Chapter 8: Crown Fire Dynamics in Conifer Forests

Martin E. Alexander and Miguel G. Cruz[1]

As for big fires in the early history of the Forest Service, a young ranger made himself famous by answering the big question on an exam, "What would you do to control a crown fire?" with the one-liner, "Get out of the way and pray like hell for rain."—Norman Maclean (1992)

Introduction

Three broad types of fire are commonly recognized in conifer-dominated forests on the basis of the fuel layer(s) through which they are spreading:

- Ground or subsurface fire
- Surface fire
- Crown fire

Ground or subsurface fires spread very slowly and with no visible flame. Heading surface fires can spread with the wind or upslope, and backing surface fires burn into the wind (fig. 8-1 A) or downslope. A crown fire is dependent on a surface fire for both its initial emergence and continued existence. Thus, a crown fire advances through both the surface and tree canopy fuel layers with the surface and crown fire phases more or less linked together as a unit (fig. 8-1 B and C). The term "crowning," therefore, refers to both the ascension into the crowns of trees and the spread from crown to crown.

From the perspective of containing or controlling wildfires or unplanned ignitions, the development and subsequent movement of a crown fire represents a highly significant event as a result of the sudden escalation in the rate of advance and the dramatic increase in flame size and thermal radiation as well as convective activity, including fire-induced vortices and, in turn, both short- to long-range spotting potential. As a consequence, crown fires are dangerous for firefighters to try to control directly by conventional means. Suppression actions and options

[1] **Martin E. Alexander,** Department of Renewable Resources and Alberta School of Forest Science and Management, University of Albert, Edmonton, Alberta, Canada. **Miguel G. Cruz,** Bush Fire Dynamics and Applications, CSIRO Ecosystems Sciences–Climate Adaptation Flagship, Canberra, ACT 2601, Australia.

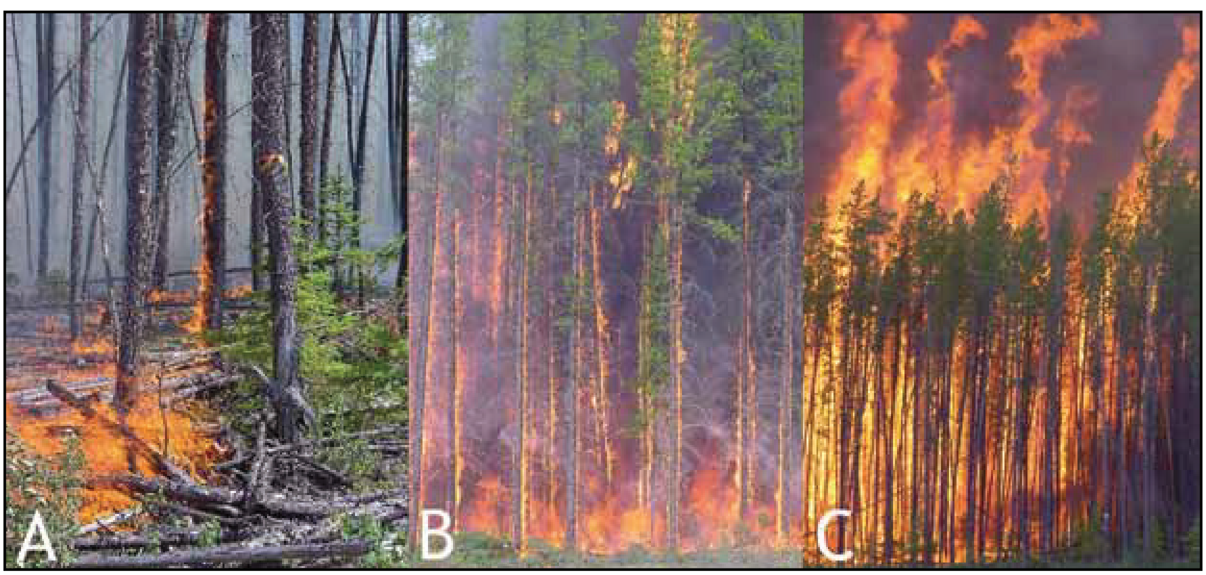

Figure 8-1—Variations in fire behavior within the jack pine/black spruce fuel complex found at the International Crown Fire Modeling Experiment study area near Fort Providence, Northwest Territories, Canada: (A) surface fire, (B) passive crown fire, and (C) active crown fire. For additional photography carried out on experimental basis, see Alexander and De Groot (1988), Alexander and Lanoville (1989), Stocks and Hartley (1995), and Hirsch et al. (2000).

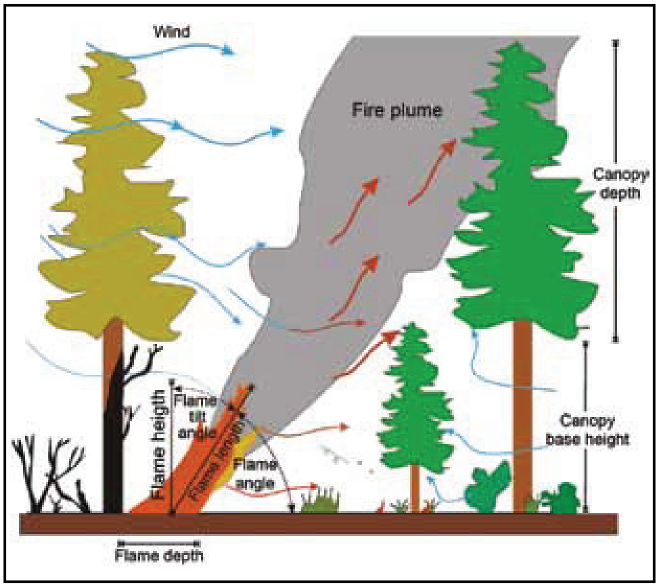

Figure 8-2—Cross section of a stylized, wind-driven surface head fire spreading behind a conifer forest canopy on level terrain.

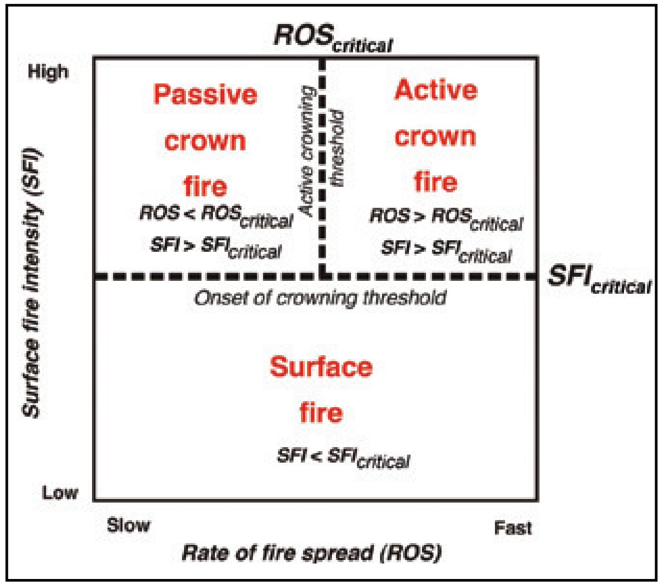

Figure 8-3—Type of fire classification scheme based on Van Wagner's (1977a) theories regarding the start and spread of crown fires in conifer forests.

at the head of the fire tend to be severely restricted until there is a major change in the prevailing fuel, weather, or topographic conditions (e.g., a drop in windspeed, a major fuel discontinuity). As a result, crown fires are capable of burning large tracts of forested landscape, thereby posing a threat to public safety and properties, potentially adversely impacting other values-at-risk, and increasing suppression expenditures.

Prolific crowning is an element or characteristic of extreme fire behavior in conifer-dominated forest cover types. This chapter constitutes a state-of-knowledge summary prepared for operational fire management personnel in the United States concerning our current understanding of the characteristics and prediction of crown fire behavior in such fuel complexes. Information on crown fire phenomenology is drawn upon from a number of sources, including relevant observations and data from Canada and Australia. The dynamics of crown fires in tall brush fields (e.g., chaparral) and other forest types (e.g., eucalypt) will not specifically be dealt with here. For present purposes, it is assumed that there is a distinct separation between the canopy fuel layer and the ground and surface fuels by an open trunk space in which ladder or bridge fuels may be present (fig. 8-2). Certain aspects of crown fire behavior are not addressed here but can be found in other chapters of this synthesis document (e.g., horizontal roll vortices, plume- or convection-dominated crown fires, influences of atmospheric conditions aloft, fire-atmosphere interactions).

Types of Crown Fires

Van Wagner (1977a) proposed that crown fires in conifer forests could be classified according to their degree of dependence on the surface fire phase and the criteria could be described by several semi-mathematical statements (fig. 8-3). He recognized three types of crown fires (box 1). According to Van Wagner (1977a), the type of crown fire to be expected in a conifer forest on any given day depends on three simple properties of the canopy fuel layer (box 2) and two basic fire behavior characteristics:

- Initial surface fire intensity
- Foliar moisture content
- Canopy base height
- Canopy bulk density
- Rate of fire spread after the onset of crown combustion

Box 1:

Crown Fire Classification

For the longest time, only two kinds of crown fire were generally recognized, namely "dependent" and "running" (Brown and Davis 1973). Van Wagner (1977a) recognized three classes or types of crown fires:

Passive Crown Fire

Passive or dependent crown fires can involve a portion or all of the canopy fuel layer in combustion, but the overall rate of spread is largely determined by the surface phase. Passive crown fires cover a range in fire behavior from moderately vigorous surface fires with frequent crown ignition occurring behind the surface flame front up to high-intensity surface fires spreading with an almost solid flame front occupying the canopy and subcanopy or trunk space that have nearly achieved the critical minimum spread rate for active crowning. Passive crown fires can occur under two broad situations. First, the canopy base height and canopy bulk density are considered optimum, but fuel moisture and wind conditions are not quite severe enough to induce full-fledged crowning (fig. 8-1 B). Second, the canopy base height and canopy bulk density are, respectively, above and below the thresholds generally

Box 1: continued

considered necessary for crowning (e.g., tall or open-forest stand types), so that even under severe burning conditions (i.e., critically dry fuels and strong surface winds), active crown fire spread is not possible, although vigorous, high-intensity fire behavior can occur.

Active Crown Fire

Active or running crown fires are characterized by the steady advancement of a tall and deep coherent flame front extending from the ground surface to above the top of the canopy fuel layer (fig. 8-1 C). The surface and crown phases are intimately linked, but fire propagation is largely determined by the crown phase. The spread of active crown fires requires (1) relatively dry and plentiful surface fuels that allow for the development of a substantial surface fire (2) low to moderately high canopy base height, and (3) a fairly continuous crown layer of moderate to high canopy bulk density (>0.1 kg/m^3) and low to normal foliar moisture content.

Independent Crown Fire

An independent crown fire no longer depends in any way on the surface phase, spreading ahead of the surface phase in the crown fuel layer entirely

Box 1: continued

on its own. Stand conditions favoring an independent crown fire are a continuous crown layer of low to moderate canopy bulk density and an abnormally low foliar moisture content. For a truly independent crown fire to develop on flat topography would require very strong, sustained winds. In mountainous terrain, slope steepness would no doubt compensate for a lesser velocity.

The vast majority of crowning forest fires spread either as passive or active crown fires, each controlled by a different set of processes. Van Wagner (1993) acknowledged that the concept of a truly independent crown fire as a stable phenomenon on level terrain is dubious but that it "may still have value in rough or steep terrain and as a short-term fluctuation under the most extreme conditions." Indeed, there are reports of the flames in the crown extending 50 to 150 m ahead of the surface burning in momentary bursts and of crown fires spreading up steep, partially snow-covered slopes in the spring (Mottus and Pengelly 2004). These incidents might possibly give the appearance of being evidence for independent crown fires. However, there is no steady-state propagation

Box 1: continued

as seen with passive and active crown fires.

It is worthwhile noting that 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.

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.

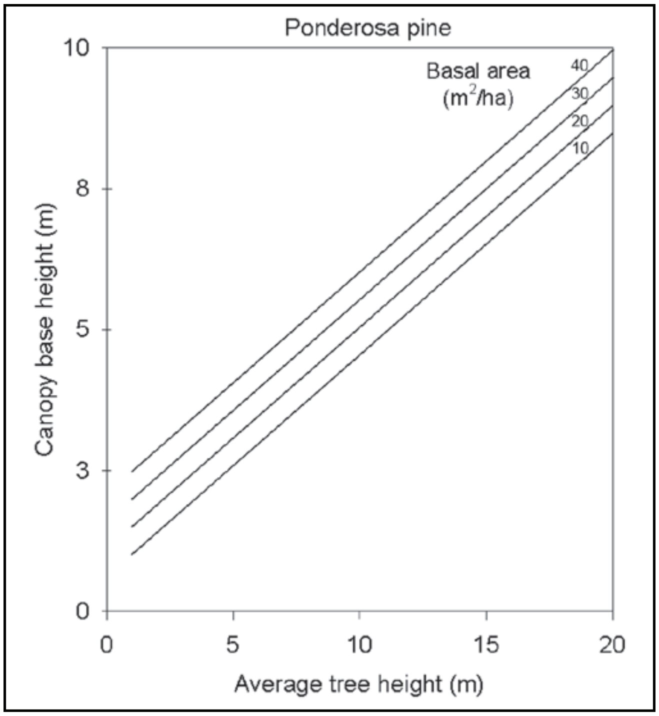

Figure 8-4—Canopy base height for ponderosa pine stands as a function of average stand height and basal area according to Cruz et al. (2003a). The regression equation used to produce this graph is not valid for tree heights of less than 1.0 m.

The first three quantities determine whether a surface fire will ignite coniferous foliage. The last two determine whether or not a continuous flame front can be sustained in the canopy fuel layer. The initial surface fire intensity and rate of fire spread after the onset of crown combustion would, in turn, include the effects of windspeed, slope steepness, fuel dryness, air temperature, relative humidity, and fuel complex characteristics. Examples of how canopy base height and canopy bulk density CBD vary with tree and stand characteristics is presented here for ponderosa pine in figures 8-4 and 8-5.

Albini and Stocks (1986) considered the factors included in Wagner's (1977a) proposed criteria for the start and spread of a crown fire as "heuristically valid." Subsequent experience and analysis has shown both the strengths and limitations of his approach (Cruz et al. 2003c, 2004, 2006a).

Crown Fire Initiation

For a crown fire to start, an intense surface fire is generally required. The questions then become: How do we define fire

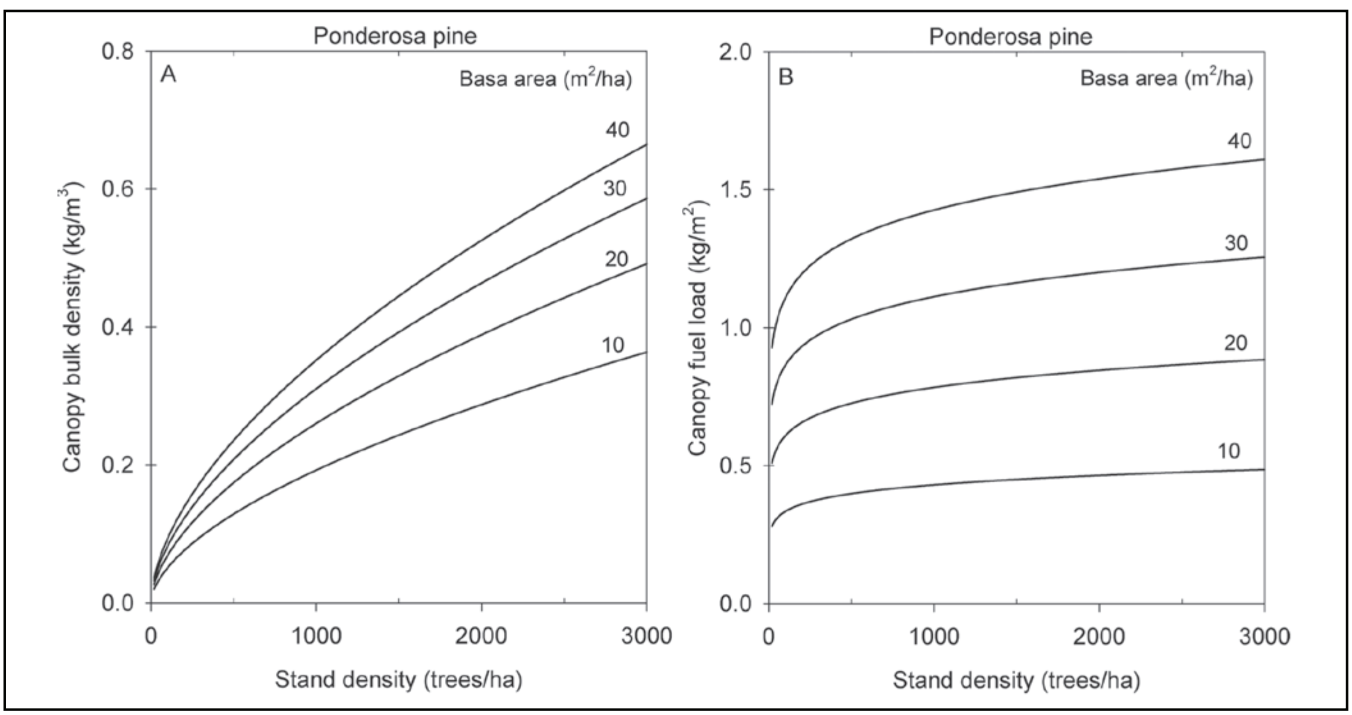

Figure 8-5—Canopy bulk density (A) and canopy fuel load (B) for ponderosa pine stands as a function of stand density and basal area according to Cruz et al. (2003a).

