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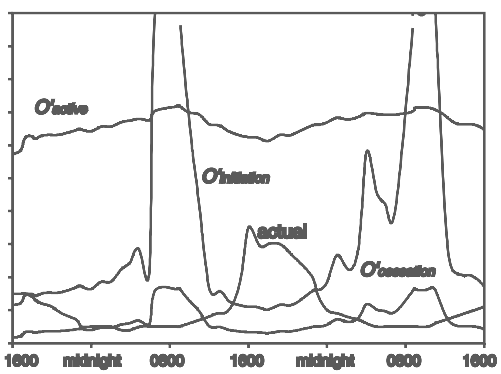
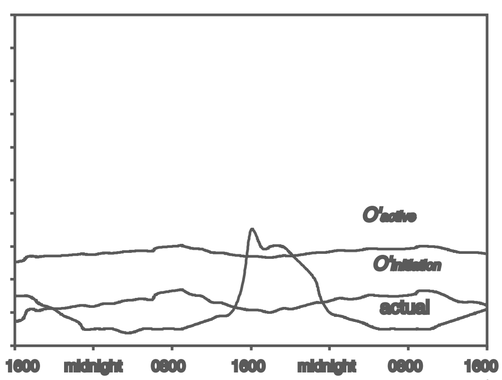
Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior

Joe H. Scott
Elizabeth D. Reinhardt





Abstract

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Fire managers are increasingly concerned about the threat of crown fires, yet only now are quantitative methods for assessing crown fire hazard being developed. Links among existing mathematical models of fire behavior are used to develop two indices of crown fire hazard—the Torching Index and Crowning Index. These indices can be used to ordinate different forest stands by their relative susceptibility to crown fire and to compare the effectiveness of crown fire mitigation treatments. The coupled model was used to simulate the wide range of fire behavior possible in a forest stand, from a low-intensity surface fire to a high-intensity active crown fire, for the purpose of comparing potential fire behavior. The hazard indices and behavior simulations incorporate the effects of surface fuel characteristics, dead and live fuel moistures (surface and crown), slope steepness, canopy base height, canopy bulk density, and wind reduction by the canopy. Example simulations are for western Montana *Pinus ponderosa* and *Pinus contorta* stands. Although some of the models presented here have had limited testing or restricted geographic applicability, the concepts will apply to models for other regions and new models with greater geographic applicability.

Keywords: canopy fuels, hazard assessment, fireline intensity, rate of spread, crown fraction burned, fire potential

Authors

Joe H. Scott has been a Forester with Systems for Environmental Management, a nonprofit research group based in Missoula, MT, since 1996. He has a B.S. degree in forestry and resource management from the University of California at Berkeley and an M.S. degree in forestry from the University of Montana. Joe has participated in investigations of surface and canopy fuels, fire behavior modeling, and crown fire hazard assessment.

Elizabeth D. Reinhardt is a Research Forester in the Prescribed Fire and Fire Effects Project at the Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT. She has degrees in English (A.B., 1978, Harvard University) and forestry (M.S., 1982, and Ph.D., 1991, University of Montana). Her research has included studies of fuel consumption, tree mortality, and prescription development.

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Software Availability

The NEXUS spreadsheet and its documentation can be obtained at www.fire.org/nexus/nexus.html. Information about other fire modeling systems described in the text can be obtained at the Fire Management Tools Online Web site at www.fire.org/perl/tools.cgi.

Contents

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INTRODUCTION

Crown fires present special problems to managers. Crown fires are more difficult to control than surface fires. Their rate of spread is several times faster than surface fires (Rothermel 1983). Spotting is frequent and can occur over long distances. Larger flames from crown fires dictate larger firefighter safety zones (Butler and Cohen 1998). Spotting and increased radiation make structures more difficult to defend from crown fire than surface fire (Cohen and Butler 1998). Effects of crown fire are more severe and lasting than surface fire. Near total tree mortality should be expected. Smoke production will be greater, and foliar nutrients may be lost from the site.

Crown fires can occur in a wide variety of forest types throughout the United States (Agee 1996). Increasingly, crown fires are taking place in forest types not historically prone to crown fires, such as ponderosa pine forests (Mutch and others 1993). A significant risk to life and property exists wherever forest stands prone to crown fire lie in proximity to residential or recreational development. Therefore, assessing the susceptibility of forest stands to crown fire and designing fuel and silvicultural treatments to reduce susceptibility have become priorities for many land management agencies.

Accepted methods exist for predicting surface fire behavior (Rothermel 1972, 1983) and crown fire behavior (Rothermel 1991a), but not for predicting the transition between them. In this paper we explore the use of Van Wagner's crown fire transition criteria (Van Wagner 1977, 1989, 1993), elements of which are used in the Canadian Forest Fire Behavior Prediction (FFBP) System (Forestry Canada Fire Danger Group 1992), to link Rothermel's separate surface fire and crown fire spread models. By linking these models we derive indices of crown fire hazard and simulate the full range of potential fire behavior possible in a forest stand—surface through active crowning.

Other models of surface fire behavior (Catchpole and others 1998) and crown fire behavior (Albini 1996; Grishin 1997; Gomes da Cruz 1999) and transition to crown fire (Alexander 1988; Gomes da Cruz 1999) are in various stages of development and testing. Until a robust fire behavior model is developed that internally simulates surface fire behavior, transition to crown fire, and crown fire behavior, we will need to rely on the links between these separate models.

From the array of available models, we chose to couple the most widely used for this analysis: Rothermel's (1972) surface and (1991a) crown fire models, and Van Wagner's (1977) models of transition to crown fire. The concepts we present, solving for critical environmental conditions that lead to crown fire and producing full-range estimates of fire behavior, can be applied to other models in the future.

The coupled model produces seamless, full-range estimates of fire behavior (whether surface or crown). However, the purpose of those fire behavior estimates is to compare the relative susceptibility of different stands to crown fire, not to predict the behavior of an actual fire. The method we developed allows direct, quantitative comparison of the relative crown fire potential of different stands from a description of surface fuels, canopy fuels, site characteristics, and environmental conditions.

Conceptual Approach to Quantifying Crown Fire Hazard

The concept of hazard has been defined many ways in the wildland fire literature (Bachman and Allgöwer 1999). Fire hazard is sometimes referenced to the specific fuel element that most contributes to the potential fire behavior of a given site. For example, the increased potential fire behavior caused by activity fuels left behind after timber harvesting is sometimes referred to as a "slash hazard."

The field of technical risk engineering defines hazard more generally as a physical situation with a potential for human injury, damage to property, or damage to the environment. Crown fire hazard, therefore, is a physical situation (fuels, weather and topography) with potential for damage or injury caused by crown fires. The nature of crown fires—intense, fast-moving, and destructive—suggests that potential for damage is great whenever a crown fire occurs. Assessing the hazard posed by crown fire is therefore a matter of assessing the potential for their occurrence—of identifying the physical situations that lead to crown fire occurrence.

The potential for crown fire occurrence does not depend on any single element of the fuel complex, nor on any one element of the fire environment. Rather, crown fires result from certain combinations of fuels, weather, and topography that lead to the development and continued spread of crown fires. The concepts and models we discuss in this paper are geared toward determining those combinations, without attempting to determine which component contributes most to the hazard.

This is not the first attempt to assess crown fire potential. Fahnestock (1970) developed a heuristic key to rate crowning potential based largely on canopy closure, (individual tree) crown density, and the presence or absence of ladder fuels. Kilgore and Sando (1975) showed a decrease in crown fire potential following prescribed burning in a giant sequoia/mixed-conifer forest by comparing canopy fuel weight, crown volume ratio, mean height to canopy base, and the vertical profile of canopy fuel packing ratio before and after a prescribed fire. Taylor and others (1998) assessed temporal changes in crown fire hazard at the landscape scale by noting the change in relative frequency of different types of crown fire in different time periods.

The mathematical nature of surface and crown fire models allows us to link them together and solve for the critical conditions that lead to crown fires. The crown fire hazard assessment method we develop in this paper is based on the determination of critical environmental conditions that lead to different types of crown fire activity.

In the next two sections we review fire behavior concepts and models pertinent to quantitative crown fire hazard assessment. In later sections we present the derivation and interpretation of two indices of stand-level crown fire hazard, discuss methods of obtaining the necessary canopy fuel inputs, and introduce seamless surface/crown fire behavior simulations that can be used to assess the likely range of fire behavior at a site and the nature of the transition from surface to crown fire. In addition, we introduce the concept of hysteresis in the crown fire phenomenon.

Types of Wildland Fire

Fire scientists and managers recognize three general types of wildland fire, depending on the fuel stratum in which the fire is burning. A ground fire is one that burns in ground fuels such as duff, organic soils, roots, rotten buried logs, and so forth. Ground fuels are characterized by higher bulk density than surface and canopy fuels. Ground fires burn with very low spread rates but can be sustained at relatively high moisture contents (Frandsen 1987, 1991). Fuel consumption through ground fire can be great, causing significant injury to trees and shrubs. Although ground fuels can be ignited directly, they are most commonly ignited by a passing surface fire.

A surface fire is one that burns in the surface fuel layer, which lies immediately above the ground fuels but below the canopy, or aerial fuels. Surface fuels consist of needles, leaves, grass, dead and down branch wood and logs, shrubs, low brush, and short trees (Brown and others 1982). Surface fire behavior varies widely depending on the nature of the surface fuel complex.

A crown fire is one that burns in the elevated canopy fuels. Canopy fuels normally consumed in crown fires consist of the live and dead foliage, lichen, and fine live and dead branchwood found in a forest canopy. They have higher moisture content and lower bulk density than surface fuels. We generally recognize three types of crown fire: passive, active, and independent (Van Wagner 1977).

A passive crown fire, also called torching or candling, is one in which individual or small groups of trees torch out, but solid flame is not consistently maintained in the canopy (fig. 1a). Passive crowning encompasses a wide range of fire behavior, from the occasional tree torching out to a nearly active crown fire. The increased radiation


a

b


Figure 1—Passive crowning (a) involves individual or small groups of trees, whereas during active crowning (b) the whole fuel complex burns as a unit. *Photo (a) by Duncan Lutes; photo (b) by Jim Kautz.*

to surface fuels from passive crowning increases flame front spread rate, especially at the upper end of the passive crown fire range. Embers lofted during passive crowning can start new fires downwind, which makes containment more difficult and increases the overall rate of fire growth. Passive crowning is common in many forest types, especially those with an understory of shade-tolerant conifers.

An active crown fire, also called a running or continuous crown fire, is one in which the entire surface/canopy fuel complex becomes involved (fig. 1b), but the crowning phase remains dependent on heat from the surface fuels for continued spread. Active crown fires are characterized by a solid wall of flame extending from the fuel bed surface through the top of the canopy. Greatly increased radiation and short-range spotting of active crown fires lead to spread rates much higher than would occur if the fire remained on the surface. Medium and long-range spotting associated with active crowning leads to even greater rates of fire growth.

An independent crown fire is one that burns in canopy fuels without aid of a supporting surface fire. Independent crown fires occur rarely and are short lived (Van Wagner 1993), requiring a combination of steep slope, high windspeed, and low foliar moisture content. Many apparently independent crown fires may actually be active crown fires in which the canopy phase is momentarily pushed ahead of the surface phase under the influence of steep slope or strong wind.

Few cases of independent crown fire have been documented. The 1987 South Mowich fire occurred over a spring snowpack on the slopes of Mount Rainier, WA (Huff 1988). However, the primary mechanism of fire spread during that fire was crown-to-crown spread in which lichens ignited first, then the foliage after being preheated by burning lichen. Radiation from the torching tree then ignited lichen on an adjacent tree. Spread rate was low—the fire took 2 days of uncontained spread to reach 25 ha.

We do not address independent crown fires in this paper because they occur so rarely and because no model of their behavior is available.

The Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992) uses the term “intermittent crown fire” to describe a fire that alternates in space and time between continuous crowning and surface fire or passive crowning. Such a phenomenon could result from spatial variability in surface and canopy fuels, or temporal variability in windspeed, especially when conditions are near the threshold for active crowning.

CHARACTERIZING CANOPY FUELS

Assessing crown fire potential requires the most accurate estimates of canopy fuel characteristics possible. However, the literature provides little guidance for determining these characteristics at the stand level. A rich body of literature does exist on quantification of tree crown and forest canopy characteristics for purposes other than fuel characterization for crown fire modeling.

Reinhardt and others (2000) are attempting to accurately measure canopy fuel characteristics in a range of forest types and stand densities. These accurate measurements will then be compared with estimates made using two indirect approaches: instrument-based optical techniques and inventory-based techniques. The indirect techniques have proven useful in a modeling framework. They now need to be calibrated and verified for operational use. In addition, photographs made of the sample stands will provide a good start for a canopy fuel photo guide.

Three main characteristics of canopy fuels must be quantified to use the coupled models: canopy bulk density, canopy base height, and foliar moisture content. Canopy bulk density is the mass of available canopy fuel per unit canopy volume. It is a bulk property of the stand, not an individual tree. We use the term crown bulk density for reference to the bulk fuel properties of an individual tree. Canopy base height is more difficult to define, but it too is a bulk property of a stand, whereas crown base height is a property of an individual tree.

Alternative techniques for estimating canopy bulk density and base height are described below. We do not yet know the relative accuracy of these methods. Inventory-based techniques hold promise for highest accuracy, but other methods are better for mapping large areas. Pending further research, we suggest using inventory-based techniques where possible.

Canopy Bulk Density

With Rothermel's (1972) surface fire model we specify the fuels that may potentially be consumed in the flaming fire front (W_o), and the model then estimates what portion of that fuel actually contributes to propagation of the fire front. However, with canopy bulk density (*CBD*) we specify, before the fact, the canopy fuels that would be consumed in the flaming front of a fully active crown fire. It is reasonable to assume that the foliage, lichen, and moss are consumed in the flaming front of a fully active crown fire. Some portion of the live and dead branch wood less than 6 mm diameter should also be consumed in the flaming front (Brown and Bradshaw 1994; Brown and Reinhardt 1991; Reinhardt and others 1997). A model by Call and Albini (1997) suggests that 65 percent of canopy fuel 0 to 6 mm diameter at 100 percent moisture content would be consumed in a crown fire. However, Call and Albini acknowledge that their model overpredicts consumption in small size classes.

For uniform stands, *CBD* can be computed as the available canopy fuel load divided by canopy depth (Keane and others 1998). This method carries the implicit assumption that canopy biomass is distributed uniformly within the stand canopy, which is unlikely to be true even in stands with simple structures; multistoried stands are probably even more poorly represented by this procedure.

