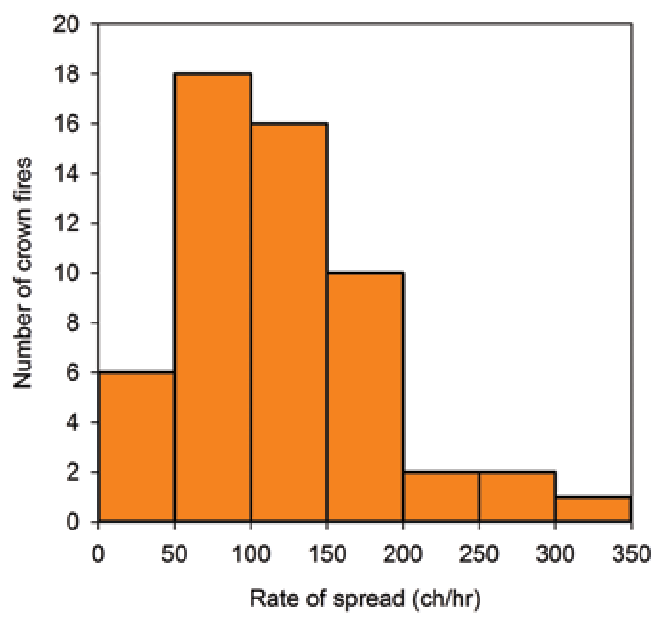


**Figure 5.**—*The distribution of active crown fire rates of spread based on observations of 57 Canadian and American wildfires compiled by Alexander and Cruz (2006).*

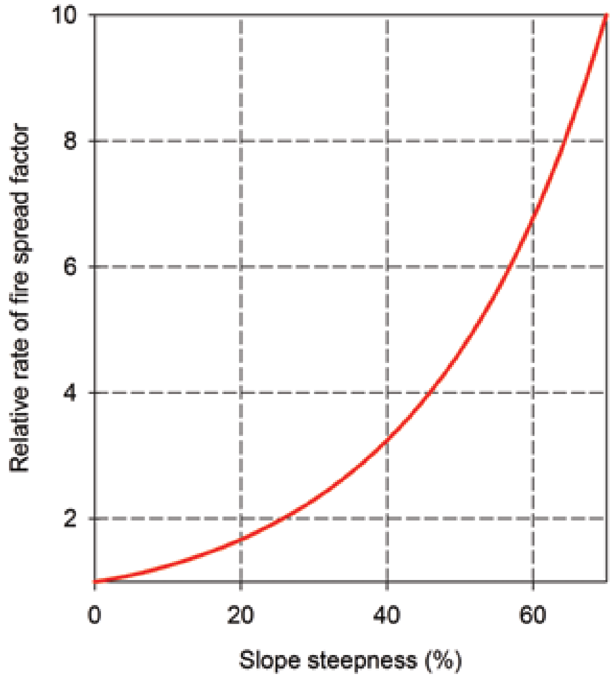


**Figure 6.**—*The effect of slope steepness on the uphill rate of spread of free-burning wildland fires in the absence of wind according to Van Wagner (1977b).*

fireline intensity and the wind speed thresholds for the onset of crowning and active crown fire spread in a lodgepole pine stand subjected to a commercial thinning operation. Seven distinct environmental scenarios, each with different assumptions regarding the estimation of fine dead fuel moisture contents and fire behavior models used, were examined. The results from the seven scenarios varied widely, sometimes exhibiting contradictory trends. This case study emphasized the care that must be taken in selecting realistic environmental inputs and what fire behavior characteristics are chosen for analysis.

## Major Assumptions Associated With Van Wagner's (1977a) Models of Crown Fire Initiation and Propagation

- The conifer forest stand possesses a minimum canopy-bulk density that will allow flames to propagate vertically through the canopy-fuel layer.
- Bridge or ladder fuels such as bark flakes on tree boles, tree lichens, shrubs and understory trees, dead bole branches, and suspended needles exist in sufficient quantity to intensify the surface fire and extend the flame height.
- The empirical constants incorporated in the models based on experimental fires carried out in a red pine plantation fuel complex and the attendant burning conditions are appropriate to other conifer forest stand types and situations.
- The function for foliar moisture content is based on the theoretical premise that all of the moisture in the fuel is driven off before ignition can occur.