Box 2:

Canopy Fuel Characteristics in Van Wagner's (1977a) Crown Fire Initiation and Propagation Models

Canopy Base Height

Canopy base height (CBH) represents the mean height from the ground surface to the lower live crown base of the conifer trees in a forest stand (fig. 8-2). Canopy base height is dependent on the mean tree height and live stem density (fig. 8-4). Ladder or bridge fuels (e.g., loose bark and dead bole branches on tree boles, lichens, shrubs, and small conifers) in the space between the ground surface and the canopy "must presumably be present in sufficient quantity to intensify the surface fire appreciably as well as to extend the flame height" (Van Wagner 1977a). Unfortunately, our ability to assess ladder or bridge fuel effects on crown fire initiation remains qualitative (Menning and Stephens 2007).

Canopy Bulk Density

Canopy bulk density (CBD) represents the amount of available crown fuel within a unit volume of the canopy. Canopy bulk density is computed by dividing the canopy fuel load (CFL) by the canopy depth (fig. 8-2), which represents the average tree height of the stand minus the CBH. The CFL

Box 2: continued

represents the quantity of crown fuel typically consumed in a crown fire, principally needle foliage. Both the CBD and CFL are, in turn, functions of stand structure characteristics (fig. 8-5).

Foliar Moisture Content

Foliar moisture content (FMC) represents a weighted average or composite moisture content for the various needle ages found within the canopy fuel layer. Needles decrease in moisture content with age following their initial flushing (Keyes 2006).

Some researchers such as Scott and Reinhardt (2001) have applied different criteria to the CBH, CFL, and CBD inputs in their use of Van Wagner's (1977a) models (Cruz and Alexander 2010, in press). However, strictly speaking, such ad hoc adjustments or modifications are not compatible with the use of these models. Still others have in some cases recommended or applied potentially unrealistically low values of FMC (Cruz and Alexander 2010). Varner and Keyes (2009) have outlined other faulty assumptions and common errors regarding modeling inputs involved in simulating fire behavior potential.

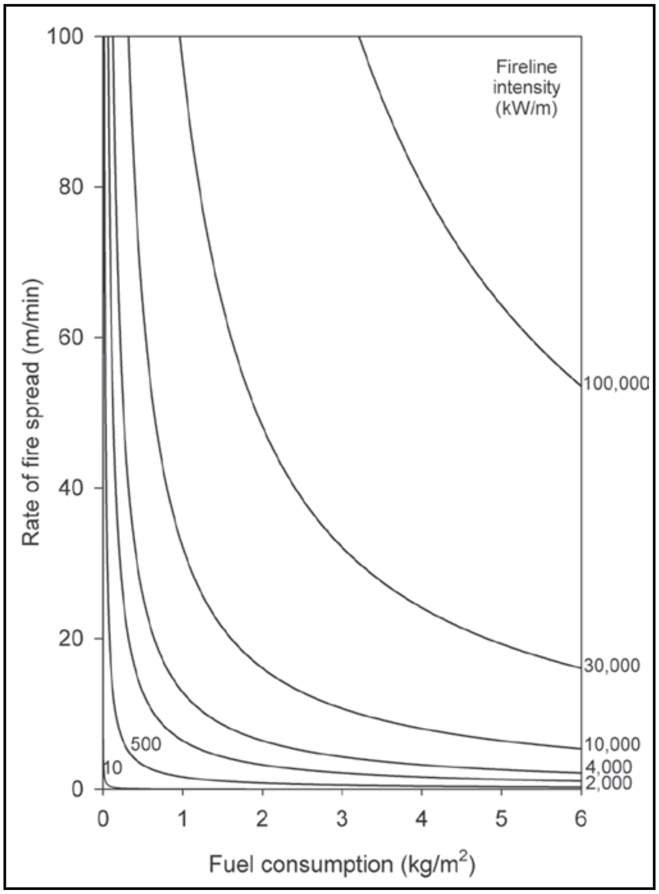

Figure 8-6—Head fire rate of spread and fuel consumed in relation to the type of fire and six distinct levels of Byram's (1959a) fireline intensity, assuming a net heat of combustion of 18 000 kJ/kg.

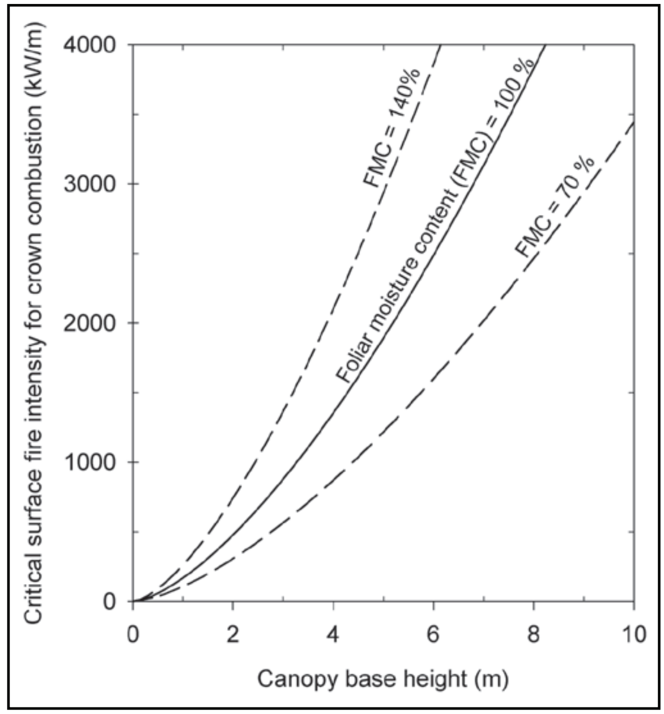

Figure 8-7—Critical surface fire intensity for crown combustion in a conifer forest stand as a function of canopy base height and foliar moisture content according to Van Wagner (1977a).

intensity? and How intense is intense enough with respect to the convective and radiative energy transferred upward to the canopy fuels necessary to initiate crowning? The distance the canopy fuel layer (fig. 8-4) is from the heat source at the ground surface will dictate how much energy is dissipated before reaching the fuels at the base of the canopy. Furthermore, if the moisture content of the canopy fuels is high, greater amounts of energy are required to raise the tree foliage to ignition temperature.

Byram (1959a) defined fireline intensity (I, kW/m) as the rate of heat released from a linear segment of the fire perimeter as calculated by the following equation:

$$I = H \times w \times r \quad (1)$$

where H is regarded as the net low heat of combustion (kJ/kg), w is amount of fuel consumed in the active flaming front (kg/m^2), and r is the rate of fire spread (m/s) (Alexander 1982). If we assume H = 18 000 kJ/kg, then the equation for calculating fireline intensity can also be expressed as follows:

$$I = 300 \times w \times ROS \quad (2)$$

where ROS is the rate of fire spread given in m/min. A graphical representation of this relation is presented in figure 8-6. Wendel et al. (1962) concluded that the probability of blowup fires decreased rapidly when available fuel loads were less than 1.35 kg/m^2.

Using physical reasoning and empirical observation, Van Wagner (1977a) proposed that vertical fire spread could occur in a conifer forest stand when the surface fire intensity (SFI) attains or exceeds a certain critical surface intensity for combustion ($SFI_{critical}$, kW/m) as dictated by the foliar moisture content (FMC, %) and the canopy base height (CBH, m) according to the following equation which is graphically presented in figure 8-7:

$$SFI_{critical} = (0.01 \times CBH \times (460 + 25.9 \times FMC))^{1.5} \quad (3)$$

Table 8-1—Fire suppression interpretations of flame length and fireline intensity

Flame length[a]	Fireline intensity	Fire suppression interpretations
Meters	kW/m	
<1.2	<346	Fire can generally be attacked at the head or flanks by persons using hand tools. Handline should hold the fire.
1.2 to 2.4	346 to 1730	Fires are too intense for direct attack on the head by persons using hand tools. Handline can not be relied on to hold fire. Equipment such as plows, dozers, pumpers, and retardant aircraft can be effective.
2.4 to 3.4	1730 to 3459	Fires may present serious control problems: torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>3.4	>3459	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

[a] Based on Byram's (1959a) flame length (*L*, m)-fireline intensity (*I*, kW/m) relation: $L = 0.0775 \times (I)0.46$.
Adapted from Burgan 1979.

Thus, according to Van Wagner's (1977a) theory of crown fire initiation, if $SFI > SFI_{critical}$, some form of crowning is presumed to be possible, but if $SFI < SFI_{critical}$, a surface fire is expected to prevail (fig. 8-3). In applying this criterion, it is assumed that a conifer forest stand possesses a minimum CBD that will allow flames to propagate vertically through the canopy fuel layer.

One of the appealing aspects of eq. (3) is its simplicity, but with this comes a major underlying assumption. According to Van Wagner (1977a), the 0.01 value given in eq. (3) is an empirical constant of "complex dimensions." He derived this value from an outdoor experimental fire in a red pine plantation stand (see "Common and Scientific Names" section) with *CBH* of 6.0 m and a *FMC* of 100 percent and the *SFI* was about 2500 kW/m just prior to crowning (Van Wagner 1968). This widely used relation represented by eq. (3) therefore incorporates a fixed set of burning conditions, fuel characteristics, and surface fire behavior (e.g., in-stand wind, ladder fuels, fuel consumed, flame depth, and spread rate). Subsequent research has shown this empirical constant to be a variable quantity dependent on these factors (Alexander 1998, Cruz et al. 2006a).

From figure 8-7, it should be clear that the higher the *CBH* and/or *FMC*, the more intense a surface fire must

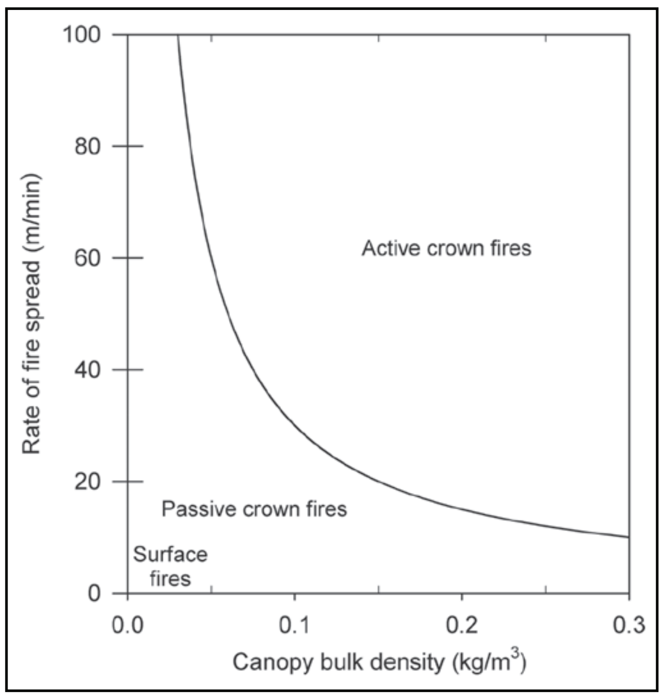

Figure 8-8—Critical minimum spread rate for active crowning in a conifer forest stand as a function of canopy bulk density according to Van Wagner (1977a).

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 (Alexander 1988). The experimental fire used by Van Wagner (1977a) to parameterize his crown fire initiation model represented by eq. (3) would, for example, have had a flame length of 2.6 m according to Byram's (1959a) formula linking flame length to fireline intensity (table 8-1).

Crown Fire Propagation

Assuming a surface fire is of sufficient intensity to initiate and sustain crown combustion from below, the question now becomes, 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. In this conceptual formulation, the flame front is viewed as stationary with the fuel moving into it.

Van Wagner (1977a) proposed that a critical minimum spread rate needed to preserve continuous crowning ($ROS_{critical}$, m/min) could be estimated on the basis of the stand's canopy bulk density (CBD, kg/m^3) using the following simplistic equation:

$$ROS_{critical} = 3.0 \div CBD \quad (4)$$

According to eq. (4), $ROS_{critical}$ increases as the CBD decreases (fig. 8-8). High CBD levels are associated with dense stands and low values with open stands (fig. 8-5). Active crowning is presumably not possible if a fire does not spread rapidly enough following initial crown combustion. Albini (1993) viewed this criterion for active crowning as a "lean flammability limit." Thus, if a fire's actual *ROS* after the initial onset of crowning, which is in turn a function largely of the prevailing windspeed or slope, is less than $ROS_{critical}$, a passive crown fire is expected to occur (fig. 8-3).

The 3.0 empirical constant given in eq. (4) was derived largely on the basis of a single experimental crown fire in a red pine plantation stand exhibiting a CBD of 0.23 kg/m^3 (Van Wagner 1964). However, the robustness of this value has since been confirmed on the basis of an analysis of a relatively large data set of experimental crown fires in several different conifer forest fuel complexes (Cruz et al. 2005) and a detailed wildfire behavior case study (Alexander 1998). These analyses also support Agee's (1996) assertion that a CBD of about 0.1 kg/m^3 constitutes a significant threshold for active crown fires. Furthermore, it appears from the function represented by eq. (4) and the available empirical evidence (fig. 8-8), that active crown fires are unlikely to occur at CBD levels below about 0.05 kg/m^3, although this is not to suggest that a very vigorous, high-intensity passive crowning is not possible.

Crown Fire Rate of Spread

Surface fires spreading beneath conifer forest canopies seldom exceed 5 to 10 m/min without the onset of crowning in some form or another (fig. 8-6). The exceptions would involve open stands with a low CBD (say less than 0.05 kg/m^3) or closed-canopied stands exhibiting a very high canopy base height (perhaps 12 to 15 m or greater), in which case, spread rates might reach as high as 25 m/min with associated fireline intensities of 10 000 kW/m.

General observations of wildfires and documentation of experimental crown fires indicate that a rather abrupt transition between surface and crown fire spread regimes is far more commonplace than a gradual transition (Van Wagner 1964). With the onset of crowning, at a minimum, a fire typically doubles or even triples its spread rate in comparison to its previous state on the ground surface (McArthur 1965). This sudden jump in the fire's rate of spread occurs as a result of (i) the enhanced radiant heating owing to the taller and deeper flame fronts, (ii) the fact that the windspeeds just above the tree canopy are two and one-half to six times that of the winds experienced near ground level inside the stand, (iii) increased efficiency of heat transfer into a tall and porous fuel layer, and (iv) an increase in spotting density and distance 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 and to a lesser extent by physical fuel properties and dryness. Continuous crowning generally takes place at spread rates between about 15 and 45 m/min. Crowning wildfires have been known to make major runs of 30 to 65 km over flat and rolling to gently undulating ground during a single burning period or over multiple days, as so vividly demonstrated, for example, on the Rodeo-Chediski Fire in northern Arizona in June 2002 (Paxton 2007). A wildfire crowning through sand pine forests in north-central Florida on March 12, 1935, travelled nearly 32 km in about 6 hours with intervening spread rates of 135 to 150 m/min (Folweiler 1937). During the major run of the Mack Lake Fire in Michigan that occurred on May 5, 1980, the crown fire rate of spread in jack pine forests peaked at nearly 190 m/min during a 15-min interval (Simard et al. 1983). Grass fires have been reported to spread at twice these rates on level ground and are thus capable of spreading the same distance as crowning forest fires in half the time (Cheney and Sullivan 2008).

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 windspeed threshold is reached with respect to a given level of fuel dryness, a dramatic change to crown fire spread suddenly occurs. This type of fire behavior has been observed in pinyon-juniper woodlands of the Western United States (Bruner and Klebenow 1979) and in the sand pine forests of Florida (Hough 1973), for example. The same phenomenon has been observed in certain grassland and shrubland fuel complexes (Cheney and Sullivan 2008, Lindenmuth and Davis 1973).