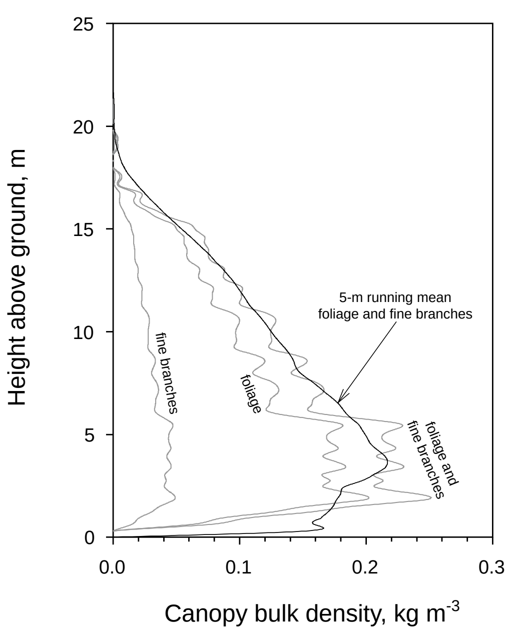

Figure 2—Vertical profile of canopy bulk density in a lodgepole pine (*Pinus contorta*) stand on the Bitterroot National Forest, Montana. Effective canopy bulk density is taken to be the maximum 5-m running mean (0.21 kg m^{-3}).

Following Sando and Wick (1972), the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS, Beukema and others 1997) uses a technique to estimate "effective" *CBD* in nonuniform stands from a stand inventory that does not assume a uniform vertical distribution of canopy fuel. Therefore, *CBD* does not necessarily equal canopy load divided by canopy depth. In FFE-FVS, *CBD* was defined as the maximum 4.5-m deep (15-foot) running mean of canopy bulk density for layers 0.3 m (1 ft) thick (fig. 2). This method yielded encouraging and realistic results when applied to stand exam data on the Idaho Panhandle National Forests. However, we have no way of knowing if the results are accurate because canopy fuels have never been measured directly.

A number of studies exist that predict foliar and branch biomass from tree dimensions, typically diameter, sometimes in combination with height, crown ratio, or sapwood thickness. Brown (1978) provides predictive equations for the common conifer tree species of the Inland West; Snell and Brown (1980) provide similar methods for Pacific Northwest conifers. A large number of allometric equations of this type from many research studies are summarized in the computer software BIOPAK (Means and others 1996). These equations, together with a list of trees representing a stand, may be used to estimate foliage load, as well as the load of branchwood of various sizes.

An alternative method of estimating foliage load is to first estimate leaf area index (LAI) using onsite measurement. Several optical instruments are available for estimating LAI (Fassnacht and others 1994; Smith and Somers 1993; Welles 1990). Leaf area index can be converted to an estimate of foliar biomass using specific leaf area factors (for example, Keane and others 1996). Published values for specific leaf area exist for many conifer species.

A canopy fuel photo guide would help managers quantify canopy bulk density in the field. Further research into the nature and properties of canopy fuels is needed before we can fully exploit existing and future models of crown fire behavior.

Canopy Base Height

Crown base height is a simple characteristic to measure on an individual tree. Canopy base height (*CBH*) is not well defined or easy to estimate for a stand. Neither the lowest crown base height in a stand nor the average crown base height is likely to be representative of the stand as a whole. Canopy base height is difficult to measure in multistory stands and stands with ladder fuels. Van Wagner (1993) reduced observed *CBH* to account for ladder fuels in a two-story stand. Defined in terms of its consequences to crown fire initiation, *CBH* is the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy. Using this definition, ladder fuels such as lichen, dead branches, and small trees are incorporated. Sando and Wick (1972) estimated canopy base height of nonuniform stands based on the height at which a minimum bulk density of fine fuel (100 lb $acre^{-1}$ ft^{-1}, 0.037 kg m^{-3}) is found.

The Fire and Fuels Extension to the Forest Vegetation Simulator (Beukema and others 1997) uses the Sando and Wick approach in combination with Brown's (1978) equations to estimate canopy base height and canopy bulk density. Canopy base height was defined as the lowest height above which at least 30 lb $acre^{-1}$ ft^{-1} (0.011 kg m^{-3}) of available canopy fuels is present.

Ladder fuels that increase the intensity of the surface fire, such as short understory trees, shrubs, and needle drape, are best accounted through custom surface fuel modeling or by simple adjustment of simulated surface fire intensity to include their effect.

Foliar Moisture Content

Foliar moisture content (*FMC*) has less influence over crown fire initiation than *CBH* , but its theoretical effect on crown fire spread rate through the foliar moisture effect (Van Wagner 1993) is much stronger (Scott 1998). Numerous studies of *FMC* have been conducted throughout North America (Alexander 1988). Moisture content of conifer foliage varies among species and seasons (Philpot and Mutch 1971), but not from day to day (Hartford and Rothermel 1991) or year to year (Philpot and Mutch 1971). The Forestry Canada Fire Danger Group (1992) related the timing of seasonal changes in *FMC* to latitude, longitude, and elevation.

In old foliage (at least 1 year old), the lowest moisture contents have been found in *Picea mariana* (Chrosciewicz 1986; Springer and Van Wagner 1984), and *Picea glauca*, *Picea banksiana*, and *Abies balsamea* (Chrosciewicz 1986), each with a low *FMC* near 75 percent (though the lowest *FMC* may occur outside the fire season). Highest old-foliage moisture content was found in *Pinus clausa* (Hough 1973) and *Abies balsamea* (Kozlowski and Clausen 1965; Little 1970), with values near 150 percent. The range of old-foliage *FMC* for most species straddles 100 percent, so this value has been used as a default *FMC* if no other information is available (Finney 1998; Scott 1998). Future research should be directed at compiling existing *FMC* data for Western conifers, then conducting field research to fill in gaps in the data. Larger errors in estimating effective *FMC* probably result from variable amounts of dry dead fuels and lichen in the canopy. Van Wagner (1993) estimated effective *FMC* by computing the loading-weighted average moisture content of the foliage and fine dead canopy fuels. Until better data exist, using 100 percent for *FMC* is a reasonable approach, especially given the relative insensitivity of the models to this parameter.

EXISTING MODELS OF SURFACE AND CROWN FIRE BEHAVIOR

The basic behavior of surface and crown fires can be described by fireline intensity (*I*), forward rate of spread (*R*), and heat (release) per unit area (*HPA*). (A complete list of symbols used in this paper can be found in table 1.) Fireline intensity is the rate of heat release in the flaming front per unit length of fire front. Byram (1959) defines fireline intensity, *I*, as

$$I = \frac{HW_f R}{60} \qquad (1)$$

where H is the heat yield of the fuel (kJ kg^{-1}), W_f is the weight of fuel consumed in the flaming front (kg m^{-2}), R is the forward rate of spread of the fire (m min^{-1}), and 60 is a conversion factor so that the units for I reduce to kW m^{-1}(kJ m^{-1} min^{-1}). Byram uses the term "available fuel" to describe W_f, but he evidently refers to the weight of fuel available to the flaming fire front, not the total amount consumed in flaming and smoldering combustion. In the remainder of this paper, intensity should be taken to mean Byram's fireline intensity as defined in equation 1.

Heat (release) per unit area is the product of the heat yield of fuels, H, and the weight of fuel consumed in the flaming front, W_f. Therefore, *HPA* is identical to the quantity HW_f in equation 1. Heat per unit area can also be expressed (Andrews and Rothermel 1982) as

$$HPA = I_R t_R \qquad (2)$$

where I_R is reaction intensity (kJ min^{-1} m^{-2}) and t_R is residence time in minutes (Anderson 1969)

$$t_R = \frac{12.595}{\sigma} \qquad (3)$$

where σ is the characteristic surface-area-to-volume ratio (cm^{-1}) of the fuel bed.

Neither Rothermel's (1972) model nor BEHAVE (Andrews 1986) explicitly computes W_f, but because HW_f in equation 1 is equivalent to *HPA*, W_f can be computed as

$$W_f = \frac{HPA}{H} \qquad (4)$$

Fuel Consumption at the Flaming Front

Conflicting and ambiguous terminology has led to confusion in determining W_f for use in equation 1 and its variants (see table 2). Total fuel load, W_t, is the maximum amount of fuel, including duff and large woody fuels (>76 mm diameter), that could possibly be consumed in a hypothetical fire of the highest intensity in the driest fuels (Byram 1959). Available fuel, W_a, is that portion of the

Table 1—Symbols and variables used in the text.

Symbol	Definition
B,C,E	Terms in Rothermel's (1972) model, all functions of ¯
CBD	Canopy bulk density, kg m^{-3}
CBH	Canopy base height, m
CFB	Crown fraction burned
FMC	Crown foliar moisture content, percent
FME	Foliar moisture effect
HPA	Heat (release) per unit area, kJ m^{-2}
H	Heat yield of fuel, kJ kg^{-1}
I	Byram's fireline intensity, kW m^{-1}
$I'_{initiation}$	Critical *I* for initiating a crown fire, kW m^{-1}
I_R	Reaction intensity, kW m^{-2}
O	Open (6.1-m) windspeed, km hr^{-1}
O'_{active}	Critical open windspeed for sustaining fully active crown fire, km hr^{-1}
$O'_{cessation}$	Critical open windspeed for crown fire cessation, km hr^{-1}
$O'_{initiation}$	Critical open windspeed for crown fire initiation, km hr^{-1}
Q_{ig}	Heat of preignition, kJ kg^{-1}
R	Forward rate of spread, m min^{-1}
R_{active}	*R* for a fully active crown fire, m min^{-1}
R'_{active}	Critical *R* for sustaining an active crown fire, m min^{-1}
R_{final}	*R* for any type of fire: surface, passive crown, or active crown, m min^{-1}
$R'_{initiation}$	Critical *R* for initiating a crown fire, m min^{-1}
$R_{surface}$	*R* for a surface fire, m min^{-1}
S	Mass-flow rate of crown fuel, kg m^{-2} s^{-1}
t_R	Flame residence time, min
U	Midflame windspeed, km hr^{-1}
W_a	Available fuel, or total fuel consumption, kg m^{-2}
W_c	Fuel available for convection, kg m^{-2}
W_{canopy}	Weight of available canopy fuel, kg m^{-2}
W_f	Weight of fuel consumed in the flaming front, kg m^{-2}
W_n	W_o with the mineral content removed, kg m^{-2}
W_o	Fine fuel that can potentially contribute to flaming front, kg m^{-2}
W_t	Total fuel load, kg m^{-2}
WRF	Wind reduction factor
β	Fuelbed packing ratio
β_{op}	Optimum fuelbed packing ratio
ε	Effective heating number
ξ	Propagating flux ratio
ρ_b	Oven-dry fuel bed bulk density, kg m^{-3}
σ	Surface-area-to-volume ratio of fuel particles, cm^{-1}
ϕ_s	Slope factor
ϕ_w	Wind coefficient
$\phi'_{w (initiation)}$	Critical wind coefficient for crown fire initiation

total fuel load that is consumed in a given fire; it must always be less than or equal to W_t (fig. 3). Unless otherwise specified, W_a includes the consumption of duff and large woody fuels, most of which takes place after passage of the fire front. Equation 1 requires W_f, the usually much smaller quantity of fuel that is consumed in the flaming fire front. The Forestry Canada Fire Danger Group (1992) uses equation 1 to define frontal fire intensity (as opposed to Byram's fireline intensity) in the Canadian Forest Fire Behavior Prediction System by using W_a (total fuel consumption) in place of W_f. In forest fuel complexes with duff and coarse fuels, W_a can be many times larger than W_f, so values of frontal

Table 2—Definition of fuel loading, consumption and availability terms and variables. All quantities are measured in mass per unit area (kg m^{-2}).

Term	Symbol	Definition
Total biomass		The total amount of living and dead vegetation per unit area, including vegetation that is never consumed in a fire, such as live tree boles and large live branches.
Total fuel load	W_t	The maximum amount of fuel per unit area that can possibly be consumed in a fire of the highest possible intensity in the driest possible fuels.
Available fuel	W_a	The total amount of fuel per unit area that is consumed by a fire, including the post-frontal consumption of duff, organic soils, and large woody fuels like logs.
Fuel available for convection	W_c	The amount of fuel per unit area that is consumed in a short enough time and with enough intensity to contribute to the convection column. It is usually larger than W_f but smaller than W_a because only a fraction of postfrontal combustion contributes to convection.
Fuel consumed within the flaming front	W_f	The amount of fuel per unit area that is consumed within and contributes to fire behavior in the flaming front of the fire. In Rothermel's (1972) surface fire model this only includes fuels less than 7.6 mm diameter.
Total fine fuel load[a]	W_o	The amount of surface fuel per unit area less than 7.6 mm diameter. This term is used in the Rothermel (1972) surface fire spread model.
Net fuel load	W_n	The net amount of surface fuel per unit area less than 7.6 mm diameter after the mineral fraction has been sub tracted. It is always slightly less than W_o. W_n is also a term from the Rothermel spread model.

[a]This term was originally called total fuel load in the Rothermel (1972) model; we modified it here to avoid conflict with Byram's definition of W_t.

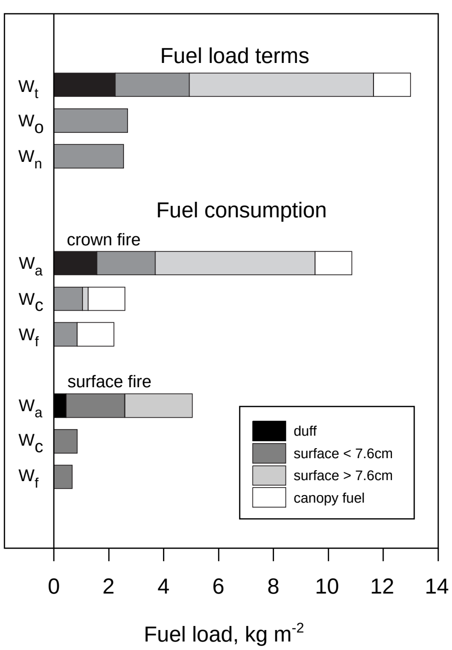

Figure 3—Comparison of fuel loading, consumption, and availability terms for a hypothetical fuel complex under conditions of (a) high dead fuel moisture that leads to surface fire, and (b) low dead fuel moisture that leads to active crown fire. Terms are defined in table 2.

fire intensity should also be many times larger than the fireline intensity used in this paper. Values of frontal fire intensity from the Canadian FFBP System are therefore not directly comparable to values of fireline intensity reported here.