## The Myth of the Conditional Crown Fire

Scott and Reinhardt (2001) claimed that the possibility exists for a stand to support an active crown fire that would otherwise not initiate a crown fire. They referred to this situation as a "conditional surface fire." Later on, Scott (2006) termed this a "conditional crown fire." To our knowledge, no empirical proof has been produced to date to substantiate the possible existence of such a situation, at least as a steady-state phenomenon. The concept assumes constant wind speed, failing to recognize the transient nature of fire propagation with bursts of high rates of spread occurring during gusts in the wind followed by periods of lower spread rates and intensity during lulls.

## Empirical- and Physics-Based Models To Predict the Onset of Crowning in Conifer Forests

### Probability of Crown Fire Initiation

Cruz and others (2003) modeled the initiation of crown fires in conifer stands using 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 behavior research database consisting of experimental surface and crown fires ($n$ = 63) 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, 33-foot (10 m) open wind speed, and four components of the FWI (that is, fine fuel moisture code, drought code, initial spread index, and buildup index). The models predicted correctly the type of fire (surface or crown) between 66 and 90 percent of the time.

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 pseudosteady state and are not deemed applicable to dead conifer forests (that is, insect-killed stands).

### Probability of Crown Fire Occurrence

Cruz and others (2004) developed a model to predict the probability of crown fire occurrence based on three fire environment variables (open wind speed, fuel strata gap, and fine dead fuel moisture) and one fire behavior descriptor (an estimate of surface fuel consumption). They developed the model on the basis of experimental surface and crown fires ($n$ = 71) covering a wide spectrum of fire environments and fire behavior characteristics and encompassing fuel complexes with diverse structures. Interestingly, foliar moisture content was not found to be significantly related to the likelihood of crown fire activity.

The model output is the likelihood or probability of a crown fire occurring. This output allows a user to interpret the results differently from the dichotomous answer offered by deterministic models (that is, crowning or no crowning). Based on the user experience with the model output in a particular fuel type, key threshold values for the onset of crowning can be locally determined for particular conifer forest types.

Evaluation of the model yielded encouraging results concerning its validity. An interesting advantage of this model over other approaches for determining the initiation of crown fires is its simplicity. The output (that is, the onset of crowning) is directly related to the main controlling environmental variables, thereby limiting error propagation. In some modeling systems (for example, BehavePlus), a number of intermediate computations—such as rate of fire spread and flame front residence time—must first be made before fireline intensity can be calculated. The resultant value is then used to predict flame length, as well as the onset of crowning or lethal crown scorch height. In the process of determining these primary outputs, compounding errors can arise from the choice of fuel model and fuel availability for flaming combustion, resulting in large overall errors (Cruz and others 2004, Cruz and Alexander 2010).

### The Crown Fuel Ignition Model

Cruz and others (2006a) developed a semi-physical model to predict the ignition of conifer forest crown fuels above a surface fire based on heat transfer theory. The Crown Fuel Ignition Model (CFIM) integrates (1) the characteristics of the energy source as defined by surface fire flame front properties, (2) buoyant plume dynamics, (3) heat sink as described by the crown fuel particle characteristics, and (4) energy transfer (gain and losses) to the crown fuels. The final model output is the temperature of the crown fuel particles, which upon reaching ignition temperature are assumed to ignite. CFIM predicts the ignition of crown fuels but does not determine the onset of crown fire spread *per se*. The coupling of the CFIM with models determining the rate of propagation of crown fires allows for the prediction of the potential for sustained crowning. CFIM has been incorporated into a fire behavior prediction system for exotic pine plantations in Australia (Cruz and others 2008).

Model evaluation (Cruz and others 2006b) indicated that the primary factors influencing crown fuel ignition are those determining the depth of the surface fire burning zone (that is, fuel available for flaming combustion), wind speed, moisture content of surface fuels, and the vertical distance between the ground/surface fuel strata and the lower boundary of the crown fuel layer. Intrinsic crown fuel properties, such as foliar moisture content and leaf size, were found to have a minor influence on the process of crown fuel ignition. Comparison of model predictions against data collected in high-intensity experimental fires and predictions from other models gave encouraging results relative to the validity of the model system.

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## Torching Does Not Constitute a Form of Crowning

The concept of passive crowning implies an element of forward movement or propagation of the flame front. The incidental ignition of an isolated tree or clump of trees, with the flames spreading vertically from the ground surface through the crown(s) without any form of forward spread following, does not constitute passive crowning. Flame defoliation of conifer trees by what amounts to stationary torching or "crowning out," especially common during the postfrontal combustion stage following passage of the surface fire, generally does not generate any kind of horizontal spread.