Slope dramatically increases the rate of spread and intensity of wildland fires by exposing the fuel ahead of the advancing flame front to additional convective and radiant heat. Fires advancing upslope are thus capable of making exceedingly fast runs compared to level topography. For example, one would expect a crown fire burning on a 35-percent slope to spread about 2.5 times as fast as one on level terrain for the same fuel and weather fuel conditions (Van Wagner 1977b). 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. Rothermel (1985) has stated that although there is no definitive research on the subject of flame attachment, “it appears from lab work and discussions with users that the flames become attached near 50 percent slope with no prevailing wind.” The critical value will actually differ depending on the prevailing wind strength (Cheney and Sullivan 2008) as well as on the fuel type characteristics. The time-lapse photography taken of the rapid upslope runs on the 1979 Ship Island Fire in central Idaho as shown in the video *Look Up, Look Down, Look Around* (National Wildfire Coordinating Group 1993) constitutes a good example of such fire behavior.

With the exception of very long slopes such as found, for example, in the Salmon River country of central Idaho, the rate of advance of wind-driven crown fires in mountainous terrain tends, over the duration of their run, to be well below what would be expected on flat ground, even under critical fire weather conditions. This is a result of the degree of terrain exposure to the prevailing winds, which limits the full effectiveness of windspeed on fire spread, as well as differences in fuel moisture owing to aspect (Schroeder and Buck 1970). However, when the advancing crown fire front encounters a situation where wind and topography result in a favourable alignment, spread rates of ~100 m/min are quite easily possible for a brief period over short distances with only moderately strong winds (e.g., Rothermel and Mutch 1986). Fire spread rates in grassland and shrubland fuel types at even twice this level can easily occur (Butler et al. 1998, Rothermel 1993).

It is worth highlighting the fact that crown fire runs in mountainous terrain are not limited to just upslope situations. Cases of crown fires burning downslope or cross-slope under the influence of strong winds have occurred in the past (Byram 1954, McAlpine et al. 1991). The major run of the Dude Fire in northern Arizona on June 26, 1990, that led to the deaths of six firefighters involved downslope and cross-slope spread as a result of the strong downdraft winds caused by the fire’s collapsing convection column (Goens and Andrews 1998).

Crown Fire Intensity and Flame Zone Characteristics

When a conifer forest stand crowns, additional fuel is consumed primarily in the form of needle foliage but also mosses and lichens, bark flakes, and small woody twigs. The additional fuel consumed by a crown fire owing to the canopy fuel involvement generally amounts to 0.5 to 2.0 kg/m^2 depending on stand characteristics (i.e., an increase in fuel consumption with respect to fireline intensity of one-quarter to a doubling in the amount). Combined with the increase in rate of fire spread after crowning, fireline intensities can easily quadruple in value within a few seconds (e.g., from 3000 kW/m to 12 000 kW/m). In such cases, is there any wonder why some fires seem to literally "blow up"?

A fire's flame zone characteristics (i.e., depth, angle, height, and length) are a reflection of its heat or energy release rate. As the fireline intensity or rate of energy released per unit area of the flame front increases because of a faster rate of spread and a larger quantity of fuel being volatilized in the flaming front, flame size or volume increases. Fireline intensities of wind-driven crown fires can exceed 100 000 kW/m for significant periods (Anderson 1968, Kiil and Grigel 1969).

The flame depth (*D*, m) of a spreading wildland fire (fig. 8-2) is a product of its *ROS* and the flame front residence time (t_r, min) which represents the duration that a moving band or zone of continuous flaming combustion persists at or resides over a given location:

$$D = ROS \times t_r \qquad (5)$$

Residence times are dictated largely by the particle size(s) distribution, load, and compactness of the fuelbed. Residence times for conifer forest fuel types at the ground surface are commonly 30 sec to 1 min compared to 5 to 10 sec in fully cured grass fuels. Assuming t_r = 0.75 min (i.e., 45 sec), a surface fire in a conifer forest spreading at 4.0 m/min would thus have flame depth of around 3.0 m according to eq. (5). Crown fires are capable of producing very deep flame fronts. The depth of the burning zone in the surface fuels of a crown fire spreading at 60 m/min would, for example, be around 45 m. The flame depth of a grass fire advancing at this rate would in contrast be only about a tenth of this value. Residence times within the canopy fuel layer of a crown fire are approximately one-half to one-third those experienced at ground level (Anderson 1968, Taylor et al. 2004). This is reflected in the gradual convergence of the flaming zone depth with height ending in the flame tip above the tree crowns.

The flame front of a crown fire on level ground appears to be roughly vertical or nearly so. This appearance has led to the popular phase "wall of flame" when it comes to describing crown fire behavior. Typically though, tilt angles are 5 to 20 degrees from the vertical. The fact that the flames of a crown fire stand so erect is a direct result of the powerful buoyancy associated with the large amount of energy released in the flame front (fig. 8-1 C). Radiation from the crown fire wall of flame can produce painful burns on exposed skin at more than 100 m from the fire edge (Albini 1984).

Given the difficulty of gauging the horizontal depth of the burning zone in a crown fire, flame height constitutes a more easily visualized dimension than flame length. However, efforts to objectively estimate flame heights of crown fires is complicated by the fact that sudden ignition of unburned gases in the convection column can result in flame flashes that momentarily extend some 100 m or more into the convection column aloft; one such flame flash was photographically documented that extended almost 200 m above the ground (Sutton 1984). Such flashes can easily result in overestimates of average flame heights, which usually range from about 15 to 45 m on high-intensity crown fires (Byram 1959b). Average flame heights of crown fires are thus generally regarded as being about two (fig. 8-1 C) to three times the stand height.

Crown Fire Area and Perimeter Growth

For forest fires of today to become large, they typically have to involve some degree of crowning. A common axiom is that 95 percent of area burned is generally caused by less than 5 percent of the fires. When a forest fire at the very minimum doubles its spread rate after the onset of crowning, the area burned for a given period will be at least four times what would have been covered by a surface fire. In other words, the area burned is proportional to the rate of

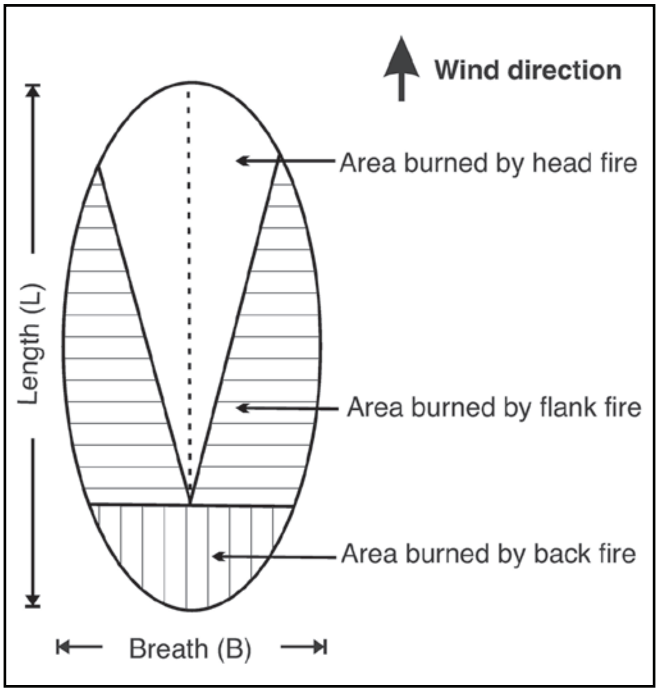

Figure 8-9—Schematic diagram of a simple elliptical fire growth model (after Van Wagner 1969). The point of ignition is at the junction of the four area growth zones.

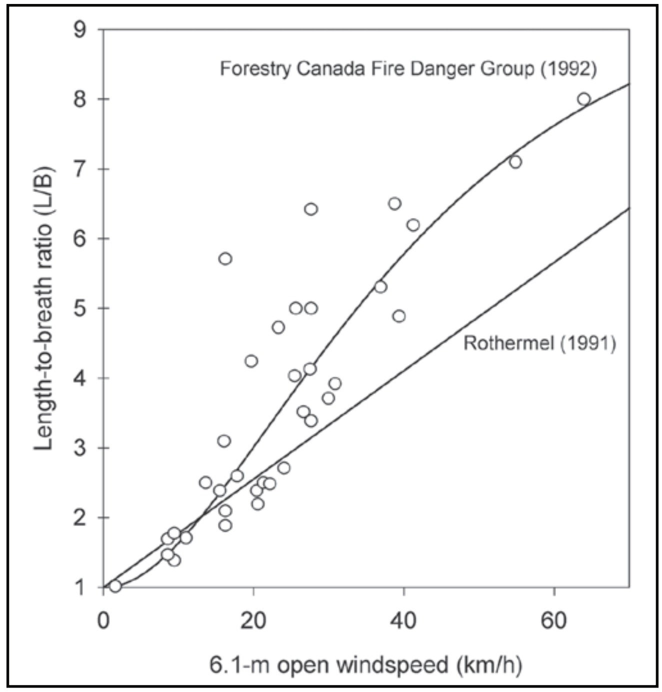

Figure 8-10—Length-to-breadth ratio of elliptical-shaped fires on level terrain as a function of windspeed, as used in the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992) and in Rothermel's (1991) guide to crown fire behavior in relation to experimental fire and wildfire observations given in Alexander (1985) and Forestry Canada Fire Danger Group (1992). The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

spread increase (following the transition to crowning) to a power of 2.0 (McArthur 1965). Thus, if a fire triples its rate of advance after crowning, the area burned will be nine times the size it would have been had it remained as a surface fire (i.e., $3.0^2 = 9$).

Other than dry and plentiful fuels, the principal ingredients for major crown fire runs are strong, sustained winds coupled with extended horizontal fuel continuity. The Hayman Fire that occurred along the Colorado Front Range, for example, burned close to 25 000 ha during its major run on June 9, 2002, and eventually grew to nearly 56 000 ha towards the end of the month (Graham 2003). Under favourable conditions, crown fires on level to gently undulating terrain have been documented to cover in excess of 70 000 ha in a single, 10-hour burning period (Kiil and Grigel 1969) and up to a third that much in mountainous areas (Anderson 1968).

Assuming continuous fuels, including no major barriers to fire spread, and no change in wind and fuel moisture conditions, the forward spread distance of a crown fire can be determined by multiplying its predicted rate of spread by a projected elapsed time. Provided the wind direction remains relatively constant and the fire environment is otherwise uniform, wind-driven surface and crown fires typically assume a roughly elliptical shape (Alexander 1985, Anderson 1983, Van Wagner 1969) defined by its length-to-breadth ratio (L:B) (fig. 8-9), which in turn is a function of windspeed (fig. 8-10). The L:B associated with crown fires generally ranges from a little less than 2.0 to a maximum of approximately 8.0 in exceptional cases (Folweiler 1937). Simple estimates of potential crown fire size in terms of area burned and perimeter length can be made on the basis of the forward spread distance and L:B (fig. 8-11).

This simplistic picture of fire growth as described here is applicable to cases involving a point source ignition (e.g., an escaped campfire or lightning fire start) or perhaps

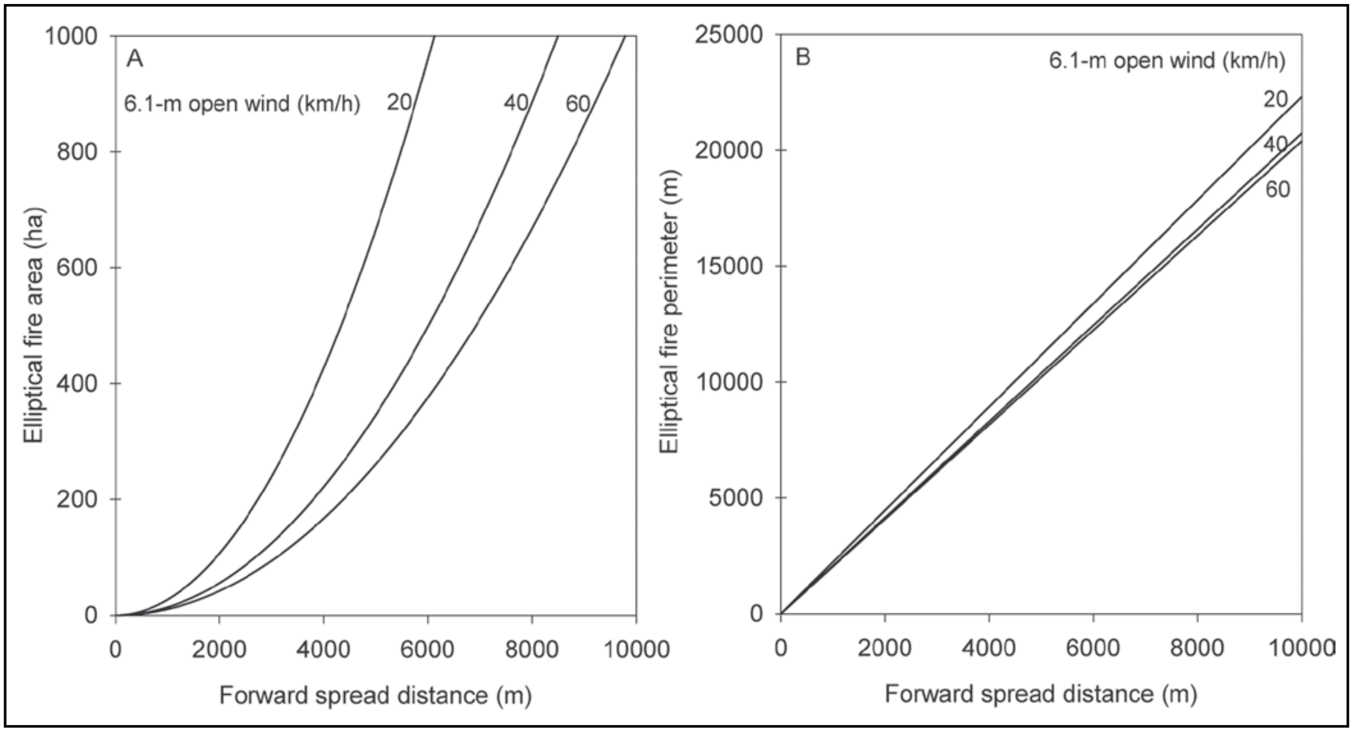

Figure 8-11—Area burned (A) and perimeter length (B) of an elliptical-shaped crown fire as a function of forward spread distance and windspeed on level terrain. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

a breach in an established control line, involving unidirectional winds and is generally limited to a 1- to 8-hour projection period. This approach is thus not appropriate to estimating crown fire growth when the perimeter becomes highly irregular in shape with the passage of time as a result of changes in wind direction, fuel types, and terrain characteristics (e.g., Rothermel et al. 1994).

One particularly dangerous synoptic fire weather situation worth highlighting with respect to crown fire behavior is the case of the dry cold frontal passage (Schroeder and Buck 1970). In the Northern Hemisphere, winds ahead of an approaching dry cold front generally shift from the southeast to south, and finally to the southwest. As the cold front passes over an area, winds shift rapidly to the west, then northwest. Windspeeds increase in strength as a front approaches, and usually become quite strong and gusty when the front passes over an area. This can result in a long crown fire run in a north-northeast direction followed by a fire's entire right flank crowning in an east-southeast direction at an even greater rate of spread and intensity (DeCoste et al. 1968, Simard et al. 1983, Wade and Ward 1973).

Crown Fire Spotting Activity

Spotting or mass ember transport can be an important mechanism determining a crown fire's overall rate of spread under certain conditions. Its general effect on crown fire rate of spread is determined by the density of ignitions and distances these ignitions occur ahead of the main fire. These two characteristics are intimately linked, with density typically decreasing with distance from the main advancing flame front.

The effect of spotting on the overall spread and growth of a wildland fire is dependent on topography and fuel distribution. In certain fuel types, the propagation of active crown fires is linked to high-density, short-range spot fires occurring up to 50 m or so ahead of the main advancing flame front followed by their subsequent coalescence.

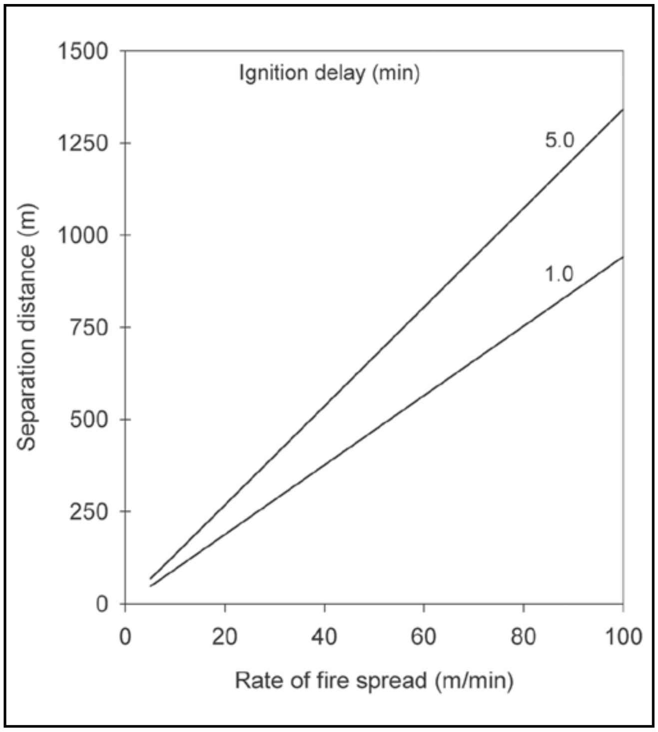

Figure 8-12—Minimum separation distance required for a newly ignited spot fire to avoid being overrun by the main flame front of an advancing crown fire as a function of rate of spread and ignition delay (adapted from Alexander and Cruz 2006). Ignition delay represents the elapsed time between a firebrand alighting, subsequent ignition, and the onset of fire spread.