Rothermel (1991a) resurrected Byram's concept of the "power of the fire" to identify potential plume-dominated fire conditions. To compute the power of the fire, Rothermel (1991a) estimated the amount of fuel consumed in a short enough time and with enough intensity to contribute to the convection column, W_c. Rothermel refers to the energy produced by W_c (that is, $H * W_c$) as the unit energy, which is analogous to heat per unit area in the surface fire model. Rothermel's analysis using Albini's (1976) BURNOUT model indicated that W_c was only slightly greater than W_f.

Further confusion is brought about by variable names from the Rothermel surface spread model (1972). In that model, W_o, which Rothermel called total fuel load, is actually a subset of the total fuel load defined by Byram. Unlike W_t, W_o includes only those fuel components that contribute significantly to fire behavior at the flaming front. By convention, only the dead fuels less than 76 mm diameter and live fuels less than 6 mm diameter are included in W_o (Rothermel 1972). In the Rothermel (1972) model, W_n is the net weight of W_o after the mineral fraction has been subtracted. Mineral fraction is usually held constant at 0.055, so $W_n = W_o(1 - 0.055)$. Some authors have incorrectly used W_n in place of W_f (for example, Bessie and Johnson 1995, equation 12). This error can result in a many-fold over-calculation of intensity, because the Rothermel model predicts that W_f is only a small fraction of W_n in forest fuels.

For crown fires, W_f is the combined weight of surface and canopy fuels consumed in the flaming front. An active crown fire consumes nearly all of the fine crown fuels in a given area, while a passive or intermittent crown fire consumes only a portion (Van Wagner 1993).

It will later be necessary to estimate the spread rate that leads to a given fireline intensity by rearranging equation 1. The difficulty of determining W_f for use in equation 1 and its derivatives can be avoided by replacing HW_f with HPA in equation 1.

$$I = \frac{HPA * R}{60} \tag{5}$$

The Rothermel surface fire spread model was developed to predict spread rate; only through combination with a model of residence time (Anderson 1969) can the Rothermel spread model be used to estimate *HPA* and *I* (Andrews and Rothermel 1982). As such, estimates of *I* are not as reliable as those of *R* from the Rothermel model. However, the Rothermel model is the best choice currently available for estimating the fireline intensity in surface fires. With testing, the BURNUP model (Albini and Reinhardt 1995; Albini and others 1995) may prove useful in estimating fuel consumed in the flaming front of surface fires.

Surface Fire Behavior

For this analysis surface fire spread rate is simulated with Rothermel's (1972) model as adjusted by Albini (1976) and implemented in BEHAVE (Andrews 1986), FARSITE (Finney 1998), NEXUS (Scott 1999), and other fire modeling systems. Headfire rate of spread for upslope winds is expressed (Rothermel 1972)

$$R_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \tag{6}$$

The Rothermel model has many input factors. Fuelbed characteristics have been combined into standard fuel models (Anderson 1982) that represent stylized fuelbeds. Custom fuel models can be created from a fuel inventory or by adjusting one of the standard fuel models (Burgan 1987; Burgan and Rothermel 1984). As employed in this analysis, the Rothermel model can be used with either standard or custom fuel models to simulate surface fire behavior. Standard fuel models often do not accurately simulate both spread rate and fireline intensity simultaneously for a given simulation. Even custom models are difficult to calibrate so that both rate of spread and fireline intensity are accurately simulated over a range of environmental conditions. For assessing crown fire hazard using the models outlined in this paper, accurate simulation of surface fireline intensity is more important than spread rate accuracy. The selection of a standard model or calibration of a custom model should reflect this importance.

Crown Fire Behavior

Foresters and ecologists use the term crown in reference to the branches and foliage of individual trees, and the term canopy when referring to the aggregation of crowns at the group or stand level. Technically, a crown fire is one that consumes the crowns of individual trees (a passive crown fire), while a canopy fire would be one that burns in the whole canopy stratum as a unit (active or continuous crowning). However, we customarily refer to both types of fires as crown fires. We will continue to use the term crown fire to refer to both crown and canopy fires because the modifiers passive and active distinguish the two types. Several models of active crown fire spread rate are now available (Albini 1996; Gomes da Cruz 1999; Grishin 1997; Rothermel 1991a). Each model carries problems or assumptions that limit its application. Despite its shortcomings, we use the Rothermel (1991a) procedure to estimate crown fire spread rate because it is the most widely used of the available models.

The Rothermel (1991a) correlation was intended for the Northern Rocky Mountains and other areas with similar fuels, climate, and topography. He used linear regression to relate coarse-scale observed crown fire spread rates to predictions made with his surface fire model using fuel parameters from Fire Behavior Fuel Model (FM) 10 (Anderson 1982). Midflame windspeed was set to 40 percent of the observed 6.1-m (20-ft) windspeed. In simple form, the Rothermel (1991a) correlation for average crown fire spread rate is

$$R_{active} = 3.34(R_{10})_{40\%} \qquad (7)$$

where $(R_{10})_{40\%}$ is the spread rate predicted with Rothermel's (1972) surface fire model using the fuel characteristics for FM 10 and midflame windspeed set at 40 percent of the 6.1-m windspeed.

The input factors from FM 10 must be used to predict crown fire spread rate using Rothermel's method, not the actual surface fuel characteristics. Bessie and Johnson (1995) used actual surface fuel characteristics, which can result in errors of nearly an order of magnitude, depending on the nature of the actual surface fuels. However, the mandatory use of FM 10 applies only to simulating crown fire spread rate with Rothermel's (1991a) correlation—surface fire spread rate can still be simulated with any appropriate standard or custom fuel model. The midflame windspeed for use in the correlation must be set at 40 percent of the open windspeed, not at the midflame wind that would be used for simulating surface fire behavior. For surface fires, midflame winds are estimated by multiplying the open wind (6.1-m in the United States) by a wind reduction factor, *WRF*, the ratio of midflame to open windspeeds. In forest stands on level ground, Albini and Baughman (1979) estimate *WRF* from stand height and crown filling fraction (the fraction of the canopy volume that is occupied by tree crowns). The *WRF* for forest stands is most often in the range 0.10 to 0.3 (Rothermel 1983).

Rothermel's correlation is limited to wind-driven crown fires—plume-dominated crown fires are not predicted by this or any other crown fire spread model.

We must make additional assumptions before applying Rothermel (1991a) to the coupled model. First, we assume the Rothermel crown model estimates the spread rate of fully active crown fires, though some of his fires, such as the 1989 Black Tiger fire (NFPA 1990), were likely not fully active. In that respect the Rothermel correlation might underestimate the spread rate of a true fully active crown fire. Second, we assume that the correlation simulates the flame front spread rate alone, without the effect of spotting. However, the observed spread rates used in the correlation included the effect of short- and medium-range spotting on overall fire spread rate. In that respect the correlation should overpredict spread rate of the flame front itself. Last, we use the average spread rate from Rothermel (1991a) rather than the maximum he observed. Therefore, crown fire runs with spread rates faster than the coarse-scale average are possible and will be underpredicted in our method. The combined effects of fires with significant spotting and less than fully active crowning in the Rothermel correlation on simulated active crown fire spread rate is uncertain.

Despite these limitations, the lack of practical alternative models requires that we use Rothermel's (1991a) method to simulate spread rate of a fully active crown fire flame front. Different models of active crown fire spread rate—an improved empirical model (Gomes da Cruz 1999) or a metamodel derived from a physical model—can be substituted as they become available.

To derive an index of crown fire potential, equation 7 must be written in its mathematical form

$$R_{active} = 3.34\left(\frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}\right)_{FM10} \qquad (8)$$

where all terms are evaluated for the characteristics of FM 10. In Rothermel's correlation, crown fire rate of spread depends only on open windspeed, surface fuel moisture contents, and slope steepness, but not on actual surface or canopy fuel characteristics. Active crown fire spread rate probably also varies with other canopy characteristics such as foliar moisture content (Van Wagner 1974, 1989) and canopy bulk density. However, the models that include canopy bulk density show contradictory effects of canopy bulk density on spread rate. Grishin's (1997) physical model indicates increasing spread rate with decreasing canopy bulk density, whereas the empirical model developed by Gomes da Cruz (1999) shows a direct relationship. Albini's crown fire model has not yet been exercised sufficiently to determine how it will respond to variation in canopy bulk density. Until the conflicting effects of canopy bulk density on crown fire spread rate can be resolved, using a model that does not include this variable is not unreasonable.

Foliar Moisture Effect

The Rothermel correlation can be extended to include the theoretical effect of foliar moisture content, *FMC*, on crown fire spread rate using the foliar moisture effect, *FME*, defined by Van Wagner (1974, 1989, 1993) as

$$FME = \left(\frac{(1.5 - .00275 FMC)^4}{460 + (25.9 FMC)}\right) \qquad (9)$$

The *FME* is always applied as a ratio of *FME* to a normal value, FME_o, which is based on the *FMC* in the data used to construct the crown spread rate model. The *FMC* of the fires used in the Rothermel correlation was not documented and surely varied among the fires. Therefore, using the *FME* concept with Rothermel's model will require a derivation of FME_o based on some alternative *FMC*, such as an overall average *FMC* among all species during the fire season in the Northern Rocky Mountains. Taking the range of *FMC* to be 85 to 120 percent and assuming an average of 100 percent, the ratio FME/FME_o would range from 0.714 to 1.31. Incorporating the *FME* concept, equation (8) becomes

$$R_{active} = 3.34\left(\frac{FME}{FME_o}\right)\left(\frac{I_R \xi (1+\phi_w+\phi_s)}{\rho_b \varepsilon Q_{ig}}\right)_{FM10} \quad (10)$$

where FME_o is 0.0007383 for a reference *FMC* of 100 percent. The foliar moisture effect will not be used further in this paper. However, *FME* is included as an option in NEXUS; interested readers can examine its effect on crown fire spread rate and the Torching and Crowning Indices themselves.

Criterion for Crown Fire Initiation

Several models of crown fire initiation are available. Most are semiempirical with a basis in convection theory (Alexander 1998; Van Wagner 1977; Xanthopoulous 1990) that consequently need estimates of heat release rate (fireline intensity) for determining the upward heat flux. Gomes da Cruz (1999) developed a logistic regression model based largely on fuel strata gap (similar to canopy base height) and total surface fuel consumption (as a surrogate for W_f). Gomes da Cruz used total surface fuel consumption to avoid difficulties in estimating fireline intensity. However, surface fuel consumption is itself difficult to estimate. Alexander's model is similar to Van Wagner's, but accounts for the effects of flaming residence time, plume angle, and fuel bed characteristics. While these additional inputs may improve predictions, they are difficult to estimate, so their inclusion is of dubious value. Because of the lack of high quality observations, none of these crown fire initiation models has been rigorously tested against independent data.

We selected Van Wagner's (1977) model of crown fire initiation because it is the most widely used of the potential models, if only because it is one of the oldest. Van Wagner (1977) theorized that canopy fuels ignite when heat supplied by a surface fire drives off their moisture and raises them to ignition temperature. He identified the critical (minimum) fireline intensity of a surface fire, $I'_{initiation}$, that will initiate a crown fire. Van Wagner's (1977) separate equations can be combined as follows to compute $I'_{initiation}$ in kW m^{-1}:

$$I'_{initiation} = \left(\frac{CBH(460+25.9FMC)}{100}\right)^{3/2} \quad (11)$$

where *CBH* is the canopy base height (m). The coefficient 100 in the denominator is an empirical constant based on a single observation.

For further analysis, $I'_{initiation}$ is converted to its equivalent rate of spread, $R'_{initiation}$, by rearranging equation 5 and substituting $I'_{initiation}$ for *I*, following the concepts in the Canadian FFBP System (Forestry Canada Fire Danger Group 1992) and Van Wagner (1993)

$$R'_{initiation} = \frac{60 I'_{initiation}}{HPA} \quad (12)$$

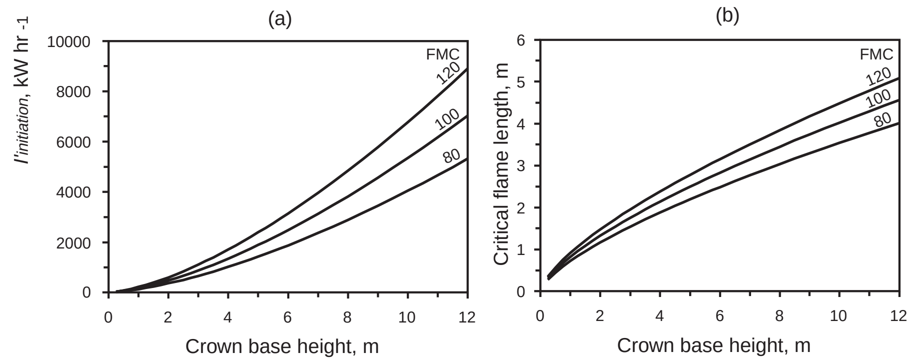

Figure 4—Van Wagner's crown fire initiation criterion (following Alexander 1988) expressed as critical surface fireline intensity (a), and critical flame length using Byram's (1959) flame length model (b). Note that critical flame length is less than canopy base height (*CBH*) for *CBH* greater than about 1 m. **Example**: a stand with *CBH* of 3 m and 100 percent *FMC* requires surface fireline intensity of 875 kW m^{-1} (flame length 1.7 m) to initiate crowning.

Because *HPA* is a function of fuel characteristics, $R'_{initiation}$ will also vary with surface fuel characteristics, even if $I'_{initiation}$ is the same.

Van Wagner's crown fire initiation criterion has not been well tested, but it includes the major variables important to initiating a crown fire—height of canopy fuels above the ground, their moisture content, and the intensity of the surface fire (fig. 4). $I'_{initiation}$ depends on foliar moisture content and canopy base height. In the Rothermel surface fire model, surface fire intensity depends on surface fuel characteristics (load, surface-area-to-volume ratio, heat content, packing ratio, and moisture contents), midflame windspeed, and slope steepness. Different fuel complexes can have the same value of $I'_{initiation}$ (for example, similar *CBH* and *FMC*) but different surface fire intensities.