*Torching lodgepole pine tree during an experimental fire undertaken near Prince George, BC (from Lawson 1972).*


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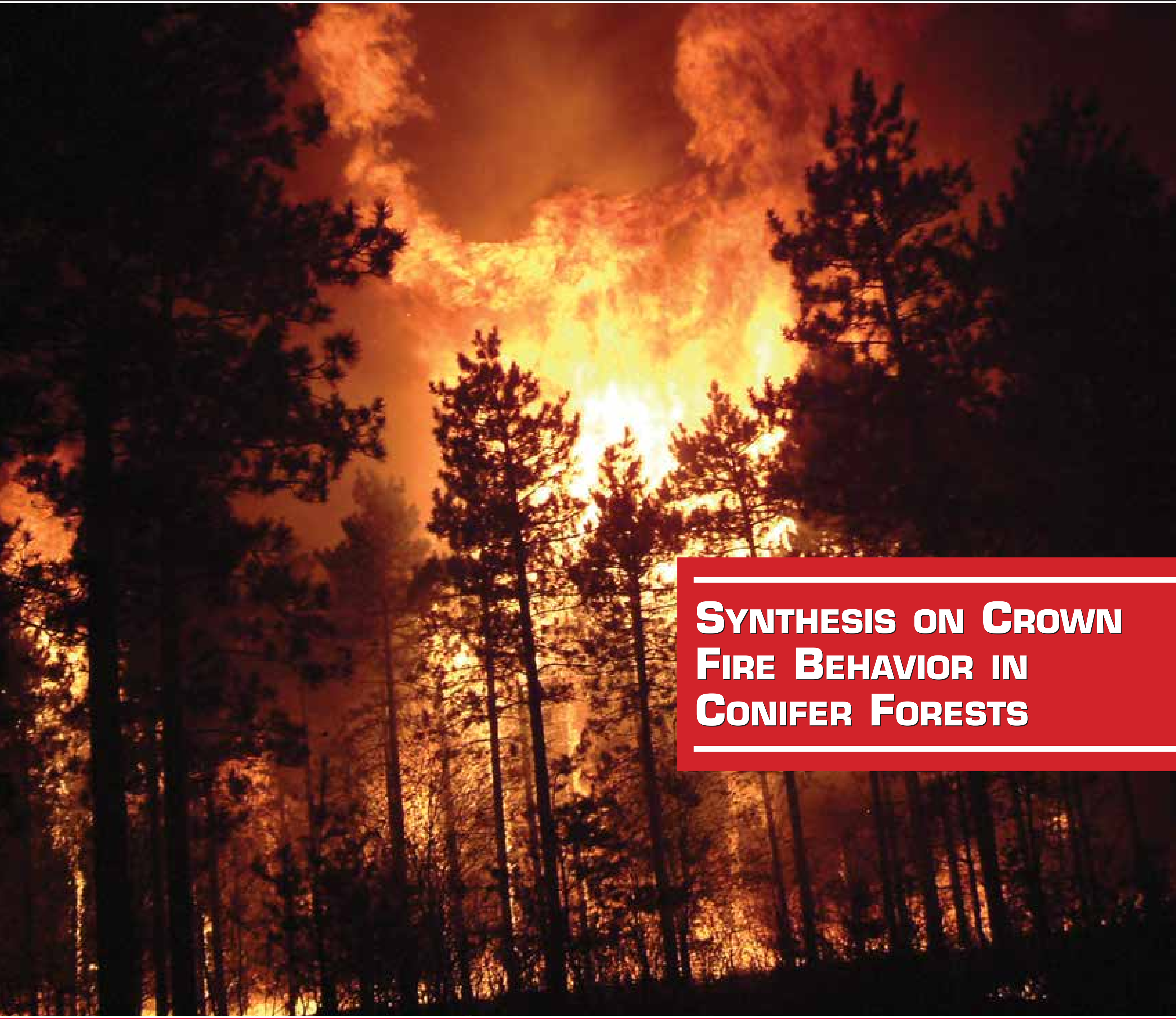

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## On the Cover:

*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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- *Innovation:* We will respect and value thinking minds, voices, and thoughts of those that challenge the status quo while focusing on the greater good.
- *Execution:* We will do what we say we will do. Achieving program objectives, improving diversity, and accomplishing targets are essential to our credibility.
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