Under such conditions, the overall fire spread is dictated by spotting as well as radiative and convective heat transfer mechanisms associated with the crowning phase (Taylor et al. 2004). In situations involving heterogeneous fuel type distributions and complex topography, spotting will allow the main advancing fire front to quickly bypass areas with low spread potential (e.g., downslope runs, pure hardwood stands in summer, discontinuous fuels) thereby effectively advancing the horizontal extent of the fire's "head." Spotting from crown fires is also effective in breaching major barriers to fire spread, including large water bodies and other nonfuel areas (e.g., rock slides, barren ground).

When fire environment conditions are uniform and winds aloft are favorable, spotting can contribute to the overall spread and growth of crown fires provided the spot fires are able to burn independently of the main advancing fire front. In most high-intensity wildfires that involve crowning, spot fires originating out ahead of the advancing flame front are typically overrun and thus incorporated into the larger fire perimeter before they are able to develop and spread independently, or otherwise be influenced by the main fire (e.g., in-draft winds). For a crown fire spreading at a rate of 50 m/min or 3 km/h and burning under homogeneous fuel, weather, and topographic conditions, spotting distances would, depending on the ignition delay, have to exceed approximately 500 to 700 m (fig. 8-12) to have the potential to increase a fire's overall rate of spread through a "leapfrog" type of effect. If there are sufficient spot fires at or just beyond this distance that can rapidly coalesce, this "mass ignition" effect will temporarily lead to the formation of pseudo flame fronts with greatly increased flame heights (Wade and Ward 1973).

Spotting distances of up to about 2 km are commonly observed on wind-driven crown fires in conifer forests, but spotting distances close to 5 km have been documented as well. Spot fire distances of 6 to 10 km were reported to have occurred in the Northern Rocky Mountains during the 1910 and 1934 fire seasons. The occurrence of spotting distances greater than 5 km require a specific combination of convection column strength and vertical wind profile. For a viable firebrand to travel such distances, a large amount of energy needs to be released (associated with the postfrontal combustion of large fuels) to transport the firebrands at significant heights. Spotting distances of this magnitude are likely to be associated with isolated peaks of fire intensity, such as those occurring in an upslope run, that will inject large quantities of firebrands in the plume. An atmospheric profile with very strong winds aloft is also necessary to considerably tilt the convection column and allow for significant drift of the firebrand after it leaves the plume. Under exceptional circumstances, spotting distances greater than 10 km have been described. Especially noteworthy is the 16- to 19-km spot fire distances associated with the 1967 Sundance Fire in northern Idaho (Anderson 1968), which were quite possibly caused by massive fire-induced vortices.

Table 8-2–Predicted fine dead fuel moisture content (FDFM) as a function of ambient air temperature and relative humidity assuming >50-percent shading between 1200–1600 hours during May–July

	Air temperature				
Relative humidity	**0 – 9**	**10 – 20**	**21 – 31**	**32 – 42**	**>43**
Percent	*Degrees Celsius*				
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 FDFM values are used in the Rothermel (1991) crown fire rate of spread model and in the Cruz et al. (2004, 2005) models for predicting crown fire occurrence and crown fire rate of spread. Adapted from Rothermel 1983.

Models, Systems, and Other Decision Aids for Predicting Crown Fire Behavior

Rothermel Guide to Predicting Size and Behavior of Crown Fires

Rothermel (1972) developed a model for predicting surface fire rate of spread and intensity that still forms the basis for the vast majority of guides and computerized decision supports for predicting fire behavior in use today in the United States. He 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 spread regimes were quite different. In the mid to late 1970s, the general guidance to gauging whether crowning was possible or not was to use the predicted surface fireline intensity or flame length (table 8-1). There was no method at that time for predicting the spread rate of crown fires, but by the early 1980s, the suggestion was being made to assume that crown fire rate of spread would be two to four times that of the predicted surface fire rate of spread of Anderson's (1982) Fire Behavior Fuel Model 10 (Rothermel 1983).

The 1988 fires in the Great Yellowstone Area are generally regarded as the impetus for developing a more robust method of predicting crown fire behavior in conifer forests (Alexander 2009), although such a general need had been recognized for many years (e.g., USDA FS 1980). Rothermel (1991) produced such a guide for the northern Rocky Mountains or mountainous areas with similar fuels and climate using currently available information, including the method of estimating fine dead fuel moisture content (table 8-2) given in Rothermel (1983). The core component of his method or approach was a simple correlation derived from eight wildfire observations of crown fire rate of spread and the corresponding predictions from his surface fire rate of spread model (i.e., a 3.34 multiplier as opposed to 2.0 to

4.0 as suggested earlier). Rothermel (1991) also included an adjustment factor (1.7) for estimating the near-maximum crown fire rate of spread associated with upslope runs or sudden surges in crown fire activity.

Rothermel (1991) emphasized that his statistical model for predicting the spread rate of wind-driven crown fires was a first approximation and that more research was needed to strengthen the analysis. At the time, he did not explicitly include any specific criteria for determining the onset of crowning other than in the most general terms (e.g., examine the fire weather forecast).

Rothermel (1991) considered his predictive methods were not applicable to plume-dominated crown fire. However, he did end up incorporating Byram's (1959b) ratio of the power of the fire versus power of the wind concepts (Nelson 1993) into his guide so as to distinguish the conditions favorable for plume-dominated crown fires as opposed to wind-driven crown fires. Neither Byram's (1959b) criteria nor Rothermel's (1991) adaptation of Byram's criteria have been evaluated for their robustness.

Rothermel's (1991) guide included a suggested method of predicting the flame lengths of crown fires. However, neither his suggestion nor the approach of others seems to work consistently well based on comparisons against data from experimental crown fires. Furthermore, his model for predicting the L:B of crown fires based on windspeed does not appear to produce realistic results in light of observational evidence (fig. 8-10).

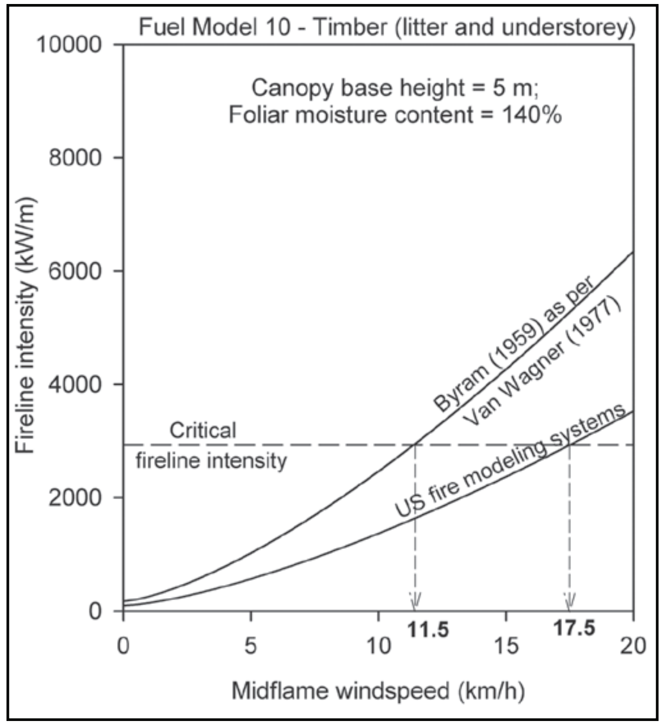

Figure 8-13—An example of the differences in the critical midflame windspeeds required for the onset of crowning resulting from the implementation of Van Wagner's (1977a) crown fire initiation model in various U.S. fire modeling systems for fuel models 2 and 10 as described by Anderson (1982) (adapted from Cruz and Alexander 2010). The following environmental conditions were held constant: slope steepness, 0 percent; fine dead fuel moisture, 4 percent; 10-h and 100-h time lag dead fuel moisture contents, 5 and 6 percent, respectively; live woody fuel moisture content, 75 percent; and live herbaceous fuel moisture content, 75 percent. The associated 6.1-m open winds would be a function of forest structure and can be approximated by multiplying the midflame windspeed by a factor ranging between 2.5 (open stand) and 6.0 (dense stand with high crown ratio) (Albini and Baughman 1979).

U.S. Fire Modeling Systems

Since the late 1990s, a number of existing and newly developed decision-support systems have either separately implemented or linked Rothermel's (1972, 1991) surface and crown rate of fire spread models with Van Wagner's (1977a, 1993) crown fire transition and propagation criteria. These include:

- BehavePlus (Andrews et al. 2008)
- FARSITE (Finney 2004)
- NEXUS (Scott and Reinhardt 2001)
- Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003)
- Fuel Management Analyst (FMA) Plus (Carlton 2005)
- FlamMap (Finney 2006)

To this list, we can also add two additional geographic information system-based decision-support systems, namely ArcFuels (Ager et al. 2011) and the Wildland Fire Decision Support System (WFDSS) (Pence and Zimmerman 2011).

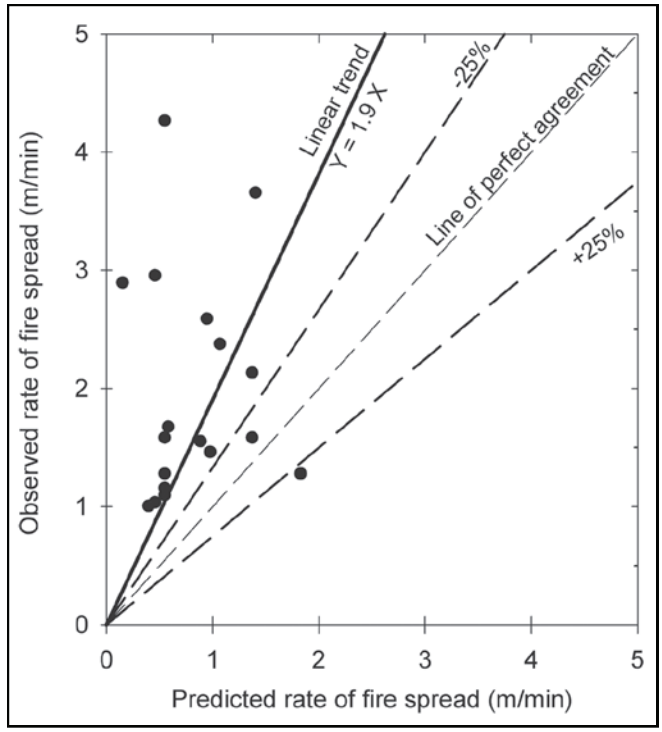

Figure 8-14—Observed head fire rates of spread >1.0 m/min associated with prescribed burning experiments in ponderosa pine forests of Yosemite National Park, California, versus predictions based on the Rothermel (1972) surface fire rate of spread model for fuel model 9-hardwood litter as described by Anderson (1982) (adapted from van Wagtendonk and Botti 1984). The dashed lines around the line of perfect agreement indicate the ± 25-percent error interval. Similar prediction trends were observed in mixed-conifer pine, mixed-conifer fir, and true fir forest fuel types.

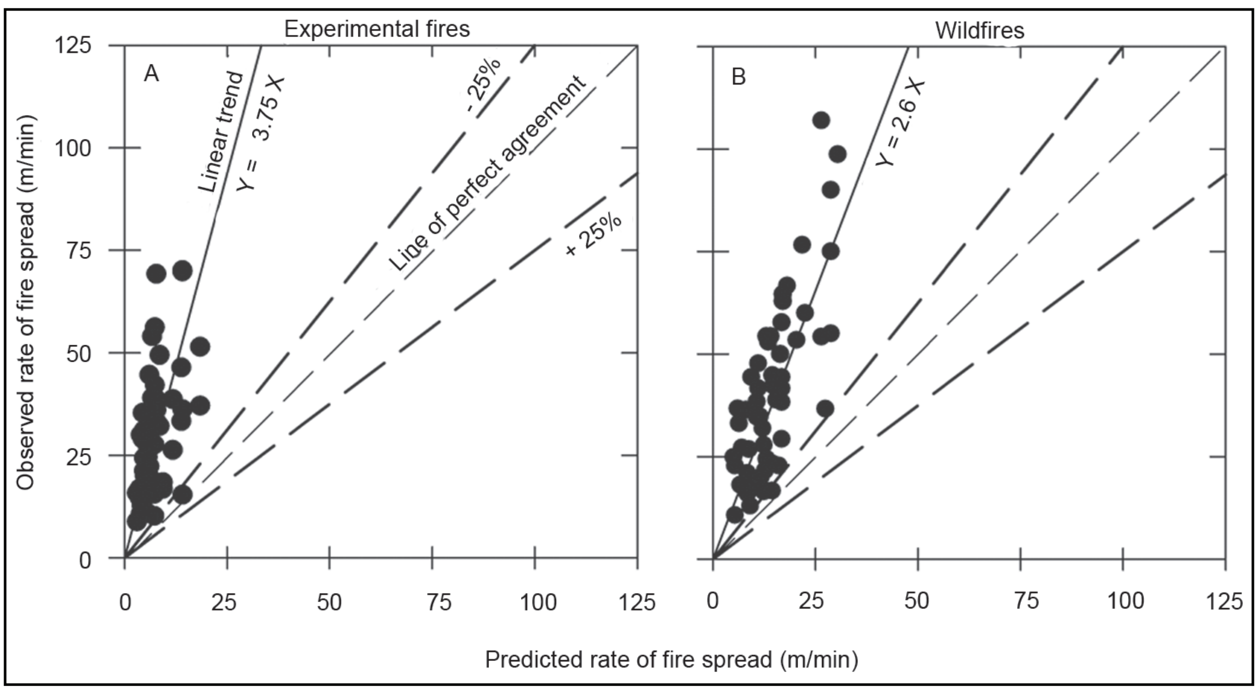

Figure 8-15–Observed rates of spread of experimental active crown fires and wildfires that exhibited extensive active crowning versus predictions based on Rothermel's (1991) crown fire rate of spread model (adapted from Cruz and Alexander 2010). The dashed lines around the line of perfect agreement indicate the ± 25-percent error interval.

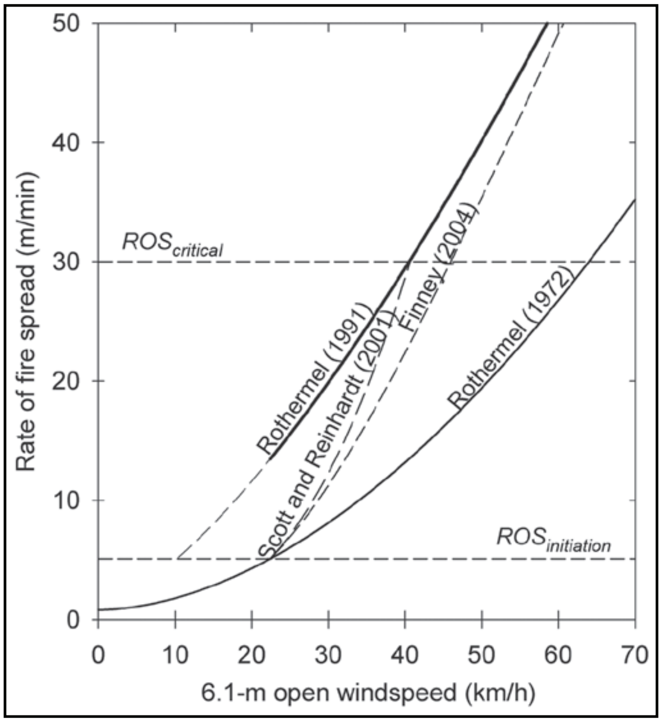

Figure 8-16–Comparison of the effect of crown fraction burned (CFB) functions on rate of fire spread developed by Scott and Reinhardt (2001) and Finney (2004) as used in various U.S. fire modeling systems (e.g., NEXUS, FFE-FVS, FARSITE, FlamMap) in relation to the Rothermel (1972, 1991) surface and crown fire rate of spread models and Van Wagner's (1977a) criteria for the critical minimum spread rates for crown fire initiation ($ROS_{initiation}$) and active crowning ($ROS_{critical}$) for the Anderson (1982) Fire Behavior Fuel Model 2–Timber (grass and understory) with a wind reduction factor of 0.2 (Albini and Baughman 1979), a canopy bulk density of 0.1 kg/m^3, and canopy base height of 1.5 m (adapted from Cruz and Alexander 2010). A CFB function is not employed in BehavePlus. The following environmental conditions were held constant: slope steepness, 0 percent; fine dead fuel moisture, 6 percent; 10-h and 100-h time lag dead fuel moisture contents, 7 and 8 percent, respectively; live woody fuel moisture content, 75 percent; live herbaceous fuel moisture content, 75 percent; and foliar moisture content, 140 percent. The dashed portion of the Rothermel (1991) curve represents output below the original data set bounds for rate of spread. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

These modeling systems are extensively used for fire operations, planning, and research. A recent review of the use of many of these fire modeling systems in several simulation studies examining fuel treatment effectiveness, revealed that many users are unaware of a significant underprediction bias that exists within these systems when it comes to assessing potential crown fire behavior in conifer forests of western North America (Cruz and Alexander 2010). The principal sources of this underprediction bias have been shown to include (i) incompatible model linkages (fig. 8-13), (ii) use of surface and crown fire rate of spread models that have inherent underprediction biases themselves (figs. 8-14 and 8-15), and (iii) a reduction in crown fire rate of spread based on the use of unsubstantiated crown fraction burned functions (fig. 8-16). The use of uncalibrated custom fuel models to represent surface fuelbeds was also identified as a fourth potential source of bias (Cruz and Fernandes 2008). The underprediction tendency was found to occur as well with the crown fire rate of spread model in the Fuel Characteristic Classification System (Schaaf et al. 2007). The Cruz and Alexander (2010) review also highlighted some issues with the manner in which users have been handling certain inputs in their crown fire modeling (i.e., foliar moisture content, canopy base height, and canopy bulk density) and in some perceived shortcomings of the two windspeed-based crown fire hazard indices developed by Scott and Reinhardt (2001).