Criterion for Active Crown Fire Spread

By rearranging a basic heat balance equation applicable to fire spread in any fuel complex, Van Wagner (1977) theorized that solid flames would form in the canopy (active crowning) if a critical horizontal mass-flow rate of fuel into the flaming zone, *S*, is exceeded

$$S = R_{active} CBD \qquad (13)$$

where R_{active} is the after-crowning forward rate of spread and *CBD* is the canopy bulk density (kg m^{-3}). Van Wagner (1977) found a critical mass flow rate of 0.05 kg m^{-2} sec^{-1} for one fire in a red pine plantation, slightly lower than the values given for experimental fuel beds by Thomas (1963). Until more data on the critical mass flow rate for crown fires in a wide range of forest types are available we will rely on Van Wagner's critical mass-flow rate of 0.05 kg m^{-2} sec^{-1}. Rearranging equation 12, substituting Van Wagner's value of 0.05 for *S*, and multiplying by 60 to compute R'_{active} in m min^{-1} (Alexander 1988), the critical (minimum) rate of spread for active crowning, R'_{active}, is

$$R'_{active} = \frac{3.0}{CBD} \qquad (14)$$

The only factor affecting the critical spread rate needed to sustain an active crown fire is *CBD* (fig. 5).

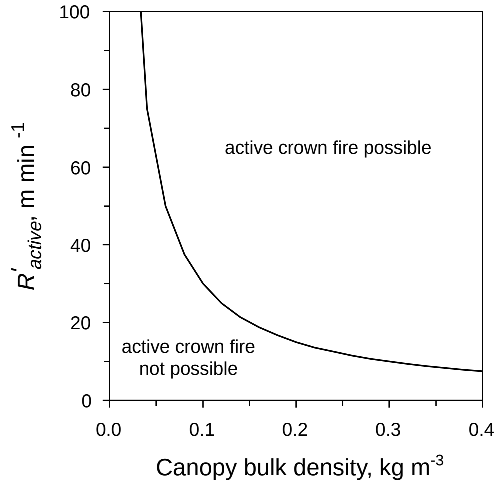

Figure 5—Van Wagner's criterion for sustained active crown fire spread based on a minimum horizontal mass-flow rate of 0.05 kg m^{-2} min^{-1}. **Example**: a stand with *CBD* of 0.2 kg m^{-3} requires a spread rate of 15.0 m min^{-1} to sustain active crowning.

Quantitative Crown Fire Classification

Following Van Wagner (1977) and Alexander (1988), we use the criteria for initiation and sustained spread of crown fires to classify a fire as surface, passive crown, or active crown fire. In the classification, two criteria must be met in order to have an active crown fire. First, a surface fire of sufficient intensity must ignite the canopy fuels; $I_{surface}$ must exceed $I'_{initiation}$. Using equation 11, the required intensity is a function of foliar moisture content and height to the base of the canopy. If this criterion cannot be met, the fire will remain on the surface. Second, if a crown fire can indeed initiate, the potential crown fire spread rate for the conditions specified must be sufficient to meet the mass-flow requirement (equation 13).

The expected type of fire then follows from simulated surface fire intensity and crown fire spread rate (fig. 6). If the classification is followed strictly, all situations in which the surface fire intensity criterion is not met are classified as surface fires. However, an alternative classification splits the surface fire class into two subclasses. These will be discussed later in the section on hysteresis.

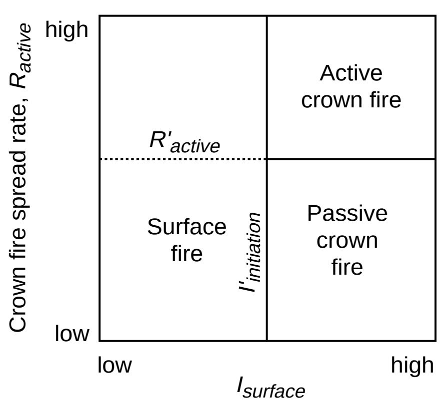

Figure 6—Fire classification based on Van Wagner (1977) and Alexander (1988). A fire for which surface fire intensity ($I_{surface}$) is less than critical ($I'_{initiation}$) falls in the surface fire class; one for which $I_{surface}$ exceeds $I'_{initiation}$ is either a passive or active crown fire depending on the crown fire spread rate criterion. Passive crowning occurs where a crown fire initiates ($I_{surface} > I'_{initiation}$) but cannot be sustained ($R_{active} < R'_{active}$). An active crown fire occurs where both criteria are exceeded.

QUANTIFYING THE HAZARD

Our objective is to produce a method of quantitatively assessing the relative crown fire hazard of different stands by coupling the existing fire behavior models presented above. At any given site, fuels and topography can be considered constant in the short term. Weather, however, varies significantly throughout a day, from day to day, and throughout a season.

In the fire behavior models presented above, weather is manifested in two basic inputs: windspeed and dead fuel moisture content. From a description of the surface fuels, canopy fuels, and site characteristics needed for the above models, we can define critical combinations of dead fuel moisture and windspeed that result in surface, passive crown, and active crown fires. Consider a simulation for a hypothetical stand with the characteristics shown in table 3. The passive crown fire region is fairly narrow (fig. 7), and active crowning can occur under moderate burning conditions.

While it is possible to compute all combinations of dead fuel moisture and windspeed that lead to crown fire activity for a given fuel complex, for purposes of a relative hazard assessment it is sufficient to set fuel moistures constant at values that represent some moisture condition of interest (for example, actual, typical, or extreme moisture conditions). Windspeed is highly variable and probably the most important environmental factor affecting crown fire initiation, sustained active spread, and final rate of spread. Therefore, we will determine the critical open wind, *O* (6.1-m above the canopy), that leads to crown fire activity for a set of site characteristics, surface and canopy fuel characteristics, and fuel moisture conditions. Sites that can initiate or sustain a crown fire at lower windspeeds are more prone to crown fire. Critical open windspeeds for crown fire initiation and active spread are stand-specific indicators of crown fire hazard. Note that although we use critical windspeeds as indices, the site conditions (surface and canopy fuels, slope steepness, and so forth), not the weather, are being rated.

Table 3—Simulation inputs for a hypothetical stand to be used in examples throughout this paper.

Input	Value
Fuel model	10 (timber litter)
Slope	0 percent
Canopy bulk density	0.15 kg m^{-3}
Canopy base height	1.5 m
Foliar moisture content	100 percent
Wind reduction factor	0.15
Live fuel moisture	Normal summer[a]

[a] See table 4 for a listing of fuel moisture content by size class.

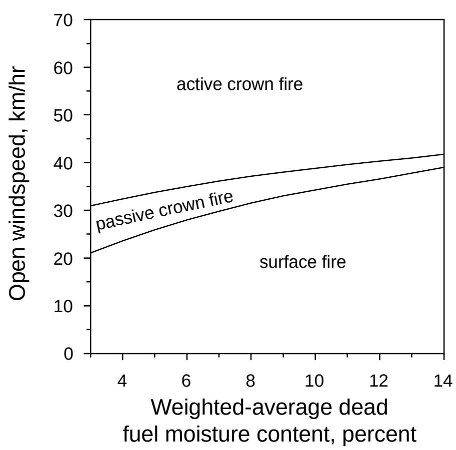

Figure 7—Van Wagner's (1977) crown fire classification under varying open windspeed and dead surface fuel moisture conditions for the example stand. For this example, a passive crown fire region separates surface fire and active crown fire. **Inputs**: fuel model 10 (timber litter and understory, Anderson 1982), canopy base height = 1.5 m, canopy bulk density = 0.15 kg m^{-3}, foliar moisture content = 100 percent, live surface fuel moisture = 78 percent, and wind reduction factor = 0.15.

The Torching Index (TI) is the 6.1-m windspeed at which crown fire is expected to initiate based on Rothermel's (1972) surface fire model and Van Wagner's (1977) crown fire initiation criteria. TI is a function of surface fuel characteristics (fuel model), surface fuel moisture contents, foliar moisture content, canopy base height, slope steepness, and wind reduction by the canopy.

The Crowning Index (CI) is the 6.1-m windspeed at which active crowning is possible, based on Rothermel's (1991a) crown fire spread rate model and Van Wagner's (1977) criterion for active crown fire spread. CI is a function of canopy bulk density, slope steepness and surface fuel moisture content.

The Torching and Crowning Indices can be determined graphically by plotting $R_{surface}$, R_{active}, $R'_{initiation}$ and R'_{active} over a range of open windspeeds (fig. 8), holding moisture content at some specified level—in this example we use Rothermel's (1991a) normal summer condition (table 4). The TI is the windspeed where the lines for $R_{surface}$ and $R'_{initiation}$ cross. The CI is where the lines for R_{active} and R'_{active} cross. Van Wagner's fire classification is also shown on the chart. At windspeeds less than TI a surface fire is expected. If the windspeed is greater than TI but less than CI we expect a passive crown fire. Finally, windspeeds greater than CI result in active crown fire.

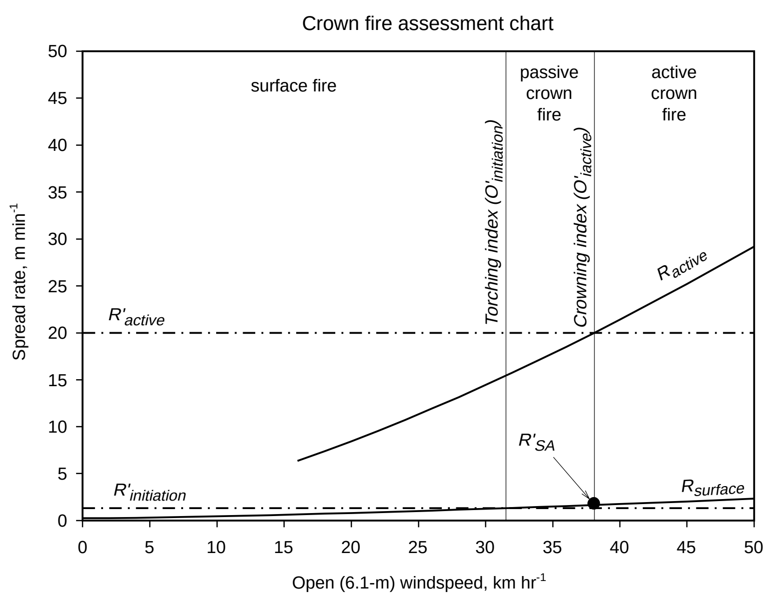

Figure 8—The Torching and Crowning Indices can be determined graphically on a crown fire assessment chart. The open windspeed at which $R_{surface}$ exceeds $R'_{initiation}$ (same as $I_{surface} > I'_{initiation}$) is the Torching Index (TI). The open windspeed at which R_{active} exceeds R'_{active} is the Crowning Index. A surface fire is expected at windspeeds below TI. Windspeeds greater than TI but less than CI lead to passive crowning. Active crown fire is expected at windspeeds above CI. The theoretical surface fire spread at CI (R'_{SA}) is shown; that quantity will be used later in the paper. **Inputs**: fuel model 10 (timber litter and understory, Anderson 1982), canopy base height = 1.5 m, canopy bulk density = 0.15 kg m^{-3}, foliar moisture content = 100 percent, normal summer surface fuel moisture condition (Rothermel 1991, table 4), and wind reduction factor = 0.15.

Table 4—Fuel moisture content values (percent) by size class for five seasonal moisture conditions, from Rothermel (1991a).

	Seasonal moisture condition				
Class	Early spring before greenup	Late spring after greenup	Normal summer	Drought summer	Late summer severe drought
1-h	8	9	6	4	3
10-h	14	11	8	5	4
100-h	18	15	10	7	6
live	65	195	117	78	70

The quantity R'_{SA}, the simulated surface fire spread rate when the windspeed = O'_{active} is also shown in figure 8; it will be referenced in the discussion of crown fraction burned in appendix A.

The effects of slope are difficult to generalize because slope can either increase or decrease fire spread rate depending on wind direction. In his analysis of crown fire spread, Rothermel (1991a) suggests assuming level ground for modeling average crown fire behavior over large areas, and assuming upslope winds for worst-case analysis. One might want to examine effects of wind direction with respect to slope on crown fire potential. Equations for determining TI and CI for cross-slope winds are on file with the authors at the Rocky Mountain Research Station, Missoula Fire Sciences Lab. The derivations of critical windspeed for crown fire initiation and sustained spread for upslope winds will be shown below.

Torching Index—The Torching Index is the open windspeed at which $I'_{initiation} = I_{surface}$. Assuming that W_f is independent of windspeed, as it is in the Rothermel surface fire model, then TI is also the windspeed at which $R'_{initiation} = R_{surface}$. Combining equations 6 and 12 allows us to express $R'_{initiation} = R_{surface}$ as

$$\frac{60 I'_{initiation}}{HPA} = \frac{I_R \xi (1 + \phi'_{w(initiation)} + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (15)$$

where $\phi'_{w\,(initiation)}$ is the critical wind coefficient for crown fire initiation. Solving equation 15 for $\phi'_{w\,(initiation)}$ gives

$$\phi'_{w(initiation)} = \frac{60 I'_{initiation} \rho_b \varepsilon Q_{ig}}{HPA \xi I_R} - \phi_s - 1 \qquad (16)$$

Rothermel (1972), expressed in SI units by Wilson (1980) with midflame windspeed (U) in km hr^{-1}, defines ϕ_w

$$\phi_w = C(54.683U)^B \left(\frac{\beta}{\beta_{op}}\right)^{-E} \qquad (17)$$

where C, B, and E are constants for any given surface fuel complex that depend only on σ, and β/β_{op} is the ratio of actual to optimum packing ratio of the fuel bed (Rothermel 1972). Combining equations 16 and 17 and converting to the open windspeed gives us $O'_{initiation.}$

$$TI = O'_{initiation} = \left(\frac{1}{54.683 WRF}\right) \left(\frac{\dfrac{60 I'_{initiation} \rho_b \varepsilon Q_{ig}}{HPA \xi I_R} - \phi_s - 1}{C\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}} \right)^{\frac{1}{B}} \qquad (18)$$

The Torching Index can be computed for any combination of surface fuels, fuel moistures, canopy base height, wind reduction factor, and foliar moisture content.

Crowning Index—Similarly, to derive the Crowning Index, O'_{active}, we solve for O'_{active} such that R_{active} equals R'_{active}, which in turn is expressed in terms of canopy bulk density (equation 13). Solving first for the critical midflame windspeed,

$$U'_{active} = \left(\frac{1}{54.683}\right)\left(\frac{\dfrac{\left(\dfrac{3.0}{CBD}\right)\rho_b \varepsilon Q_{ig}}{3.34 I_R \xi} - \phi_s - 1}{C\left(\dfrac{\beta}{\beta_{op}}\right)^{-E}}\right)^{\frac{1}{B}} \qquad (19)$$

As in equation 8, the terms from Rothermel's crown fire rate of spread equation are evaluated only for FM 10, so all terms are constant except I_R and $\varepsilon\ Q_{ig}$, which vary with fuel moisture, and *CBD* and ϕ_s. Simplifying equation 19, substituting fuel characteristics for FM 10 and converting to open wind, we have

$$CI = O'_{active} = 0.0457\left(\frac{\dfrac{164.8\varepsilon Q_{ig}}{I_R CBD} - \phi_s - 1}{.001612}\right)^{0.7} \qquad (20)$$

where the terms are evaluated for the fuel characteristics of FM 10.

Nomograms for computing TI and CI for flat ground have been created (see appendix D). For more complex situations, the spreadsheet NEXUS (Scott 1999, www.fire.org/nexus/nexus.html) can be used. The Torching and Crowning Indices have been incorporated into FFE-FVS, and have been coded to operate directly in ArcInfo GIS.

SIMULATING OVERALL SPREAD RATE AND INTENSITY

Methods for simulating surface fire behavior, active crown fire behavior, and the thresholds for crown fire initiation and active crown fire spread for the Northern Rocky Mountains were described earlier. In this section we simulate the behavior of a fire as it makes the transition from surface to crown fire as burning conditions worsen.

Overall Spread Rate

An elusive goal of fire modelers has been to simulate the full range of fire behavior exhibited in forest stands using one model or system of models. Any single model is unlikely to adequately simulate surface fire behavior, transition to crown fire, and crown fire behavior in the near future. However, existing models can be linked together to produce such simulations. Final rate of fire spread (R_{final}), whether surface or crown, is computed following Van Wagner (1989, 1993) and the Forestry Canada Fire Danger Group (1992) as

$$R_{final} = R_{surface} + CFB(R_{active} - R_{surface}) \qquad (21)$$

where *CFB* is a transition function, termed “crown fraction burned,” that ranges from 0 for a surface fire to 1 for a fully active crown fire (Van Wagner 1993). (In the Canadian FFBP System, the Forestry Canada Fire Danger Group [1992] defines a surface fire as having *CFB* > 0.1 and an active crown fire as having *CFB* > = 0.9.) Conceptually, *CFB* is the fraction of canopy fuels consumed in a fire. Several alternative derivations of *CFB* are available (Finney 1998; Forestry Canada Fire Danger Group 1992; Van Wagner 1989, 1993), but none are based on observed (for example, Stocks 1987, 1989) or modeled (for example Call and Albini 1997) canopy fuel consumption. Instead, *CFB* is simply a transition function to estimate final spread rate from simulations for surface and fully active crown fires, and to estimate of the degree of crowning (Van Wagner 1989, 1993). In all of the above models, the proportion of canopy fuels burned (for estimating fireline intensity, for example) is assumed to equal the value of the transition function.

We used a linear *CFB* transition function for scaling spread rate between $R_{surface}$ and R_{active}. A detailed discussion of alternative methods of estimating *CFB* can be found in appendix A. For the example stand described earlier, R_{final} and *CFB* are plotted on the crown fire hazard assessment chart (fig. 9). Crown fraction burned is zero until the windspeed equals the TI, then increases linearly to 1.0 where the windspeed equals the CI. For windspeeds less than TI, a surface fire is expected and R_{final} equals $R_{surface}$. For windspeeds in excess of CI, a fully active crown fire is expected, and R_{final} equals R_{active}. In the passive crown fire region between TI and CI, passive crowning is expected, and R_{final} is scaled between $R_{surface}$ and R_{active} (equation 21) based on *CFB*.

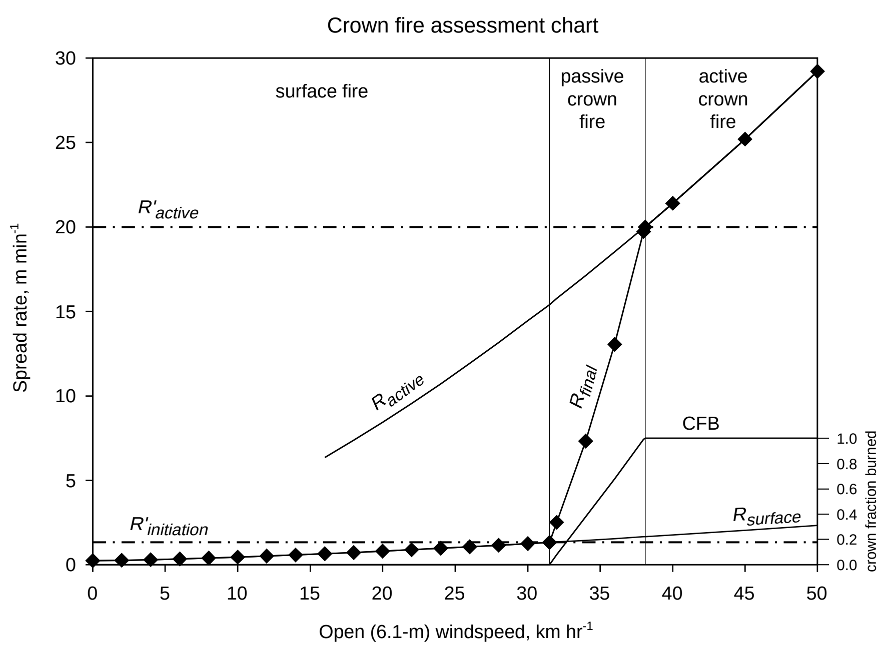

Figure 9—Final spread rate (R_{final}) and crown fraction burned (*CFB*) plotted over a range of windspeeds. Crown fraction burned (right-hand Y-axis) is 0 until windspeed reaches the TI, then increases to 1 where windspeed reaches CI. In the surface fire region, R_{final} = $R_{surface}$. In the passive crown fire region, final spread rate is scaled between $R_{surface}$ and R_{active}. In the active crown fire region, $R_{final} = R_{active}$. **Inputs**: fuel model 10 (timber litter and understory, Anderson 1982), canopy base height = 1.5 m, canopy bulk density = 0.15 kg m^{-3}, foliar moisture content = 100 percent, normal summer surface fuel moisture condition (Rothermel 1991a, table 4), and wind reduction factor = 0.15.

Overall Fireline Intensity

Final fireline intensity is computed by modifying equation 5 as follows:

$$I_{final} = \frac{\left(HPA_{surface} + \left(W_{canopy} H_{canopy} CFB\right)\right) R_{final}}{60} \qquad (22)$$

where W_{canopy} is the available canopy fuel load, and H_{canopy} is the heat yield of canopy fuels (including a reduction for moisture content). Following FARSITE (Finney 1998) we assume a heat yield of 18,000 kJ kg^{-1} for canopy fuels.

HYSTERESIS IN CROWN FIRE: THE CONDITIONAL SURFACE FIRE

Conventional wisdom is that a surface fire must first go through a passive crown fire phase before becoming active as burning conditions worsen (for example, as windspeed increases), and that any stand not capable of initiating a crown fire would not support an active crown fire under the same conditions. However, the links among models of surface and crown fire behavior indicate a different possible behavior during transition to crown fire. In this section we discuss the evidence of hysteresis in the linked surface and crown fire models and its potential impact on fire behavior and crown fire hazard assessment.

For many stand conditions, such as those with low canopy base height (which makes initiation easier) and low canopy bulk density (which makes active crowning more difficult), a period of passive crowning would be experienced as conditions worsen and active crowning is approached. In these situations the Torching Index is less than the Crowning Index; the region between the two indices is the passive crown fire region (fig. 8). In stands that have higher canopy base height or higher canopy bulk density, such as those associated with dense, single-storied stands, the TI can be higher than the CI. That is, stronger winds may be required to initiate crowning than are needed to sustain active crowning once started. For example, by modifying characteristics of our example stand so that *CBH* = 2 m and *CBD* = 0.25 kg m^{-3}, the TI is 45 while the CI is only 26 (fig. 10). This "reversal" of TI and CI only occurs with certain combinations of *CBH* and *CBD*. The combinations of those variables where TI = CI (for level ground, normal summer

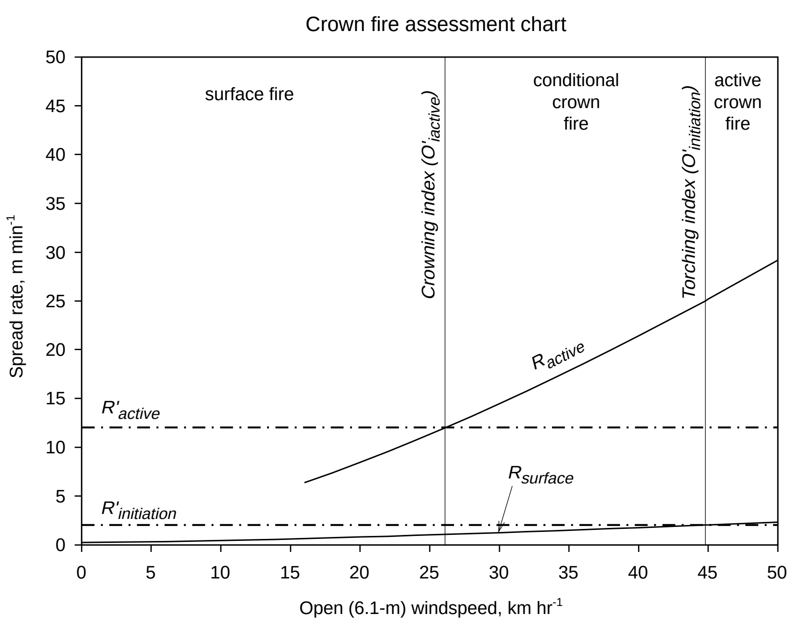

Figure 10—In conditions of relatively high *CBH* and *CBD*, the CI is less than the TI. That is, more extreme conditions (of wind and fuel moisture) are required to initiate crown fire than to maintain active crown fire. This situation can lead to a hysteresis in spread rate and intensity. **Inputs**: fuel model 10 (timber litter and understory, Anderson 1982), canopy base height = 2.0 m, canopy bulk density = 0.25 kg m^{-3}, foliar moisture content = 100 percent, normal summer surface fuel moisture condition (Rothermel 1991a, table 2), and wind reduction factor = 0.15.

fuel moisture conditions and *WRF* = 0.15) can be plotted for a range of surface fuel models (fig. 11). For the example in figure 11, if the *CBD* = 0.2 kg m^{-3} there can be a hysteresis if *CBH* is greater than about 0.2 m for fuel model 8, 1.5 m for fuel model 10, and 3.5 m for fuel model 12. Many stands of that *CBD* have *CBH* greater than those critical values, so the hysteresis may not be a rare phenomenon.

Following Van Wagner's (1977) classification, any stand for which surface fireline intensity does not meet the initiation criterion is classed as a surface fire (that is, when the windspeed is less than the TI). For a before-the-fact classification of the type of fire, surface fireline intensity is estimated from a model of surface fire behavior (for example, Rothermel 1972), which implicitly assumes that the origin of the fire in the stand of interest is a surface fire. But what if fire spreads to the stand of interest as a crown fire, having made the transition earlier or elsewhere? How then should fireline intensity be estimated for the stand of interest?

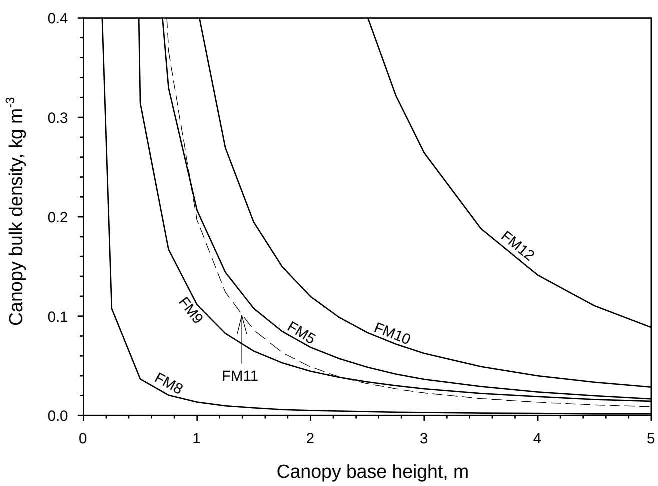

Figure 11—Combinations of canopy base height (*CBH*) and canopy bulk density (*CBD*) for which the Torching Index equals the Crowning Index, for various surface fuel models. Combinations of *CBH* and *CBD* that fall above the lines will exhibit a hysteresis in some range of environmental conditions. **Inputs**: level ground, 100 percent foliar moisture content, and normal summer fuel moisture condition (Rothermel 1991a).

In applying his classification model to experimental fires in mature and immature stands of jack pine, Van Wagner (1993) calculates surface fireline intensity as the product of fuel consumption and observed spread rate. That is, he computed the contribution of surface fuels to the total fireline intensity, whether the fire was on the surface or in the crowns. Therefore, surface fireline intensity depended in large part on the type of fire observed, with the higher spread rates associated with crown fire leading to higher surface fireline intensity. According to Rothermel's (1991a) model, crown fire spread rate can be as many as six to eight times faster than that of a surface fire burning in the same conditions (Scott 1998), which means that surface fuel contribution to fireline intensity would also be as much as six to eight times greater during active crowning than for normal surface fire spread.

With separate models of surface and crown fire behavior, we need to know the type of fire before applying the classification to determine exactly that—the type of fire. This circularity occurs only when the Torching Index is greater than the Crowning Index. In that case, when the windspeed is between the two indices, two different results are possible—surface fire or active crown fire—depending on the type of originating fire. Rothermel described this phenomenon as a cusp catastrophe in an unpublished paper presented at the 1999 National Fire Behavior Workshop (March 1–5, 1999; Phoenix, AZ).

If the fire begins as a surface fire, then the former classification would correctly predict surface fire until the wind reached the TI, at which time active crowning would begin almost immediately, without experiencing a period of passive crown fire, because both criteria are met. However, if the fire spreads into the stand as an already-initiated crown fire, then the higher spread rate of the crown fire is used to estimate the contribution of surface fuels to fireline intensity. This higher intensity may be sufficient to meet the crown fire initiation criterion at a lower windspeed. The type of fire experienced therefore depends on the origin of fire in the subject stand.

We call the region of the classification where the active crowning criterion is met but the initiation criterion is not a "conditional surface fire" (fig. 12). This is equivalent to the range between the CI and TI when TI > CI. If the fire originates as a surface fire, then it is expected to remain so. If the fire originates as an active crown fire in an adjacent stand, then we compare the contribution of surface fuels to overall fireline intensity (using the higher crown fire spread rate) against the threshold for crown fire initiation. If the intensity is greater than critical, then the active crown fire could continue through the stand, otherwise the fire is expected to drop to the ground.