Canadian Forest Fire Behavior Prediction System

Do alternative methods exist for predicting crown fire behavior? The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992, Taylor et al. 1997, Wotton et al. 2009) constitutes one such possibility, at least for certain regions of the United States possessing fuel complexes structurally similar to those found in adjacent areas of Canada. The FBP System is a module of the larger Canadian Forest Fire Danger Rating System (CFFDRS), which also includes the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). Some states have adopted all or part of the CFFDRS (e.g., Alaska, Minnesota, Michigan).

Table 8-3—Type of fire as a function of the Initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index (FWI) System for the coniferous (C) forest fuel types found in the Canadian Forest Fire Behavior Prediction System

Fuel type	Descriptive name	Surface fire	Passive crown fire	Active crown fire
C-1	Spruce-lichen woodland	<8	9 to 15	>16
C-2	Boreal spruce	<1	2 to 7	>8
C-3	Mature jack or lodgepole pine	<9	10 to 15	>16
C-4	Immature jack or lodgepole pine	<2	3 to 8	>9
C-5	Red and white pine	<25	26 to 40	>41
C-6	Conifer plantation	<8	9 to 17	>18
C-7	Ponderosa pine/Douglas-fir	<15	16 to 30	>31

The ISI is a relative numerical rating that combines the effects of fine fuel moisture (based on past and current weather conditions) and windspeed on the expected rate of fire spread. In the above tabulation, level terrain, a foliar moisture content of 97 percent, and a buildup index (BUI) of 81 to 120 is assumed. The BUI component of the FWI System is a relative numerical rating of the fuel available for combustion based on fuel dryness as determined by past and current weather conditions (Van Wagner 1987). In addition, a canopy base height of 7.0 m has been assigned to fuel type C-6. Adapted from Taylor et al. 1997.

The FBP System provides estimates of head fire spread rate, fuel consumption, fireline intensity, type of fire description (table 8-3), and with the aid of an elliptical fire growth model, it gives estimates of fire area, perimeter, and perimeter growth rate as well as flank and backfire behavior characteristics for 16 major fuel types, 11 of which are subject to crowning (i.e., 7 coniferous and 4 mixed-wood types). The FBP System includes functions for the acceleration in rate of fire spread for a point source ignition to a quasi-steady-state equilibrium (McAlpine and Wakimoto 1991), including a prediction of the elapsed time to crown fire initiation. Emphasis is placed on the influences of fire weather (i.e., fuel moisture and wind) on potential fire behavior for a given fuel type and the mechanical effects of slope steepness. The FBP System forms the basis for a major component of PROMETHEUS—the Canadian wildland fire growth simulation model (Tymstra et al. 2010), which is similar to FARSITE.

The FBP System is similar in many respects to predictive systems currently used in the United States. The principal difference is in the technical basis. The Rothermel (1972) surface fire model is based largely on laboratory fires and physical theory. The FBP System, on the other hand, is largely empirically based, representing the culmination of nearly 30 years of outdoor experimental burning work in major Canadian fuel types coupled with monitoring and documentation of numerous high-intensity wildfires.

Other Empirically Based Approaches

Another possibility in lieu of the Canadian FBP System is the suite of empirically based models for predicting fire behavior incorporated into the Crown Fire Initiation and Spread (CFIS) software system (Alexander et al. 2006). These models are based largely on a reanalysis of the experimental fires carried out as part of developing the Canadian FBP System. The main outputs of CFIS are:

- Likelihood of crown fire initiation or occurrence based on two distinct approaches, one of which relies on the CBH or certain components of the Canadian FWI System (Cruz et al. 2003b), whereas the other is determined by the fine dead fuel moisture (table 8-2), CBH, windspeed, and an estimate of surface fuel consumption (Cruz et al. 2004) (fig. 8-17).
- Type of crown fire (passive crown fire or active crown fire) and its associated rate of spread based on fine dead fuel moisture, CBD and windspeed (Cruz et al. 2005) (figs. 8-18 and 8-19).
- Minimum spotting distance required to increase a crown fire's overall forward rate of spread assuming a point ignition and subsequent fire acceleration to

Table 8-4—Beaufort scale for estimating 6.1-m open windspeeds

Wind class	Windspeed range	Description	Observed wind effects
	km/h		
1	<5	Very light	Smoke rises nearly vertically. Leaves of quaking aspen in constant motion; small branches of bushes sway; slender branchlets and twigs of trees move gently; tall grasses and weeds sway and bend with wind; wind vane barely moves.
2	6 to 11	Light	Trees of pole size in the open sway gently; wind felt distinctly on face; loose scraps of paper move; wind flutters small flag.
3	12 to 19	Gentle breeze	Trees of pole size in the open sway very noticeably; large branches of pole-size trees in the open toss; tops of trees in dense stands sway; wind extends small flag; a few crested waves from on lakes.
4	20 to 29	Moderate breeze	Trees of pole size in the open sway violently; whole trees in dense stands sway noticeably; dust is raised in the road.
5	30 to 39	Fresh	Branchlets are broken from trees; inconvenience is felt walking against wind.
6	40 to 50	Strong	Tree damage increases with occasional breaking of exposed tops and branches; progress impeded when walking against wind; light structural damage to buildings.
7	51 to 61	Moderate gale	Severe damage to tree tops; very difficult to walk into wind; significant structural damage occurs.
8	>62	Fresh gale	Surfaced strong Santa Ana; intense stress on all exposed objects, vegetation, buildings; canopy offers virtually no protection; windflow is systematic in disturbing everything in its path.

Adapted from Rothermel 1983.

an equilibrium rate of spread based on the presumed crown fire rate of spread and ignition delay (Alexander and Cruz 2006) (fig. 8-12).

The primary models incorporated into CFIS have been evaluated against both outdoor experimental fires and wildfire observations and shown to be reasonably reliable (e.g., Alexander and Cruz 2006, Cronan and Jandt 2008, Stocks et al. 2004). The CFIS does allow one to evaluate the impacts of proposed fuel treatments on potential crown fire behavior based on the ability to manipulate three characteristics of a forest fuel complex (i.e., available surface fuel load, CBH and CBD) using silvicultural techniques.

The CFIS system is considered most applicable to free-burning fires that have reached a pseudo steady state, burning in live, boreal, or near-boreal type conifer forests found in western and northern North America (i.e., they are not applicable to insect-killed or otherwise "dead" stands). Furthermore, the models underlying CFIS are not applicable to prescribed fire or wildfire situations that involve strong convection activity as a result of the ignition pattern. Level terrain is assumed, as the CFIS does not presently consider the mechanical effects of slope steepness on crown fire behavior, although this is being planned for in a future version of the system.

Physically Based Models

Physically based models are formulated on the basis of the chemistry and physics of combustion and heat transfer processes involved in a wildland fire. They range in complexity from models for calculating rate of fire spread based solely on the radiation from the flaming front (e.g., Albini 1996) to three-dimensional models coupling fire and atmospheric processes. Examples of the latter include FIRETEC (Linn et al. 2002), FIRESTAR (Dupuy and Morvan 2005), and Wildland Fire Dynamics Simulator (WFDS) (Mell et al.

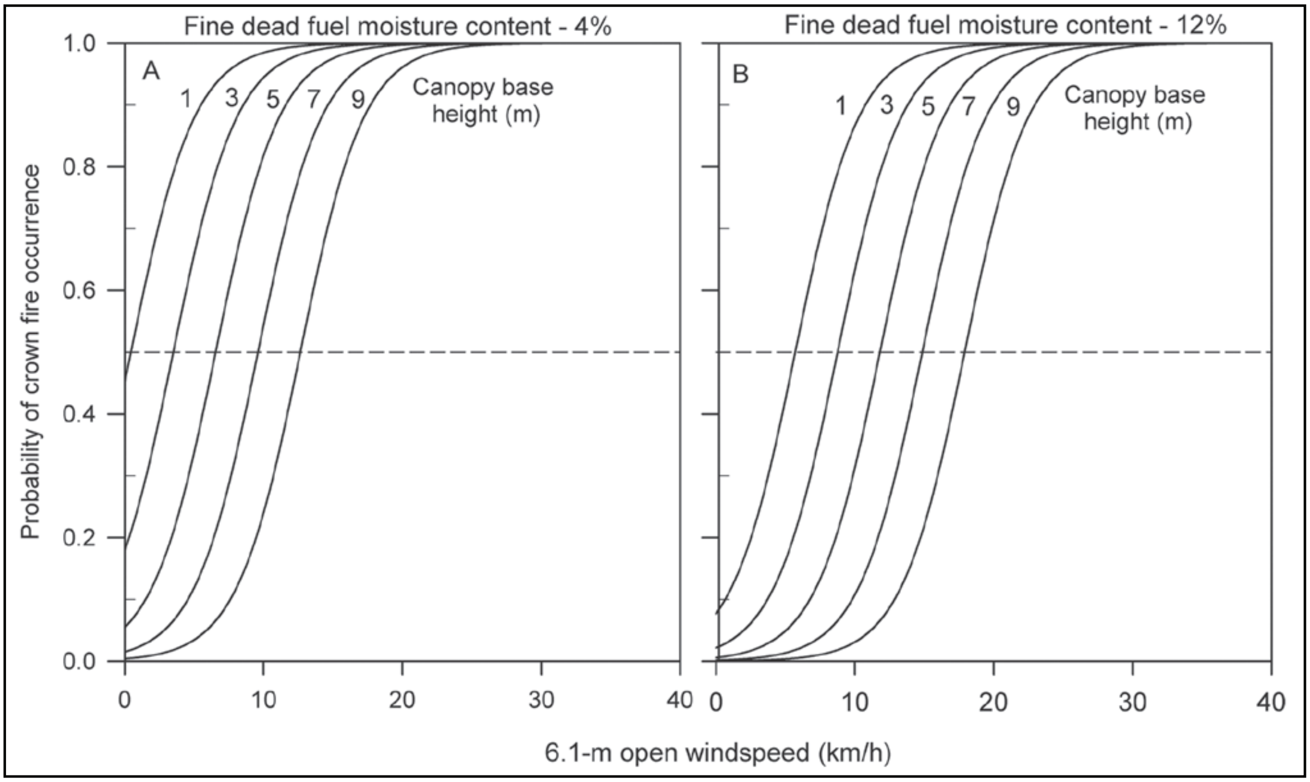

Figure 8-17—The likelihood of crown fire occurrence as a function of canopy base height and windspeed for two fine dead fuel moisture levels, assuming a surface fuel consumption of 1.0 to 2.0 kg/m^2, based on the Cruz et al. (2004) probability model. The horizontal dashed line in each graph represents the approximate threshold value for the onset of crowning. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

2007). Physically based models hold great promise in being able to advance our theoretical understanding of wildland fire dynamics and could possibly be used for operational prediction of wildand fire behavior in the future (Sullivan 2009b). By their completeness, these models should be able to predict the development, the demise or cessation, spread rate, fuel consumption, intensity, and flame dimensions of crown fires in relation to any combination of fuel, weather, and topographic variables. In recent years, these models have been extensively used as research tools to evaluate the effect of canopy fuel structure on crown fire dynamics. Such modelling efforts could possibly allow one to investigate the effect of fuel treatments on crown fire potential. Nonetheless, the capacity of these models to describe crown fire behavior is still open to question given that no evaluation against any empirical crown fire data set has been undertaken to date to our knowledge.

What is quite likely to happen is the continuing mergence of empirical and physically based approaches (Sullivan 2009b, Van Wagner 1985). An example of such an approach is the semiphysically based crown fuel ignition model (CFIM) developed by Cruz et al. (2006b) to predict the onset of crowning based on fundamental heat transfer principles. A series of submodels that take into account surface fire characteristics along with canopy fuel properties are used to predict the ignition temperature of canopy fuels above a spreading surface fire. An evaluation of CFIM has been undertaken involving a sensitivity analysis of input parameters, comparison against other similar models under different burning conditions, and testing against outdoor experimental fires (Cruz et al. 2006a). Results have been favorable and provided new insights into the factors controlling the initiation of crown fires.

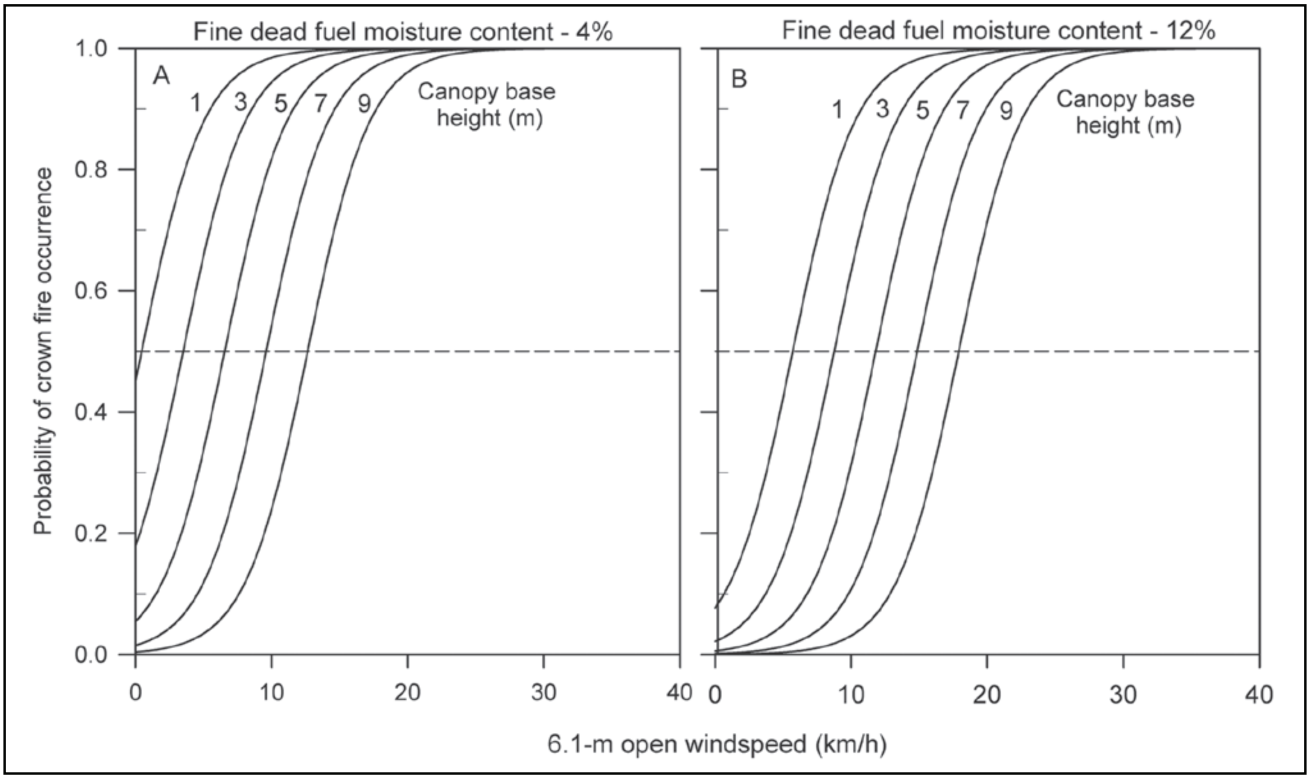

Figure 8-18–Threshold conditions for passive versus active crown fire spread in terms of windspeed and fine dead fuel moisture for two canopy bulk density levels based on the Cruz et al. (2005) crown fire rate of spread models and Van Wagner's (1977a) criteria for active crowning. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