The contribution of surface fuels to total fireline intensity during a crown fire is the product of $HPA_{surface}$ and R_{active}. For any given surface fuel model, $HPA_{surface}$ varies only with fuel moisture. Using Rothermel's crown fire spread correlation, R_{active} varies primarily with windspeed, but also with slope and surface fuel moisture. For level ground and 100 percent foliar moisture content, the critical open windspeed that could be expected to cause cessation ($O'_{cessation}$) increases with *CBH* (fig. 13).

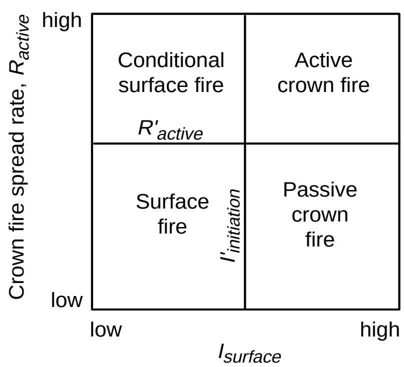

Figure 12—Extension of Van Wagner's (1977) original classification to include conditional surface fire. Cases in which *CBD* is sufficient to support active crowning but surface fire intensity (from Rothermel's surface fire model) is below the threshold for initiation fall into the conditional surface fire class. Within this class, the type of fire observed depends on the origin of the fire in the subject stand; surface fires are expected to remain on the surface, and active crown fires remain fully active.

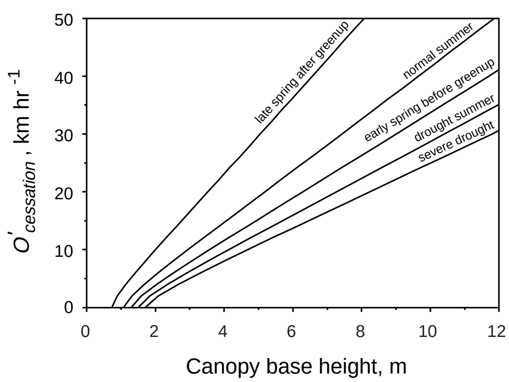

Figure 13—Theoretical open windspeeds for crown fire cessation using Van Wagner's (1977) initiation criterion for a range of canopy base heights and a variety of dead fuel moisture conditions (Rothermel 1991a). Fireline intensity computed as the product of heat per unit area from fuel model 10 (Anderson 1982) and active crown fire spread rate from Rothermel (1991a). **Inputs**: Slope = 0 percent, foliar moisture content = 100 percent.

Conditions for Crown Fire Cessation

The process of crown fire cessation has not yet been studied on its own. However, Van Wagner's two criteria for crown fire initiation can be modified and applied to cessation. There are again two criteria to check; failure to meet either one will lead to crown fire cessation.

Mass-Flow Rate too Low—The mass-flow rate through the canopy must be at least 3.0 kg m^{-2} s^{-1}, which leads to a critical spread rate (equation 14). If the product of the potential active crown fire spread rate and canopy bulk density does not meet this threshold, then active crowning is not possible and active crowning ceases. Cessation from failure to meet the mass-flow requirement is quantified by the Crowning Index. If the windspeed falls below CI then an active crown fire could be expected to cease.

Intensity in Surface Fuels too Low—The after-crowning contribution of surface fuels to fireline intensity must be sufficient to meet the threshold for initiation (equation 11). If the product of R_{active} and $HPA_{surface}$ falls below the threshold for crown fire initiation, we assume that the crown fire could not continue. Using the criterion in this way implies that crown fire spread can be modeled as a series of crown fire initiations, similar in concept to assumptions made for surface fire spread (Rothermel 1972). It is not known whether this mechanism is realistic for crown fires.

Assuming flat ground and normal summer surface fuel moisture condition (Rothermel 1991a), the open windspeed that leads to cessation of active crown fire depends on surface fuel model and *CBH* (fig. 14). We use equation 5 for determining the contribution of surface fuels to fireline intensity; R is R_{active}, but *HPA* is determined in the Rothermel surface fire model from surface fuel characteristics. Cessation from failure to meet the initiation criterion is quantified by $O'_{cessation}$, the open windspeed at which the product of $HPA_{surface}$ and R_{active} equals the minimum necessary for crown fire initiation.

In formulating crown fire mitigation strategies, forest managers are just as concerned with causing crown fire cessation as limiting its initiation. Crown fire cessation is indexed as the higher of *CI* and $O'_{cessation}$, which we call the Surfacing Index (SI). The Surfacing Index can be plotted on the crown fire assessment chart along with TI and CI (fig. 15). In the example in figure 15, *CI* is greater than $O'_{cessation}$ so SI = CI.

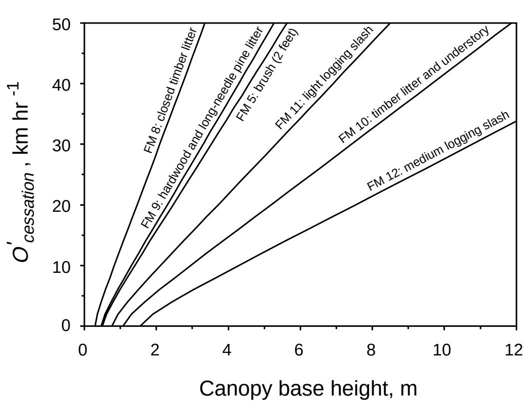

Figure 14—Theoretical open windspeed for crown fire cessation using Van Wagner's (1977) initiation criterion for a range of canopy base heights and a variety of surface fuel models (Anderson 1982). Fireline intensity is computed as the product of heat per unit area from the various fuel models and active crown fire spread rate from Rothermel (1991a). **Inputs**: slope = 0 percent, live fuel moisture = 100 percent, foliar moisture content = 100 percent, dead fuel moisture content = 5 percent.

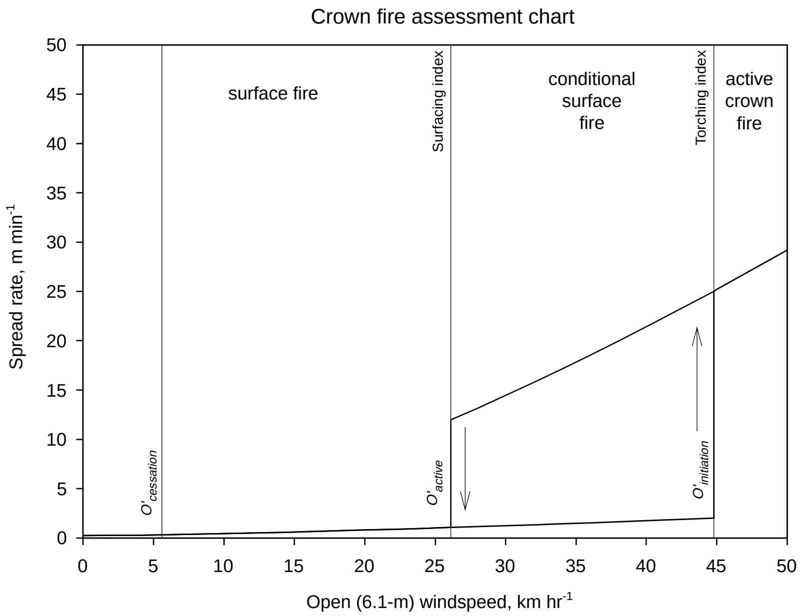

Figure 15—The Surfacing Index (SI) is the higher of $O'_{cessation}$ and O'_{active}. In this example, O'_{active} is higher than $O'_{cessation}$, so SI = CI. A crown fire is expected to surface when the windspeed drops below SI. **Inputs**: fuel model 10 (timber litter and understory, Anderson 1982), canopy base height = 2.0 m, canopy bulk density = 0.25 kg m^{-3}, foliar moisture content = 100 percent, normal summer surface fuel moisture condition (Rothermel 1991a, table 4), and wind reduction factor = 0.15.

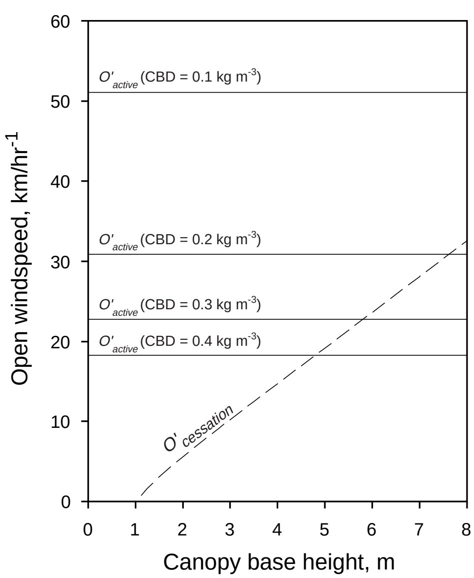

Figure 16—The open windspeed for crown fire cessation ($O'_{cessation}$) and sustained active crown fire spread (O'_{active}) plotted for a range of canopy base heights (*CBH*) and a variety of canopy bulk densites (*CBD*). The intersections of plots for $O'_{cessation}$ and O'_{active} indicate combinations of *CBH* and *CBD* where they equally limit continued crown fire spread. **Inputs**: level ground, 100 percent foliar moisture content, normal summer fuel moisture condition (Rothermel 1991a), and wind reduction factor = 0.15.

It is helpful to know whether CI or $O'_{cessation}$ is the limiting factor in crown fire cessation, which depends mainly on *CBH* and *CBD*. For level ground, fuel model 10 (Anderson 1982), and normal summer fuel moisture conditions, the combinations of *CBH* and *CBD* where CI (O'_{active}) equals $O'_{cessation}$ can be found graphically (fig. 16). For those conditions, if *CBD* = 0.2 kg m^{-3} then $O'_{cessation}$ is limiting only if *CBH* is greater than about 7.5 m. We get a better picture of the tradeoffs by plotting the intersections of O'_{active} and $O'_{cessation}$ for a variety of fuel models (fig. 17). With fuel model 12 (medium logging slash) for example, $O'_{cessation}$ is limiting only if *CBH* is greater than about 8 m even if *CBD* = 0.3 kg m^{-3}. By contrast, the low *HPA* for fuel model 8 means that $O'_{cessation}$ is limiting if *CBH* is greater than about 2 m; otherwise cessation is determined by the mass-flow rate requirement.

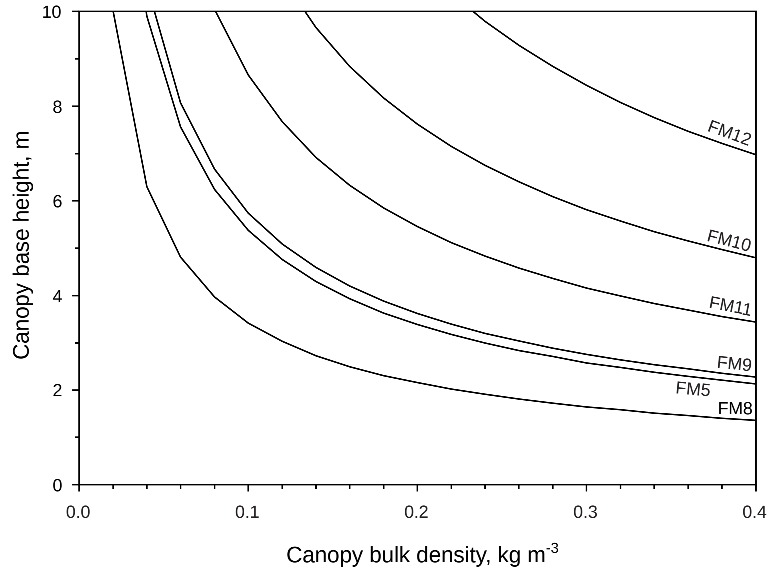

Figure 17—Combinations of canopy base height (*CBH*) and canopy bulk density (*CBD*) where they equally limit continued crown fire spread, for a variety of surface fuel models. A combination of *CBH* and *CBD* that falls above the line for the appropriate fuel model indicates that *CBH* is more limiting than *CBD*. **Inputs:** level ground, 100 percent foliar moisture content, normal summer fuel moisture condition (Rothermel 1991a), and wind reduction factor = 0.15.

With separate sets of criteria for initiation and cessation, a hysteresis is possible in which the path of fire behavior as windspeed increases may be different from the path as it decreases (see fig. 15). Two behaviors are possible in the conditional surface fire region depending on whether the region is approached from the lower windspeeds as a surface fire or as a crown fire from the higher windspeeds. Even with constant winds, spatial variability in surface fuels, canopy fuels, and topography can lead to the incidence of active crown fire where the former classification always predicts a surface fire.

Implications of Hysteresis in Crown Fire

This procedure for determining the actual type of fire within the conditional surface fire class is an untested theoretical extension of Van Wagner's (1993) classification. The mechanisms of crown fire cessation are poorly understood. This approach simulates two possible mechanisms. However, not using this revised classification leads to expectation of surface fire when crown fire may be encountered. Stands that are considered safe from crown fire initiation cannot necessarily be relied upon to cause crown fire cessation.

This phenomenon has several important consequences that should be further investigated. The conditions that lead to crown fire initiation may be quite different from the conditions that lead to crown fire cessation. If initiation and cessation of crown fires follow different paths, then a hysteresis is created in which a crown fire can be sustained even if conditions ameliorate. Hysteresis could explain the persistence of crown fires well into the night during major crown fire runs, such as those that occurred in Yellowstone National Park, WY, in 1988 (Hartford and Rothermel 1991).

The transition from surface fire spread to active crown fire spread can occur as an abrupt change, with no period of passive crowning to act as a warning. Even small changes in the fire environment can cause a surface fire to become fully active quickly. Sudden changes in fire behavior have contributed to the entrapment of many wildland firefighters.

The fire environment is highly variable in space and time. A hysteresis in the crown fire phenomenon could take advantage of this variability by initiating crown fire activity during the short periods when conditions are most favorable, yet continue with active spread through the lulls. Large fires may be more likely to exhibit crown fire activity than smaller ones because, with more perimeter length, large fires are more likely to encounter fuel and topographic conditions conducive to crown fire initiation (Rothermel 1991b). Once initiated, it may be possible for crown fire to spread through adjacent stands that could not initiate crown fire on their own. This has implications for how we determine model inputs in the face of spatial and temporal variability. The extremes of the fire environment become much more important than the mean when identifying thresholds.

Hysteresis in crown fire initiation and cessation is not proven to exist. However, in light of the evidence of hysteresis in high intensity wildland fire, fire managers should consider its possibility until further investigations can be carried out.

EXAMPLE SIMULATIONS USING THE COUPLED MODEL

All models we used in deriving the indices of crown fire potential and overall spread rate and intensity have already been tested and verified to some degree, though not comprehensively. Proper validation of the indices and coupled model requires numerous observations of surface and crown fire behavior coupled with accurate, stand-level descriptions of surface and canopy fuels, weather, and topography. Unfortunately, wildfire documentation, the sole source of crown fire spread observations in the United States, does not contain enough information to provide useful data. Too many vital model inputs must be inferred or estimated after the fact rather than observed. In those cases one cannot determine whether fire behavior observations that deviate from simulations result from errors in the model or from errors in estimating inputs or fire behavior.

We used data from a few well-documented fires that exhibited various degrees of crowning (1990 Dude Fire, 1974 Burnt Fire, 1977 Pattee Canyon Fire) in an attempt to verify that our method was performing reasonably. However, even those fires left significant gaps in pertinent information (for example, fuel moisture, onsite windspeeds, stand-specific surface, and canopy fuel data), and contained only coarse-scale observations of fire behavior. Despite encouraging results of the trials, the lack of complete data sets (and the attendant need to substitute estimates) renders the verification meaningless, so it is not presented here. Validation data of good quality are difficult to come by; their collection on wild, prescribed, and experimental fires in the United States should become a high priority for research and management.

In this section we will demonstrate the application of the indices and fire behavior simulations by comparing the relative crown fire potential of two contrasting forest stands on the Bitterroot National Forest, MT. No observations of crown fire activity are available for these stands.

We examine the effects of fuel treatments on crown fire potential and discuss the implications of individual fuel treatment options on crown fire hazard. Finally, we couple the indices with diurnal weather and fuel moisture data to determine the expected type of fire throughout the day.

Crown Fire Hazard in Two Stands on the Bitterroot National Forest

The application of the linked models is demonstrated by comparing crown fire hazard and simulated fire behavior in two contrasting stands on the Bitterroot National Forest, Montana. Both stands are on the east slope of the Bitterroot Range, near the town of Hamilton, MT. Stand A (PIPO) is a midelevation stand of old-growth ponderosa pine (*Pinus ponderosa*) with under and middle stories of Douglas-fir (*Pseudotsuga menzeizii*), grand fir (*Abies grandis*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*). Stand B (PICO) is higher elevation (table 5) and dominated by lodgepole pine (fig. 18). The PIPO stand is

Table 5—Summary of stand and site characteristics for a *Pinus ponderosa* stand (A) and *Pinus contorta* stand (B) in the Bitterroot Mountains, Montana, U.S.A.

Characteristic	Stand A	Stand B
Slope, percent	20	20
Aspect	E	NE
Elevation, m	1,520	1,860
Total basal area, m^2/ha	29.8	36.4
Surface fuel model	5	10
Canopy characteristics		
CBH , m	1.5	0.9
CBD, kg/m^3	0.06	0.21
W_{canopy}, kg/m^2	1.22	2.25
H_{crown}, kJ/kg	18,000	18,000
FMC, percent	100	100
WRF	0.15	0.12
Surface fuel moisture, percent		
0-6 mm dia. class	5	8
6-25 mm dia. class	6	9
25-76 mm dia. class	8	10
Fine live fuels	117	117

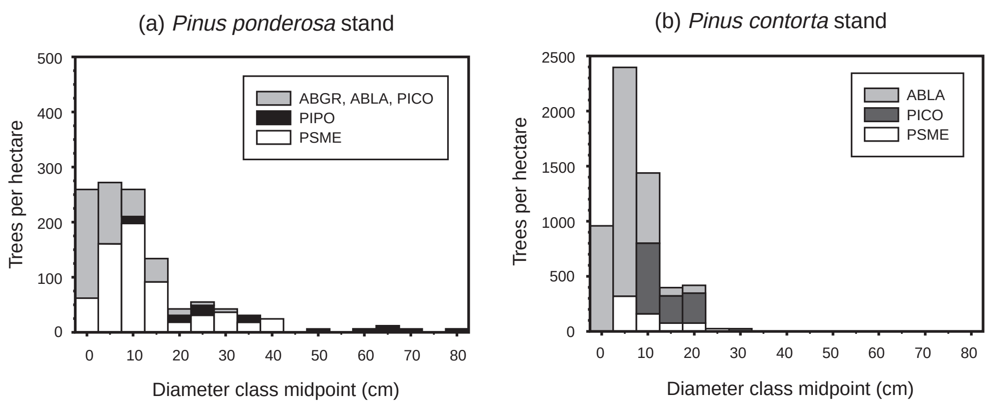

Figure 18—Structure of example *Pinus ponderosa* (a) and *Pinus contorta* (b) stands on the Bitterroot National Forest, Montana. Note: the y-axis scales are different for the two stands.

wholly within the B-4 plot described by Arno and others (1995). It had a pre-1900 mean fire return interval of 13 years, with the last recorded fire in 1908.

Analysis—Canopy fuel load and bulk density were estimated using allometric equations (Brown 1978). Rather than assume a uniform vertical distribution of canopy fuels, we estimated *CBD* in thin layers (0.3 m in height) by summing the crown fuel load in these horizontal layers (Kilgore and Sando 1975, Sando and Wick 1972). The "effective" *CBD* for use in the coupled models was the maximum 4.5-m (15-ft) running mean *CBD* within the canopy, as in the Fire and Fuels Extension to the Forest Vegetation Simulator. This is illustrated for stand B in figure 2.

Following Sando and Wick (1972), "effective" canopy base height (that is, with ladder fuels incorporated) was estimated by computing the minimum height above ground where a *CBD* of 0.037 kg m^{-3} (100 lbs $acre^{-1}$ ft^{-1}) occurs. Although the critical canopy bulk density set by Sando and Wick was arbitrary, the results for these stands agree with visual inspections.

Moisture contents of fine dead surface fuels were estimated using the moisture tables from the Fire Behavior Field Reference Guide for a July day with high temperature of 30 °C and low relative humidity of 20 percent at 1600 hours at the elevation of the PIPO stand (table 5). Differences in dead fuel moisture between the PIPO and PICO stands arise primarily from differences in elevation and sheltering from sun. Live surface fuel moisture content was set at Rothermel's "normal summer" value of 117 percent for both stands.

Foliar moisture content varies with species and time of year. For the species present and time of year of the simulation, *FMC* is near 100 percent (Brown 1978; Philpot and Mutch 1971), so we used a value of 100 percent for both stands. We assumed a nominal value of 18,000 kJ kg^{-1} for H_{crown} (Finney 1998; Forestry Canada Fire Danger Group 1992). We estimated wind reduction factor from the degree of sheltering (Rothermel 1983), with guidance from Albini and Baughman (1979). Based on visual inspection, surface fuels were best represented by FM 5 in the PIPO stand and FM 10 in the PICO stand.

Results—The results of this simulation are shown in table 6. We estimated type of fire and potential fire behavior at a windspeed of 40 km hr^{-1}. Surface fire spread rate and fireline intensity are estimated to be higher in the PIPO stand. However, the higher *CBH* in the PIPO stand also requires a higher $I'_{initiation}$ and $R'_{initiation}$. On balance, the PIPO stand is not expected to initiate a crown fire until the open wind reaches 28 km hr^{-1} (the Torching Index), whereas the PICO stand can initiate crown fire activity at a windspeed of only 16 km hr^{-1}.

Table 6—Intermediate and final output values for the example simulation. Site, fuel and environmental conditions are as described in **Table 5**, with open windspeed of 40 km/hr for both stands.

Parameter	Source	Stand A	Stand B
Surface fire			
$I_{surface}$, kW m^{-1}	Equation 5	470	313
$I'_{initiation}$, kW m^{-1}	Equation 11	309	144
$HPA_{surface}$, kJ m^{-2}	Equation 2	6	13
$R_{surface}$, m min^{-1}	Equation 6	4.6	1.4
$R'_{initiation}$, m min^{-1}	Equation 12	3.0	0.6
R'_{SA}, m min^{-1}	Figure 8	9.2	1.1
Crown fire			
R_{active}, m min^{-1}	Equations 7, 8	23.1	20.4
R'_{active}, m min^{-1}	Equation 14	50	14
Final, or overall			
Type of fire	Figure 12	Passive	Active
CFB	Equation 28 (Appendix A)	0.25	1.00
R_{final}, m min^{-1}	Equation 21	9.2	20.4
I_{final}, kW m^{-1}	Equation 22	1,788	18,337
Crown fire hazard indices			
Torching Index, km hr^{-1}	Equation 18	28	16
Crowning Index, km hr^{-1}	Equation 20	70	30
Surfacing Index, km hr^{-1}		70	30

Potential crown fire spread rate is not different in the stands; Rothermel's (1991a) correlation does not take into account the possible effect of variation in canopy bulk density on spread rate. Foliar moisture content is the same in both stands, so nothing in this example would be gained by using Van Wagner's foliar moisture effect. Because R_{active} is similar in the stands, the Crowning Index is mainly a function of *CBD*, which differs considerably in the two stands. The PIPO stand, with its relatively open canopy, would not support active crowning until the open windspeed reached 70 km hr^{-1}. In contrast, the dense canopy of the PICO stand would support active crowning at windspeeds of only 30 km hr^{-1}.

Crown fraction burned is 0.25 in the PIPO stand and 1.0 in the PICO stand. Therefore, under the conditions specified, we could expect a passive crown fire in the PIPO stand and a fully active crown fire in the PICO stand. Final spread rate in the PICO stand is estimated to be 20.4 m min^{-1}, roughly twice that in the PIPO stand. Fireline intensity in the PIPO stand is only 1,788 kW m^{-1}, but 18,337 kW m^{-1} in the PICO stand. For reference, the limit of mechanical fire control is 3,459 kW m^{-1} (1,000 BTU ft^{-1} s^{-1}).

At windspeeds less than 20 km/hr, spread rate in the PIPO stand is slightly greater than in the PICO stand (fig. 19a), due to the more open forest cover. Above that windspeed, though, crowning in the PICO stand leads to much higher spread rates than in the PIPO stand. The difference in fireline intensity is even greater (fig. 19b), largely because $HPA_{surface}$ and W_{canopy} in the PICO stand are much greater than in the PIPO stand. The limit of mechanical control is exceeded in the PICO stand at a windspeed of about 22 km hr^{-1}, whereas a fire in the PIPO stand would not exceed that intensity until windspeed reached about 46 km hr^{-1}. Because winds exceeding 22 km hr^{-1} occur far more frequently than winds exceeding 46 km hr^{-1}, we could expect fires burning under the dry, summer conditions simulated to be controllable less often in the PICO stand than the PIPO stand. Knowledge of the wind climatology of the site would improve this assessment by indicating how often we might expect the critical wind/fuel moisture combinations to occur.

Discussion—The purpose of the fire behavior simulations is to assess the relative fire potential in these stands, not to predict the behavior of an actual fire. From the above simulation it is clear that both stands can experience some kind of crown fire activity under moderate winds during the summer. However, the PIPO stand is likely to attain only passive crowning even under high winds, whereas the PICO stand can support fully active crowning under even moderate winds.

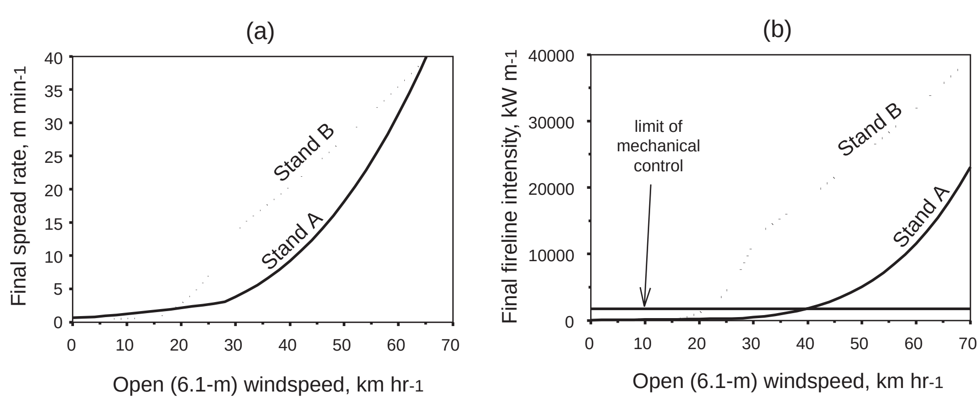

Figure 19—Final rate of spread (a) and fireline intensity (b) for the two example stands on the Bitterroot National Forest, Montana. The limit of mechanical control (3500 kW m^{-1}) is indicated.

Assessing the Effects of Alternative Treatments

Managers who wish to reduce crown fire hazard must determine how different fuel treatments affect torching and crowning. This is done by first simulating the effects of a treatment on the inputs to the coupled model. Fuel treatments that reduce crown fire hazard involve a combination of thinning, pruning, pile burning, broadcast burning, lopping, and chipping. The effects of these treatments change over time. For example, a broadcast burn reduces surface fuels immediately after the burn. However, depending on stand structure, resulting mortality and needle scorch may lead to higher fuel load a few years after the burn. As fuels decompose, fuel load may again decrease. Managers must consider the time frame of interest when comparing treatments. The Fire and Fuels Extension to the Forest Vegetation Simulator (Beukema and others 1997) simulates longer term effects of fuel treatments. Surface and canopy fuel treatments have variable effects on the factors affecting torching and crowning (table 7). Foliar moisture content is assumed to be independent of fuel treatment.

A thinning designed to reduce crown fire hazard will usually raise the effective *CBH* . However, in a partial harvest such as selection or crown thinning, mainly large trees with high crown bases are removed, so the effective *CBH* may not change. Similarly, a broadcast burn will usually increase *CBH* by scorching lower branches. However, a broadcast burn under moderate burning conditions may be patchy and of insufficient intensity to raise effective *CBH* for the whole stand. Understory removal is the harvest of submerchantable trees in the lower stratum of a multistoried stand. This story usually consists of shade-tolerant conifers with low crowns. Where the understory is well developed, its removal may also reduce the effective *CBD* of the stand.

A combination of treatments, such as thinning with broadcast burning, is simulated by adding the individual effects. The overall effect of a combination of treatments on a factor where the individual effects are in opposition (such as the effects of thinning with whole-tree harvest on fuel load) must be determined by computing TI and CI and simulating fire behavior in the treated and untreated stands.

When simulating the effect of fuel treatments on potential crown fire behavior, it is important to simulate effects on midflame windspeed and fuel moisture. Thinning to reduce canopy bulk density reduces the moderating effect of the canopy on windspeed, so midflame windspeed will increase. The increased fuel-level windspeed coupled with increased insolation also leads to lower dead fuel moisture in treated stands during summer. These two factors tend to exacerbate surface fire behavior. However, properly executed treatments also tend to reduce the crown fire potential. Crown fire mitigation treatments often represent a tradeoff—the decrease in crown fire potential comes at the expense of

Table 7—The immediate-term effects of fuel treatments on factors that affect the Torching and Crowning Indices (from Scott 1998). A blank cell in the table indicates no effect. I = increase, D = decrease, NE = no effect. The whole-tree yarding treatment is only applicable in conjunction with a harvest.