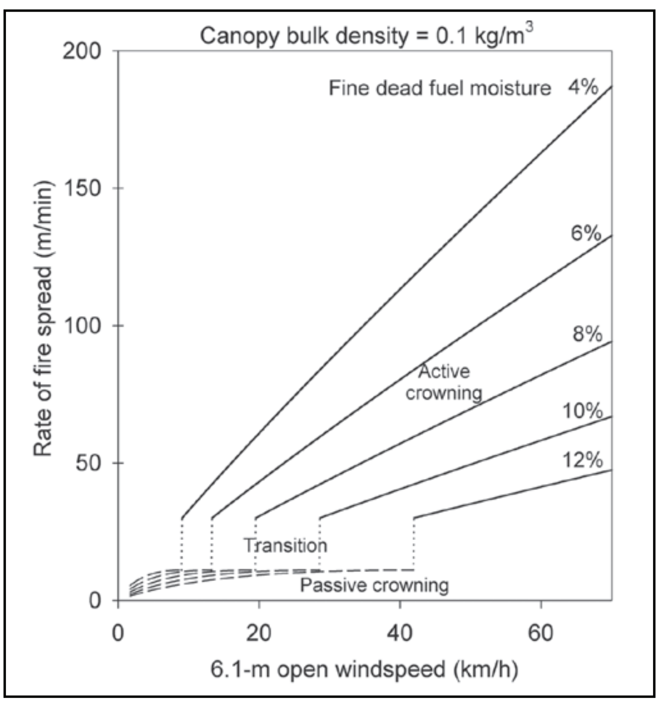

Figure 8-19—Passive and active crown fire spread rates as a function of windspeed and fine dead fuel moisture for a canopy bulk density of 0.1 kg/m^3 based on the Cruz et al. (2005) crown fire rate of spread models. The vertical "kinks" in the fine dead fuel moisture curves are considered to represent the windspeed thresholds between passive and active crowning. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

Another example of the merging of empirical and physical modelling approaches was the International Crown Fire Modeling Experiment (ICFME). One of the objectives of this experimental burning program carried out in the Northwest Territories of Canada from 1995 to 2001 (Alexander 2005) was to test a newly developed, deterministic physical model for predicting crown fire rate of spread (Albini 1996, Butler et al. 2004). Measurements of flame radiometric properties and temperatures allowed for the parameterizing of the heat transfer components in Albini's (1996) crown fire rate of spread model. Model evaluation indicated that the model predicted the relative response of fire spread rate to fuel and environmental variables, but it consistently overpredicted the magnitude of the spread rates observed on the ICFME crown fires.

Not all physically based models for predicting wildland fire spread specifically take into account the effects of spotting in increasing a fire's rate of spread. The effects of spotting on a fire's overall rate of advance are implicitly accounted for in both the FBP System and the Rothermel (1991) crown fire rate of spread model as a result of the empirical nature of their development (i.e., the use of wildfire observations as a data source). This assumes, however, that the fuels are continuous. Neither approach indicates how barriers to fire spread are to be handled. Short-range spotting from a crown fire is presumably able to easily breach fuel discontinuities of up to 100 m in width (Stocks et al. 2004, Taylor et al. 2004). Nominal spotting from crown fires is undoubtedly capable of breaching even much wider barriers, perhaps up to 1000 m (Alexander et al. 2004). What is unknown, however, is how much of a reduction there will be in the head fire rate of spread as a result of the time delay involved (which might possibly be 30 to 60 min or longer) for the fire to resume its forward, equilibrium rate of advance.

Albini (1979) developed a physically based model for predicting the maximum spotting distance from single or group tree torching that covers the case of intermediate-range spotting of up to perhaps 3.0 km. This model is included within the BehavePlus modeling system, and a manual procedure is given in Rothermel (1983). Rothermel (1991) pointed out at the time he prepared his guide that no model existed for predicting the spotting distances for running or active crown fires. Venkatesh et al. (2000) subsequently extended Albini's (1979) model to the case of wind-driven crown fires. The result was a 20- to 25-percent increase in spotting distance. However, no testing of this model has been undertaken to date to our knowledge. The Venkatesh et al. (2000) model like the one developed by Albini (1979) provides a prediction of the firebrand transport distance. Determining whether a given ember or firebrand will actually cause a spot fire must still be assessed based on its ignition probability (e.g., Rothermel 1983).

More recently, an alternative predictive system has been put forth for estimating the maximum spotting distance from active crown fires as a function of the firebrand particle diameter at alighting based on three inputs, namely, canopy top height, free flame height (i.e., flame distance above the canopy top height), and the windspeed at the height of the canopy.[2] Although the system has not been specifically validated, the estimates produced by the system appear realistic in light of existing documented observations.

Example of a Practical Application of Linking Empirical and Physically Based Models

Pine Plantation Pyrometrics (PPPY) is a new modeling system developed to predict fire behavior in industrial pine plantations over the full range of burning conditions in relation to proposed changes in fuel complex structure from fuel treatments (Cruz et al. 2008). The system comprises a series of submodels, including CFIM and elements of CFIS, that describe surface fire characteristics and crown fire potential in relation to the surface and crown fuel structures, fuel moisture contents, and windspeed (fig. 8-20). A case study application of the PPPY modeling system has highlighted the complex interactions associated with fuel

[2] **Albini, F.A.**; **Alexander, M.E.**; **Cruz, M.G.** Preciding the maximum potential spotting distance from an active crown fire. Under review.

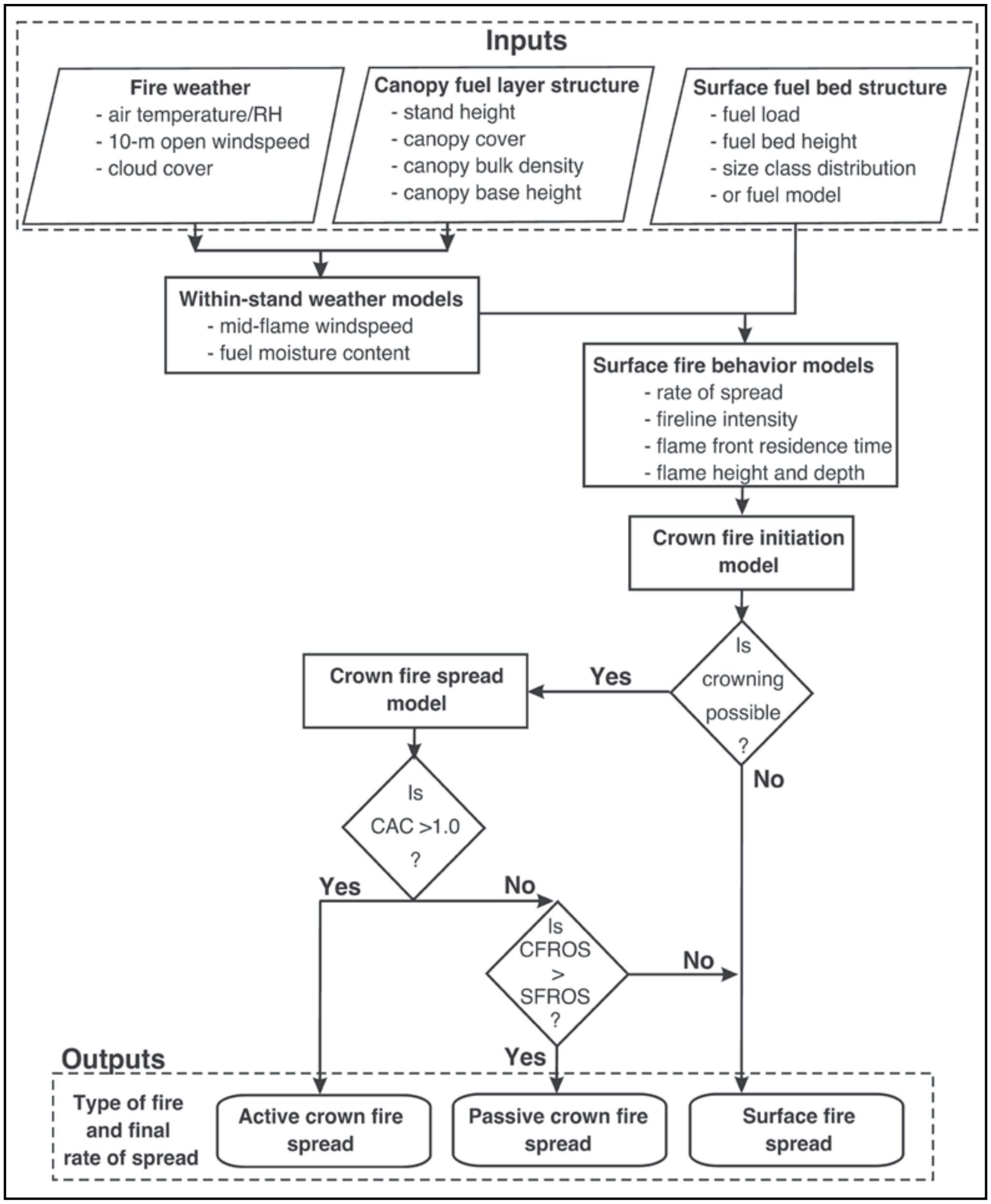

Figure 8-20—Flow diagram of the Pine Plantation Pyrometrics modeling system for predicting fire behavior in exotic pine plantations (adapted from Cruz et al. 2008). CAC is the criteria for active crowning (Van Wagner (1977a), CFROS is the crown fire rate of spread, and SFROS is the surface fire rate of spread.

treatments such as pruning and thinning have on surface and crown fire behavior potential (fig. 8-21). It is also noteworthy that no definite reduction or increase in rate of spread was identified. Although a direct evaluation of the system's overall performance has yet to be undertaken, its main components have been evaluated against independent data sets.

Implications for Fire and Fuel Management

In the broadest sense, the general conditions favorable for the development of crowning in conifer forests have

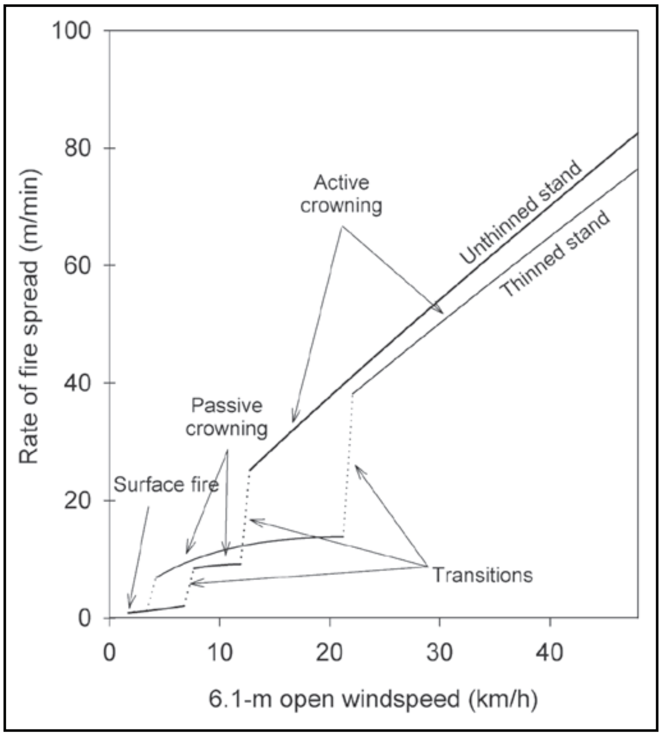

Figure 8-21—Head fire rate of spread as a function of windspeed for 12-year-old thinned (50 percent basal area reduction treatment) and unthinned pine plantation stands based on the Pine Plantation Pyrometrics (PPPY) modeling system (adapted from Cruz et al. 2008). The fuel complex characteristics for the thinned and unthinned stands were, respectively, surface fuel available for combustion, 1.1 and 0.5 kg/m^2; canopy base height, 1.7 and 0.9 m; and canopy bulk density, 0.05 and 0.1 kg/m^3. Given an air temperature of 40 °C and a relative humidity of 20 percent, the fine dead fuel moistures for the surface litter were, in turn, judged to be 5 and 7 percent, respectively. Foliar moisture content was set at 100 percent in both cases, and level terrain was assumed. The Beaufort scale for estimating 6.1-m open windspeeds is presented in table 8-4.

been known for some time and also apply to nonforested fuel types as well that exhibit high rates of fire spread and fireline intensities or very long flame lengths (e.g., Butler and Reynolds 1997). These include:

- Continuous fine fuels in sufficient quantity and arrangement, both vertically and horizontally.
- A dry spell of sufficient length to reduce the moisture content of dead fuels to a uniformly low level coupled with high ambient air temperatures and low relative humidity.
- Strong prevailing winds or steep slopes.

In the past 25 years or so, these conditions have, in turn, been crudely codified in various forms suitable for use by field personnel. Other aspects of the fire environment may lead to an increase in crown fire potential but by themselves are not a major predisposing factor (e.g., low foliar moisture content, high foliar heat content, presence of flammable oils and resins in the needle foliage).

Assuming a threshold level in dryness has been reached in the forest floor layer, the potential for crown fire development and spread would generally follow the daily diurnal cycle in fire weather conditions, typically peaking in late afternoon (Beck et al. 2002). However, crown fire activity can extend late into the day if fire weather conditions are favorable for maintaining the moisture content of fine, dead surface fuels at low levels (Hartford and Rothermel 1991).

Rothermel (1991) quite rightly pointed out that "Fires are seldom uniform and well behaved." Given the chaotic nature of most extreme fire phenomena, can we expect the behavior of crown fires to ever really be truly predictable? That depends on how accurate you expect the prediction to be. Certainly the minute-by-minute movement of a crown fire will probably never be predictable. However, in looking at crown fire propagation across longer timeframes, for example (e.g., 30 min to several hours), the available data have shown that some models are very capable of predicting fire spread within a margin of error that is useful to fire managers. Nevertheless, given the coarseness and uncertainty associated with the inputs in the crown fire initiation and propagation models, managers should be wary of their use for near-real-time predictions of fire behavior. Underestimating the potential for the onset of crowning under conditions that would sustain active crown fire propagation can, in turn, lead to substantial underpredictions in crown fire rate of spread and fireline intensity.

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 data range used in their development (Sullivan 2009a). Overestimates of fire behavior can easily be readjusted

Box 3:

Useful Links to Further Information

U.S. Fire Modeling Systems

- http://www.firemodels.org/

Canadian Forest Fire Danger Rating Systems

- http://frames.nbii.gov/cffdrs
- http://cwfis.cfs.nrcan.gc.ca/en_CA/background/summary/fdr

Crown Fire Initiation and Spread System

- http://frames.nbii.gov/cfis

International Crown Fire Modeling Experiment

- http://frames.nbii.gov/icfme
- http://www.youtube.com/watch?v=FYup7cYKE3w
- http://www.youtube.com/watch?v=zvPa_yEEd4E

Joint Fire Science Program Crown Fire Synthesis Project

- http://www.fs.fed.us/wwetac/projects/alexander.html
- http://www.myfirecommunity.net/Neighborhood.aspx?ID=816

Box 4:

Crown Fire Dynamics in Conifer Forests—A Summary of the Salient Points

Types of Crown Fires

Three kinds or classes of crown fire are recognized according to their degree of dependence on the surface phase of fire spread (i.e., passive, active, and independent, although the latter is generally regarded as a rare and short-lived occurrence).

Crown Fire Initiation

The amount of heat energy required in the form of convection and radiation to induce the onset of crowning is dictated by the canopy base height and foliar moisture content as manifested in the surface fire's intensity. A rather abrupt increase in fire activity should be expected as a fire transitions from the surface to crown fire phase.

Crown Fire Propagation

Whether a passive or active crown fire develops following the onset of crowning depends on the spread rate after initial crown combustion and is, in turn, related to canopy bulk density. A minimum value of about 0.1 kg/m^3 appears to represent a critical threshold for active crowning.

Box 4: continued

Crown Fire Rate of Spread

At a minimum, a doubling or tripling in a fire's rate of advance follows the onset of crowning. Wind-driven crown fires have been documented to spread at up to 100 m/min for several hours and in excess of 200 m/min for up to an hour. Although the mechanical effect of slope steepness on increasing a fire's rate of spread is well known, fires in mountainous terrain generally do not spread nearly as far for a given period of time compared to those on flat topography.

Crown Fire Intensity and Flame Zone Characteristics

As a result of the increase in spread rate and fuel available for combustion, a fire can easily quadruple its intensity in a matter of seconds when crowning takes place (e.g., from 3000 kW/m to 12 000 kW/m). The resulting wall of flame, standing nearly erect, is on average up to two to three times the tree height and emits fierce radiation. Flame fronts commonly exceed 30 to 45 m in depth.

Crown Fire Area and Perimeter Growth

The area burned by a crown fire is at least four to nine times that of a surface fire for the same period.

Box 4: continued

Assuming unlimited horizontal fuel continuity, crown fires are capable of burning an area of up to 70 000 ha with a perimeter length of 160 km in a single burning period and have done so in the past.

Crown Fire Spotting Activity

Crown fires commonly display high-density, short-range spotting (<50 m). Spotting distances of up to about 2.0 km, although less common, are frequently seen on crown fires, resulting in normal barriers to fire spread being breached. Many spot fires are simply overrun by the main advancing flame front of a crown fire before they effectively contribute to an increase in the fire's overall rate of advance. Cases of long-distance spotting in excess of 10 km have been reported.

Models, Systems, and Other Decision Aids for Predicting Crown Fire Behavior

The current set of guides and decision-support system for assessing potential crown fire behavior used in the United States are considered deficient in the absence of considerable adjustment on the part of trained and informed users (e.g., fire behavior analysts, long-term fire analysts). Alternative models and systems that have undergone far more

Box 4: continued

extensive testing and requiring a minimum of inputs are available.

Implications for Fire and Fuel Management

Operational fire management personnel can readily help themselves when it comes to being able to assess crown fire behavior by engaging in a more rigorous program of wildfire monitoring and case study documentation than has been undertaken to date.

without serious consequences. However, underestimates can be potentially disastrous (Cheney 1981). In this regard, the underprediction trend in predictions of crown fire behavior evident in the existing fire modeling systems used in the United States is of concern on a number of fronts. For example, if a system predicts or simulates that a fire will behave as a moderate-intensity surface fire under extreme fire weather conditions, why would it be necessary to undertake any form of fuel treatment or even be concerned about the general flammability of an area? As for human safety, if people are led to believe that some stand structures will not support crowning under a given set of weather conditions—but in actual fact they will—are they not putting themselves and others in grave danger?

It has been suggested that most wildland fire operations personnel base their expectations of how a fire will behave largely on experience and, to a lesser extent, on guides to forecasting fire behavior (Burrows 1984). Experienced judgement is certainly needed in any assessment of wildland fire potential, but it does have some limitations (Gisborne 1948). The same can be said for mathematical models and computerized decision-support systems. Given the present realities, practical knowledge and sound professional judgment coupled with experience is still needed and perhaps should take on an even more prominent role when it comes to adjusting, interpreting, and applying crown fire behavior predictions. Predicting wildland fire behavior is, after all, both an "art and a science."

Wildland fire research has done much to contribute to our current understanding of crown fire behavior through laboratory experiments, outdoor experimental burning, numerical modeling, and wildfire case histories (box 3). Although operational fire behavior specialists have also made substantial contributions (e.g., Beighley and Bishop 1990, Murphy et al. 2007), valuable information and insights are not being captured in a systematic way. The continuance of basic research into fire fundamentals is essential to gaining a complete understanding of crown fire behavior, but scientific knowledge alone will not be enough to develop a complete picture of crown fire dynamics. There is still an overriding need to bolster the efforts in observing crown fire behavior and completing the necessary case study documentation in order to evaluate new and existing predictive models of crown fire behavior. Such a program should be regarded as a shared responsibility between wildland fire research and fire management and be considered part of adaptive management (Alexander and Taylor 2010).

Future Outlook

In discussing his dichotomous key for appraising crowning potential, Fahnestock (1970) indicated that "No technique is available for calculating the mathematical probability that a fire will crown under given conditions." In turn, Kerr et al. (1971) considered that "In the foreseeable future there is little prospect of predicting the behavior of a fast spreading crown fire in timber over any extended period of time." More recently, Agee (1993) stated, "The chances of firebrand spotting and crown fires can be estimated, but the behavior of crown fire is still relatively unpredictable." In light of these comments, obviously much has been accomplished and experienced in the past 20 to 40 years when viewed from the point of our current understanding and predictive capability with respect to crown fires (box 4).

Presumably, the future holds the same promise as the recent past provided we are willing to readily admit what we know and, more importantly, what we presumably still do not know about crown fires with respect to their environment, characteristics, and prediction. Several knowledge gaps have been alluded to throughout this summary. Furthermore, a good many basic wildland fire behavior research needs identified over 25 years ago, some of which are relevant to crown fires, have yet to be addressed (Albini 1984). Research must be directed at both the operational products desired by fire and fuel managers, and the fundamental understanding that forms the basis for such end-user tools (Cohen 1990).

Further discoveries and advancements in understanding of crown fire dynamics in conifer forests will require a dedication in time, money, and staff (Blatchford 1972). In actual fact, new research into the complexities of crown fire phenomenology has already been initiated (e.g., Cruz and Alexander 2009). However, in the long run, scientific investigations into crown fire behavior might be best accomplished in the form of a collaborative, international research, development, and application effort (Christensen et al. 2007, Weber 1995). Networked, multidisciplinary teams that can build on extant understanding while creating new knowledge regarding the mechanisms associated with crown fire initiation and spread may provide the necessary platform.

Literature Cited

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Agee, J.K. 1996. The influence of forest structure on fire behavior. In: Sherlock, J., ed. Proceedings of the 17^{th} annual forest vegetation management conference. Redding, CA: Forest Vegetation Management Conference: 52–57.

Ager, A.A.; Vaillant, N.M.; Anderson, J.; Miller, L. 2011. ArcFuels user guide: for use with ArcGIS 9.X. Prineville, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Western Wildland Environmental Threat Assessment Center. 256 p. http://www.fs.fed.us/wwetac/arcfuels/downloads/ArcFuels_UserGuide.pdf. (3 February 2011).

Albini, F.A. 1979. Spot fire distance from burning trees—a predictive model. Gen. Tech. Rep. INT-56. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 73 p.

Albini, F.A. 1984. Wildland fires. American Scientist. 72: 590–597.

Albini, F.A. 1993. Dynamics and modelling of vegetation fires: observations. In: Crutzen, P.J.; Goldammer, J.G., eds. Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. Environ. Sci. Res. Rep. 13. Chichester, England: John Wiley & Sons: 39–52.

Albini, F.A. 1996. Iterative solution of the radiation transport equations governing spread of fire in wildland fuel. Combustion, Explosion, and Shock Waves. 32: 534–543.

Albini, F.A.; Baughman, R.G. 1979. Estimating windspeeds for predicting wildland fire behavior. Res. Pap. INT-221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Albini, F.A.; Stocks, B.J. 1986. Predicted and observed rates of spread of crown fire in immature jack pine. Combustion Science and Technology. 48: 65–76.

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany. 60: 349–357.

Alexander, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. In: Donoghue, L.R.; Martin, R.E., eds. Proceedings of eighth conference on fire and forest meteorology. SAF Publ. 85-04. Bethesda, MD: Society of American Foresters: 287–304.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. In: Fischer, W.C.; Arno, S.F., comps. Proceedings of symposium and workshop on protecting people and homes from wildfire in the interior West. Gen. Tech. Rep. INT-251. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 147–156.

Alexander, M.E. 1998. Crown fire thresholds in exotic pine plantations of Australasia. Canberra, ACT: Australian National University. 228 p. Ph.D. thesis.

Alexander, M.E. 2005. Long-term experiment takes some of the mystery out of crown fires. Fire Management Today. 65(3): 36–37.

Alexander, M.E. 2009. The 1988 fires of Yellowstone and beyond as a wildland fire behavior case study. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Wildland Fire Lessons Learned Center. 30 p. www.wildfirelessons.net/documents/Alexander_Yellowstone88_FB.pdf. (3 February 2010).

Alexander, M.E.; Cruz, M.G. 2006. Evaluating a model for predicting active crown fire rate of spread using wildfire observations. Canadian Journal of Forest Research. 36: 3015–3028.

Alexander, M.E.; Cruz, M.G.; Lopes, A.M.G. 2006. CFIS: a software tool for simulating crown fire initiation and spread. In: Viegas, D.X., ed. Proceedings of 5th international conference on forest fire research. [CD-ROM]. Amsterdam, The Netherlands: Elsevier BV. 13 p.

Alexander, M.E.; De Groot, W.J. 1988. Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. [Poster with text.] Edmonton, AB: Government of Canada, Canadian Forestry Service, Northern Forestry Centre.

Alexander, M.E.; Lanoville, R.A. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. [Poster with text.] Edmonton, AB and Fort Smith, NT: Forestry Canada, Northern Forestry Centre and Government of Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre.

Alexander, M.E.; Taylor, S.W. 2010. Wildland fire behavior case studies and the 1938 Honey Fire controversy. Fire Management Today. 70(1): 15–25.

Alexander, M.E.; Tymstra, C.; Frederick, K.W. 2004. Incorporating breaching and spotting considerations into PROMETHEUS—the Canadian wildland fire growth model. Chisholm/Dogrib Fire Res. Initiative Quicknote 6. Hinton, AB: Foothills Model Forest. 2 p.

Anderson, H.E. 1968. Sundance Fire: an analysis of fire phenomena. Res. Pap. INT-56. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 39 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Anderson, H.E. 1983. Predicting wind-driven wild land fire size and shape. Res. Pap. INT-305. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 26 p.

Andrews, P.L.; Bevins, C.D.; Seli, R.C. 2008. BehavePlus fire modeling system, version 4.0: user's guide. Gen. Tech. Rep. RMRS-GTR-106WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 116 p.

Beck, J.A.; Alexander, M.E.; Harvey, S.D.; Beaver, A.K. 2002. Forecasting diurnal variation in fire intensity to enhance wildland firefighter safety. International Journal of Wildland Fire. 11: 173–182.

Beighley, M.; Bishop, J. 1990. Fire behavior in high-elevation timber. Fire Management Notes: 51(2): 23–28. [Republished in 2003 as: Fire Management Today. 63(4): 56–62.]

Blatchford, A.N. 1972. Dissemination and application of research information in the field. Res. Develop. Pap. 88. London, England: Forestry Commission. 5 p.

Brown, A.A.; Davis, K.P. 1973. Forest fire: control and use. 2nd ed. New York, NY: McGraw-Hill. 686 p.

Bruner, A.D.; Klebenow, D.A. 1979. Predicting success of prescribed fire in pinyon-juniper woodland in Nevada. Res. Pap. INT-219. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Burgan, R.E. 1979. Fire danger/fire behavior computations with the Texas Instruments TI-59 calculator: user's manual. Gen. Tech. Rep. INT-61. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 25 p.

Burrows, N.D. 1984. Predicting blow-up fires in the jarrah forest. Tech. Pap. No. 12. Perth, Western Australia: Forests Department of Western Australia. 27 p.

Butler, B.W.; Bartlette, R.A.; Bradshaw, L.S.; Cohen, J.D.; Andrews, P.L.; Putnam, T.; Mangan, R.J. 1998. Fire behavior associated with the 1994 South Canyon Fire on Storm King Mountain, Colorado. Res. Pap. RMRS-RP-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 82 p.

Butler, B.W.; Finney, M.A.; Andrews, P.; Albini, F.A. 2004. A radiation-driven model of crown fire spread. Canadian Journal of Forest Research. 34: 1588–1599.

Butler, B.W.; Reynolds, T.D. 1997. Wildfire case study: Butte City Fire, southeastern Idaho, July 1, 1994. Gen. Tech. Rep. INT-GTR-351. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 15 p.

Byram, G.M. 1954. Atmospheric conditions related to blowup fires. Stn. Pap. No. 35. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 34 p.

Byram, G.M. 1959a. Combustion of forest fuels. In: Davis, K.P., ed. Forest fire: control and use. New York: McGraw-Hill: 61–89.

Byram, G.M. 1959b. Forest fire behavior. In: Davis, K.P., ed. Forest fire: control and use. New York: McGraw-Hill: 90–123.

Carlton, D. 2005. Fuels Management Analyst Plus software, version 3. Estacada, OR: Fire Program Solutions LLC. http://www.fireps.com/fmanalyst3/index.htm. (8 November 2009).

Cheney, N.P. 1981. Fire behaviour. In: Gill, A.M.; Groves, R.H.; Noble, I.R., eds. Fire and the Australian biota. Canberra, ACT: Australian Academy of Science: 151–175.

Cheney, P.; Sullivan, A. 2008. Grassfires: fuel, weather and fire behaviour. Collingwood, South Australia: CSIRO Publishing. 150 p.

Christensen, N.L. (chair); Alexander, M.E.; Benson, N.C.; Brown, T.J.; Cortner, H.J.; Omi, P.N.; Schmidt, R.G.; Shlisky, A.; Swallow, S.K. 2007. U.S. Forest Service R&D wildland fire external peer review. Report submitted to USDA Forest Service Research and Development, Washington, DC. 25 p.

Cohen, J.D. 1990. Research has part of the answer. In: Are forests the answer? Proceedings of the 1990 Society of American Foresters National Convention. SAF Publ. 90-02. Bethesda, MD: Society of American Foresters: 117–120.

Cronan, J.; Jandt, R. 2008. How succession affects fire behavior in boreal black spruce forest of interior Alaska. BLM-Alaska Tech. Rep. 59. Anchorage, AK: U.S. Department of the Interior, Bureau of Land Management, Alaska State Office. 15 p.

Cruz, M.G.; Alexander, M.E. 2009. Assessing discontinuous fire behaviour and uncertainty associated with the onset of crowning [extended abstract]. In: Masters, R.E.; Galley, K.E.M.; Despain, D.G., eds. The '88 Fires: Yellowstone and beyond. Tall Timbers Misc. Publ. No. 16. Tallahassee, FL: Tall Timbers Research Station: 20.

Cruz, M.G.; Alexander, M.E. 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. International Journal of Wildland Fire. 19: 377–398.

Cruz, M.G.; Alexander, M.E. [In press]. Evaluating regression model estimates of canopy fuel stratum characteristics in four crown fire prone fuel types in western North America. International Journal of Wildland Fire.

Cruz, M.G.; Alexander, M.E.; Fernandes, P.A.M. 2008. Development of a model system to predict wildfire behaviour in pine plantations. Australian Forestry. 70: 113–121.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003a. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. International Journal of Wildland Fire. 12: 39–50.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003b. Assessing the probability of crown fire initiation based on fire danger indices. Forestry Chronicle. 79: 976–983.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003c. Definition of a fire behavior model evaluation protocol: a case study application to crown fire behavior models. In: Omi, P.N.; Joyce, L.A., tech. eds. Fire, fuel treatments and ecological restoration: conference proceedings. Proc. RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 49–67.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. Forest Science. 50: 640–658.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research. 35: 1626–1639.

Cruz, M.G.; Butler, B.W.; Alexander, M.E. 2006a. Predicting the ignition of crown fuels above a spreading surface fire. Part II: Model behavior and evaluation. International Journal of Wildland Fire. 15: 61–72.

Cruz, M.G.; Butler, B.W.; Alexander, M.E.; Forthofer, J.M.; Wakimoto, R.H. 2006b. Predicting the ignition of crown fuels above a spreading surface fire. Part I: Model idealization. International Journal of Wildland Fire. 15: 47–60.

Cruz, M.G.; Fernandes, P.M. 2008. Development of fuel models for fire behaviour in maritime pine (*Pinus pinaster* Ait.) stands. International Journal of Wildland Fire. 17: 194–204.

DeCoste, J.H.; Wade, D.D.; Deeming, J.E. 1968. The Gaston Fire. Res. Pap. SE-43. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 36 p.

Dupuy, J.L.; Morvan, D. 2005. Numerical study of a crown fire spreading toward a fuel break using a multiphase physical model. International Journal of Wildland Fire. 14: 141–151.

Fahnestock, G.R. 1970. Two keys for appraising forest fire fuels. Res. Pap. PNW-99. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 26 p.

Finney, M.A. 2004. FARSITE: Fire area simulator—model development and evaluation. Res. Pap. RMRS-RP-4 Revised. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M.A. 2006. An overview of FlamMap fire modelling capabilities. In: Andrews, P.L.; Butler, B.W., comps. Fuels management—how to measure success: conference proceedings. Proc. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213–220.

Folweiler, A.D. 1937. Theory and practice of forest fire protection in the United States. St. Louis, MO: John S. Swift Co., Inc. 163 p.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep. ST-X-3. Ottawa, ON: Forestry Canada, Science and Sustainable Development Directorate. 63 p.

Gisborne, H.T. 1948. Fundamentals of fire behavior. Fire Control Notes. 9(1): 13–24. [Republished in 2004 as: Fire Management Today. 64(1): 15–23.]

Goens, D.W.; Andrews, P.L. 1998. Weather and fire behavior factors related to the Dude Fire, AZ. In: Preprint volume of second symposium on fire and forest meteorology. Boston, MA: American Meteorological Society: 153–158.

Graham, R.T., tech. ed. 2003. Hayman Fire case study. Gen. Tech. Rep. RMRS-GTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p.

Hartford, R.A.; Rothermel, R.C. 1991. Fuel moisture as measured and predicted during the 1988 fires in Yellowstone National Park. Res. Note INT-396. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 7 p.

Hirsch, K.G.; Martell, D.L.; Corey, P.N. 2000. Probability of containment by medium initial attack crews in the boreal spruce fuel type. [Poster with text.] Edmonton, AB: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre.

Hough, W.A. 1973. Fuel and weather influence wildfires in sand pine forests. Res. Pap. SE-174. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 11 p.

Kerr, W.L.; Buck, C.C.; Cline, W.E.; Martin, S.; Nelson, W.D. 1971. Nuclear weapons effects in a forest environment—thermal and fire. Rep. N2: TR 2-70. Santa Barbarba, CA: General Electric Company-TEMPO and Department of Defense Nuclear Information Analysis Center.

Keyes, C.R. 2006. Role of foliar moisture content in the silvicultural management of forest fuels. Western Journal of Applied Forestry. 21: 228–231.

Kiil, A.D.; Grigel, J.E. 1969. The May 1968 forest conflagrations in central Alberta—a review of fire weather, fuels and fire behavior. Inf. Rep. A-X-24. Edmonton, AB: Canada Department of Fisheries and Forestry, Forestry Branch, Forest Research Laboratory. 36 p.

Lindenmuth, A.W., Jr.; Davis, J.R. 1973. Predicting fire spread in Arizona's oak chaparral. Res. Pap. RM-101. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 11 p.

Linn, R.; Reisner, J.; Colman, J.J.; Winterkamp, J. 2002. Studying wildfire behavior using FIRETEC. International Journal of Wildland Fire. 11: 233–246.

Maclean, N. 1992. Young men and fire. Chicago, IL: University of Chicago Press. 301 p.

McAlpine, R.S.; Lawson, B.D.; Taylor, E. 1991. Fire spread across a slope. In: Andrews, P.L.; Potts, D.F., eds. Proceedings of the 11th conference on fire and forest meteorology. SAF Publ. 91-04. Bethesda, MD: Society of American Foresters: 218–225.

McAlpine, R.S.; Wakimoto, R.H. 1991. The acceleration of fire spread from point source to equilibrium spread. Forest Science. 37: 1314–1337.

McArthur, A.G. 1965. Fire behaviour characteristics of the Longford Fire. Leafl. No. 91. Canberra, Australian Capital Territory: Commonwealth of Australia, Forest and Timber Bureau, Forest Research Institute. 19 p.

Mell, W.; Jenkins, M.A.; Gould, J.; Cheney, P. 2007. A physics-based approach to modelling grassland fires. International Journal of Wildland Fire. 16: 1–22.

Menning, K.M.; Stephens, S.L. 2007. Fire climbing in the forest: a semiqualitative, semiquantitative approach to assessing ladder fuel hazards. Western Journal of Applied Forestry. 22: 88–93.

Mottus, B.; Pengelly, I. 2004. An analysis of the meteorological conditions associated with the 1999 Panther River Fire in Banff National Park [abstract]. In: Engstrom, R.T.; Galley, K.E.M.; de Groot, W.J.; eds. Proceedings of the 22nd Tall timbers fire ecology conference: fire in temperate, boreal, and montane ecosystems. Tallahassee, FL: Tall Timbers Research Station: 239.

Murphy, K.; Rich, T.; Sexton, T. 2007. An assessment of fuel treatment effects on fire behavior, suppression effectiveness, and structure ignition on the Angora Fire. Tech. Publ. R5-TP-025. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. 32 p.

National Wildfire Coordinating Group. 1993. Look up, look down, look around [VHS videotape; 50 minutes]. Publication NFES 2244. Boise, ID: National Fire Equipment System, Boise Interagency Fire Center.

Nelson, R.M., Jr. 1993. Byram's energy criterion for wildland fires: units and equations. Res. Note INT-415. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Paxton, J. 2007. The monster reared his ugly head—the story of Rodeo-Chediski Fire and fire as a tool of nature. Snowflake, AZ: Cedar Hill Publishing. 217 p.

Pence, M.; Zimmerman, T. 2011. The Wildland Fire Decision Support System: integrating science, technology, and fire management. Fire Management Today. 71(1): 18–22.

Reinhardt, E.D.; Crookston, N.L., tech eds. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

Rothermel, R.C. 1985. Fire behavior considerations of aerial ignition In: Mutch, R.W., tech. coord. Prescribed fire by aerial ignition, proceedings of a workshop. Missoula, MT: Intermountain Fire Council: 143–158.

Rothermel, R.C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. Res. Pap. INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 46 p.

Rothermel, R.C. 1993. Mann Gulch Fire: a race that couldn't be won. Gen. Tech. Rep. INT-299. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 10 p.

Rothermel, R.C.; Hartford, R.A.; Chase, C.H. 1994. Fire growth maps for the 1988 Greater Yellowstone Area fires. Gen. Tech. Rep. INT-304. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 64 p.

Rothermel, R.C.; Mutch, R.W. 1986. Behavior of the life-threatening Butte Fire: August 27–29, 1985. Fire Management Notes. 47(2): 14–24. [Republished in 2003 as: Fire Management Today. 63(4): 31–39.]

Schaaf, M.D.; Sandberg, D.V.; Schreuder, M.D.; Riccardi, C.L. 2007. A conceptual framework for ranking crown fire potential in wildland fuelbeds. Canadian Journal of Forest Research. 37: 2464–2478.

Schroeder, M.J.; Buck, C.C. 1970. Fire weather … a guide for application of meteorological information to forest fire control operations. Agric. Handb. 360. Washington, DC: U.S. Department of Agriculture. 229 p.

Scott, J.H. 2006. Comparison of crown fire modeling systems used in three fire management applications. Res. Pap. RMRS-RP-58. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 25 p.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Simard, A.J.; Haines, D.A.; Blank, R.W.; Frost, J.S. 1983. The Mack Lake Fire. Gen. Tech. Rep. NC-83. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 36 p.

Stocks, B.J.; Alexander, M.E.; Wotton, B.M.; Stefner, C.N.; Flannigan, M.D.; Taylor, S.W.; Lavoie, N.; Mason, J.A.; Hartley, G.R.; Maffey, M.E.; Dalrymple, G.N.; Blake, T.W.; Cruz, M.G.; Lanoville, R.A. 2004. Crown fire behaviour in a northern jack pine-black spruce forest. Canadian Journal of Forest Research. 34: 1548–1560.

Stocks, B.J.; Hartley, G.R. 1995. Fire behavior in three jack pine fuel complexes. [Poster with text.] Sault Ste. Marie, ON: Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre.

Sullivan, A.L. 2009a. Improving operational models of fire behaviour. In: Anderssen, R.S.; Braddock, R.D.; Newham, L.T.H., eds. Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on modelling and simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation: 2377–2383. http://www.mssanz.org.au/modsim09/A4/sullivan.pdf. (14 February 2010).

Sullivan, A.L. 2009b. Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. International Journal of Wildland Fire. 18: 349-368.

Sutton, M.W. 1984. Extraordinary flame heights observed in pine fires on 16 February 1983. Australian Forestry. 47: 199–200.

Taylor, S.W.; Pike, R.G.; Alexander, M.E. 1997. Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Spec. Publ. 11. Edmonton, AB: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. 60 p.

Taylor, S.W.; Wotton, B.M.; Alexander, M.E.; Dalrymple, G.N. 2004. Variation in wind and crown fire behaviour in a northern jack pine-black spruce forest. Canadian Journal of Forest Research. 34: 1561–1576.

Tymstra, C.; Bryce, R.W.; Wotton, B.M.; Taylor, S.W.; Armitage, O.B. 2010. Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Inf. Rep. NOR-X-417. Edmonton, AB: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. 102 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 1980. Report on the National Fire Behavior Research conference. Washington, DC: Forest Fire and Atmospheric Sciences Research. 75 p. plus appendices.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2010. The PLANTS database. http://plants.usda.gov. (3 February 2011).

Van Wagner, C.E. 1964. History of a small crown fire. Forestry Chronicle. 40: 202–205, 208–209.

Van Wagner, C.E. 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Dep. Publ. No. 1229. Ottawa, ON: Canada Department of Forestry and Rural Development, Forestry Branch. 30 p.

Van Wagner, C.E. 1969. A simple fire-growth model. Forestry Chronicle. 45: 103–104.

Van Wagner, C.E. 1977a. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23–34.

Van Wagner, C.E. 1977b. Effect of slope on fire spread rate. Canadian Forestry Service Bi-monthly Research Notes. 33: 7–8.

Van Wagner, C.E. 1985. Fire behavior modelling—how to blend art and science. In: Donoghue, L.R.; Martin, R.E., eds. Proceedings of eighth conference on fire and forest meteorology. SAF Publ. 85–04. Bethesda, MD: Society of American Foresters: 3–5.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. For. Tech. Rep. 35. Ottawa, ON: Government of Canada, Canadian Forestry Service. 37 p.

Van Wagner, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research. 23: 442–449.

van Wagtendonk, J.W.; Botti, S.J. 1984. Modeling behavior of prescribed fires in Yosemite National Park. Journal of Forestry. 82: 479–484.

Varner, J.M.; Keyes, C.R. 2009. Fuels treatments and fire models: errors and corrections. Fire Management Today. 69(3): 47–50.

Venkatesh, S.; Saito, K.; Rothermel, R.C. 2000. Maximum spotting distance in wind-driven crown fires. Nensho no Kagaku to Gijutsu. 7: 221–233. [In English.]

Wade, D.D.; Ward, D.E. 1973. An analysis of the Air Force Bomb Range Fire. Res. Pap. SE-105. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 38 p.

Weber, M.G. 1995. Fire research and the global village. Forestry Chronicle. 71: 584–588.

Wendel, G.W.; Storey, T.G.; Byram, G.M. 1962. Forest fuels on organic and associated soils in the Coastal Plain of North Carolina. Stn. Pap. 144. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Wotton, B.M.; Alexander, M.E.; Taylor, S.W. 2009. Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System. Inf. Rep. GLC-X-10. Sault Ste. Marie, ON: Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. 45 p.

Acknowledgments

The Extreme Fire Behavior synthesis was funded by the Joint Fire Science Program (JFSP) Project Number 09-2-01-11 and a contribution from Project Number 09-S-03-1. The following individuals reviewed the entire manuscript and provided insightful comments: Don Haines (U.S. Forest Service, retired), Robert Ziel (Program Coordinator, Lake States Fire Science Consortium) and John Snook (Fire Weather/Predictive Services Program Manager, Northern California Geographic Area Coordination Center).

Each chapter was also peer reviewed, and we wish to acknowledge those individuals for their comments that significantly improved the document. Listed below are the chapter reviewers:

- Effects of Complex Terrain—Tom Rolinski (Fire Weather Program Manager, Southern California Geographic Area Coordination Center) and Kenn McCarty (California Department of Forestry and Fire Protection).
- Critical Fire Weather Patterns—Rick Ochoa (National Interagency Fire Center Predictive Services, retired), Heath Hockenberry (National Weather Service), John Saltenberger (Fire Weather Services Program Manager, Northwest Geographic Area Coordination Center) and Julia Rutherford (National Weather Service).
- Fire Interactions and Mass Fires—Two anonymous reviewers.
- Column/Plume Dynamics and Spot Fires—Joseph J. Charney (U.S. Forest Service, Northern Research Station) and Don Haines (U.S. Forest Service, retired) for plume section; Nicholas Gellie (Australian Fire Behavior Analyst) and Marty Alexander (Alberta School of Forest Science and Management, University of Alberta, Edmonton, Canada) for spotting section.
- Vortices and Wildland Fire—Don Haines and two anonymous reviewers.
- Crown Fire—Dave Thomas (U.S. Forest Service, retired), Philip Omi (Professor Emeritus, Colorado State University), C. Hoffman (University of Idaho) and J. Kern (Florida Division of Forestry).

The authors also thank Victoria Werth for her help in writing the final document summary and to Victoria Werth and Lynn Sullivan for editing and formatting the manuscript in preparation for publication.

Unit Conversion Factors[a]

SI unit	Multiplication factor	English unit	Inverse factor
Degrees Celsius (°C)	5/9 (°F - 32)	= Degrees Fahrenheit (°F)	(9/5 °C) + 32
Hectares (ha)	2.47	= Acres (ac)	0.405
Kilograms (kg)	2.205	= Pounds (lb)	0.454
Kilograms per cubic meter (kg/m^3)	0.624	= Pounds per cubic foot (lb/ft^3)	16.0
Kilograms per square meter (kg/m^2)	0.205	= Pounds per square foot (lb/ft^2)	4.88
Kilograms per second per square meter (kg sec^{-1} m^{-2})	737.463	= Pounds per hour per square foot (lb hr^{-1}.ft^2)	0.001356
Kilograms per square meter (kg/m^2)	4.46	Tons per acre (t/ac)	0.224
Hectopascals (hPa)	0.0145	= Pounds per square inch (lb/in^2)	68.94

SI unit	Multiplication factor	English unit	Inverse factor
Kilojoules per kilogram (kJ/kg)	0.430	British thermal units per pound (BTU/lb)	2.32
Kilometers (km)	0.621	= Miles (mi)	1.61
Kilometers per hour (km/h)	0.621	= Miles per hour (mi/h)	1.61
Kilowatts per meter (kW/m)	0.289	= BTUs per second per foot (BTU/s-ft)	3.46
Megawatts (MW)	56,869	= BTUs per minute (BTU/min)	0.0000176
Centimeters (cm)	0.394	Inches	2.54
Meters (m)	3.28	Feet (ft)	0.305
Square meters (m^2)	10.764	= Square feet	0.0929
Meters per minute (m/min)	3.28	Feet per minute (ft/min)	0.305
Meters per minute (m/min)	2.98	= Chains per hour (ch/h)	0.335
Meters per second (m/s)	3.28	= Feet per second (ft/s)	0.305
Number per hectare (No./ha)	0.405	= Number per acre (No./ac)	2.47
Square meters per hectare (m^2/ha)	4.36	= Square feet per acre (ft^2/ac)	0.230

[a] Factors are given to three significant digits. To convert an English unit to a Standard Inernationad Unites (SI) unit, multiply by the inverse factor given in the right-hand column.

Common and Scientific Names[a]

Common name	Scientific name
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Eucalyptus	*Eucalyptus* spp.
Jack pine	*Pinus banksiana* Lamb.
Lodgepole pine	*Pinus contorta* Douglas ex. Louden
Ponderosa pine	*Pinus ponderosa* C. Lawson
Red pine	*Pinus resinosa* Aiton
Sand pine	*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.
Singleleaf pinyon	*Pinus monophylla* Torr. & Frém.
Utah juniper	*Juniperus osteosperma* (Torr.) Little
White pine	*Pinus strobus* L.
Spruce	*Picea* spp.

[a] Source: USDA NRCS 2008.

Abstract

Werth, Paul A.; Potter, Brian E.; Clements, Craig B.; Finney, Mark A.; Goodrick, Scott L.; Alexander, Martin E.; Cruz, Miguel G.; Forthofer, Jason A.; McAllister, Sara S. 2011. Synthesis of knowledge of extreme fire behavior: volume I for fire managers. Gen. Tech. Rep. PNW-GTR-854. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 144 p.

The National Wildfire Coordinating Group definition of extreme fire behavior (EFB) indicates a level of fire behavior characteristics that ordinarily precludes methods of direct control action. One or more of the following is usually involved: high rate of spread, prolific crowning/spotting, presence of fire whirls, and strong convection column. Predictability is difficult because such fires often exercise some degree of influence on their environment and behave erratically, sometimes dangerously. Alternate terms include “blow up” and “fire storm.”

Fire managers examining fires over the last 100 years have come to understand many of the factors necessary for EFB development. This work produced guidelines included in current firefighter training, which presents the current methods of predicting EFB by using the crown fire model, which is based on the environmental influences of weather, fuels, and topography.

Current training does not include the full extent of scientific understanding. Material in current training programs is also not the most recent scientific knowledge. National Fire Plan funds have sponsored newer research related to wind profiles’ influence on fire behavior, plume growth, crown fires, fire dynamics in live fuels, and conditions associated with vortex development. Of significant concern is that characteristic features of EFB depend on conditions undetectable on the ground, relying fundamentally on invisible properties such as wind shear or atmospheric stability.

Obviously no one completely understands all the factors contributing to EFB because of gaps in our knowledge. These gaps, as well as the limitations as to when various models or indices apply should be noted to avoid application where they are not appropriate or warranted. This synthesis will serve as a summary of existing extreme fire behavior knowledge for use by fire managers, firefighters, and fire researchers.

The objective of this project is to synthesize existing EFB knowledge in a way that connects the weather, fuel, and topographic factors that contribute to development of EFB. This synthesis will focus on the state of the science, but will also consider how that science is currently presented to the fire management community, including incident commanders, fire behavior analysts, incident meteorologists, National Weather Service office forecasters, and firefighters. It will seek to clearly delineate the known, the unknown, and areas of research with the greatest potential impact on firefighter protection.

Keywords: Extreme fire behavior, fuels, fire behavior.