Fuel treatment	Surface fuel load	Dead fuel moisture	Canopy base height	Wind reduction factor	Canopy bulk density
Overstory thinning	I	D	I or NE	I	D
Understory removal	I		I		D or NE
Pruning	I		I		
Pile burning	D				
Whole-tree yarding	D				
Broadcast burning	D		I or NE		

increased surface fire spread rate and intensity. The greatly increased spread rate and intensity of crown fires makes this tradeoff reasonable.

Assessing Crown Fire Potential Throughout a Day

In planning for crown fires it is helpful to know at what time of the day crowning might begin and how long such conditions would persist, and perhaps compare these estimates for different treatments. For such an analysis we need diurnal fuel moisture and windspeed data. As an example we use the published diurnal weather measured on the North Fork Fire in Yellowstone National Park in August 1988 (Hartford and Rothermel 1991a). Temperature, relative humidity, and fine fuel moisture were measured for 48 hours in late August (fig. 20). By coupling the moisture data with the stand characteristics for the Bitterroot PIPO and PICO stands and a hypothetical trace of open windspeed (fig. 21), we plotted potential spread rate and intensity throughout the period (fig.22). This type of analysis may be useful where the timing and duration of a crown fire run needs to be estimated, or where proposed tactics must be weighed against potential fire behavior. However, calibration of such simulations with onsite observations must be done before attempting to use this analysis operationally.

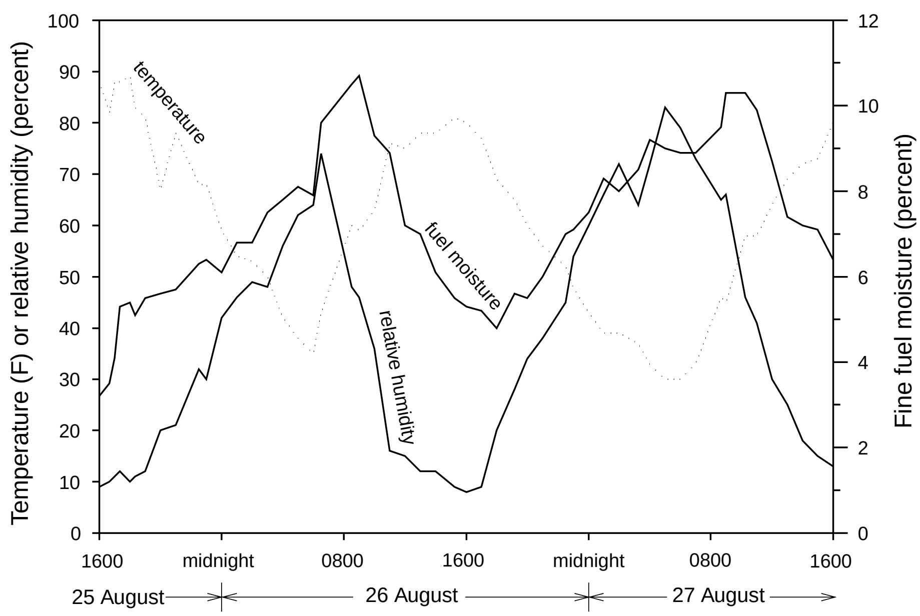

Figure 20—Temperature, relative humidity, and fine dead fuel moisture measured for a 48-hour period on the North Fork Fire, Yellowstone National Park, Wyoming, 1988 (Hartford and Rothermel 1991a).

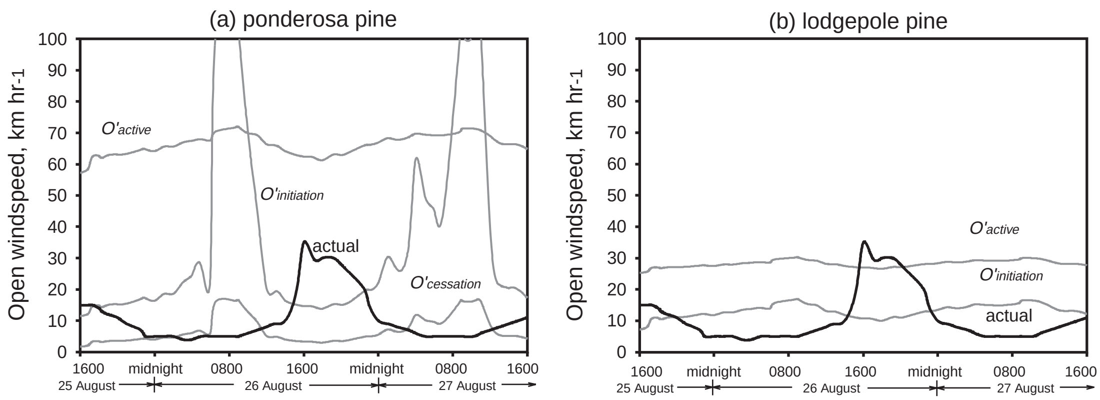

Figure 21—Critical windspeeds for crown fire initiation, sustained active spread, and cessation for the diurnal weather depicted in figure 20 for a ponderosa pine stand (a) and lodgepole pine stand (b) on the Bitterroot National Forest, Montana. For demonstration, a hypothetical trace of "actual" windspeed is shown.

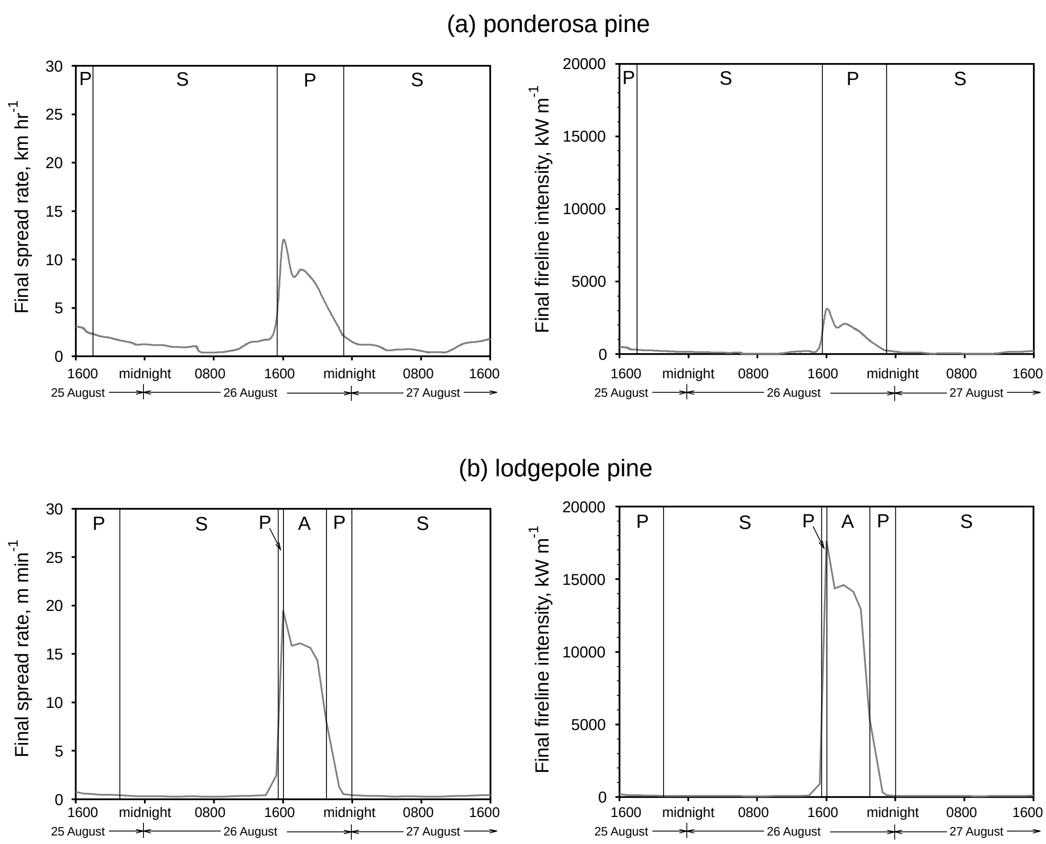

Figure 22—Final rate of spread and fireline intensity for the diurnal weather depicted in figure 20 and the hypothetical windspeed shown in figure 21 for the ponderosa pine stand (a) and lodgepole pine stand (b) on the Bitterroot National Forest, Montana. Fire classification is also shown: S = surface fire, P = passive crown fire, A = active crown fire.

DISCUSSION

Crown fire is a complex phenomenon; we are only beginning to understand the processes of crown fire development, spread, and cessation. Accurate description of canopy fuels and reliable simulation of these processes remain elusive. Yet crown fires present special problems for managers today. Crown fires' high spread rates and resistance to control lead to high acreage burned and significant adverse effects. We must take steps now to assess and mitigate crown fire potential.

This paper presents a method of assessing crown fire potential by linking separate models of surface fire spread and intensity, crown fire spread rate, and transition to crown fire. Three indices of crown fire potential are computed from a description of surface fuels, canopy fuels, and site characteristics. The Torching Index is the open windspeed at which the transition from surface to crown fire is expected. The Crowning Index is the open windspeed at which fully active crown fire is possible. The Surfacing Index is the open windspeed at which an active crown fire is expected to cease, either from failure to meet the minimum mass-flow rate or from failure of the after-crowning contribution of surface fuels to fireline intensity to meet the minimum necessary for crown fire initiation.

From the linked models we also seamlessly simulate the wide range of surface and crown fire behavior that occurs in forest stands. These simulations are used for comparing relative fire behavior of different stands or after treatments to mitigate crown fire, not for operational prediction of the behavior of a going fire. The accuracy of simulations can be improved by calibrating model results with onsite observations.

Due to a lack of high-quality validation data, this and similar methods have not been validated. As such, users should apply results cautiously. Gathering high-quality data from prescribed and wild fires for building and testing models of fire behavior should be made a high priority.

Calculation of the indices for simple cases can be made in the field with nomograms (appendix D) or by using NEXUS (Scott 1999), which also allows simulation of the full range of surface and crown fire behavior encountered in forest stands.

The links among the existing models indicate the potential for a hysteresis in the crown fire phenomenon; the conditions for crown fire cessation may be quite different from those for crown fire initiation. If so, many forest stands that seem to be safe from crown fire because they cannot initiate a crown fire may still be susceptible to active crown fire if a crown fire has initiated elsewhere. Spatial and temporal variability in the fire environment leads to higher crown fire activity than predicted using average conditions.

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APPENDIX A: CROWN FRACTION BURNED

The equation commonly used for the *CFB* transition function (Finney 1998; Van Wagner 1989, 1993; Forestry Canada Fire Danger Group 1992) is of the general form

$$CFB = 1 - e^{(-ax)} \qquad (23)$$

where a is a scaling factor and x is based on the difference between predicted and critical spread rates. In this section we will review the alternative implementations of this *CFB* transition function and derive a new form of our own.

The concept of a transition function for scaling between surface and crown fire spread rate predictions was first proposed by Van Wagner (1989). In that model, $x = R_{surface} - R'_{initiation}$ and $a = 0.23$ in order to force $CFB = 0.9$ when $R_{surface}$ exceeds $R'_{initiation}$ by an arbitrary 10 m min^{-1}. Van Wagner does not state how the 10 m min^{-1} threshold was selected. The functional form of Van Wagner's (1989) *CFB* equation is thus

$$CFB = 1 - e^{\left(-.23\left(R_{surface} - R'_{initiation}\right)\right)} \qquad (24)$$

In the Canadian FFBP System, the Forestry Canada Fire Danger Group (1992) employs the *CFB* concept for both two-equation and one-equation models of crown fire spread rate. In the two-equation model for Conifer Plantation Fuel Type C-6, the Forestry Canada Fire Danger Group (1992) uses equation 24 directly. In the one-equation models, a single equation describes spread rate for the full range of fire behavior, surface through crown. Thus, R_{final} is estimated directly—intermediate estimates of $R_{surface}$ and R_{active} are avoided — and the implicit *CFB* equation is

$$CFB = 1 - e^{\left(-.23\left(R_{final} - R'_{initiation}\right)\right)} \qquad (25)$$

In this one-equation model, *CFB* is used only to estimate the degree of crowning and final fire intensity, but not the final fire spread rate as in equation 21. Although the Forestry Canada Fire Danger Group (1992) sets the value of a at 0.23 such that $CFB = 0.9$ when $R_{surface}$ exceeds $R'_{initiation}$ by 10 m min^{-1}, this same value of a is used in equation 23, which is based on the amount by which R_{final} (rather than $R_{surface}$) exceeds $R'_{initiation}$.

Van Wagner (1993) modified his *CFB* concept to allow dynamic calculation of the coefficient a to account for variation in canopy fuel characteristics. In that paper he states that the coefficient a was "based on the difference between [$R'_{initiation}$] and [R'_{active}], that is, on the difference between the point where crown consumption begins and the point where it becomes complete" (p. 446). Van Wagner (1993) set the value of a such that $CFB = 0.9$ for R_{final} = 90 percent of the difference between R'_{active} and $R'_{initiation.}$ (Due to the form of the *CFB* equation [equation 24], *CFB* approaches 1.0 asymptotically, so the point at which $CFB = 1.0$ cannot be specified.) Thus, a is

$$a = \left(\frac{-\ln(0.1)}{0.9\left(R'_{active} - R'_{initiation}\right)} \right) \qquad (26)$$

For Van Wagner's (1993) immature jack pine data set, $R'_{initiation}$ was 2.15 m min^{-1} and R'_{active} was 12.89 m min^{-1}, the difference between these being 10.74 m min^{-1}. Ninety percent of this difference (9.666 m/min) yields $a = 0.238$ in the above model. This value, however, is only valid in stands where 90 percent of (R'_{active} $R'_{initiation}$) is about 9.666 m/min. To that end, Van Wagner also estimated *a* for a mature stand of jack pine where $R'_{initiation}$ = 1.45 m min^{-1} and R'_{active} = 25.14 m min^{-1} and obtained *a* = 0.108. Van Wagner's (1993) *CFB* equation is of the same functional form as equation 24, but with different values of *a* for the immature and mature stands.

For assessing crown fire hazard *CFB* should vary with fuel characteristics believed to be important in determining crown fire behavior and be consistent with Van Wagner's (1977) crown fire initiation and sustained spread thresholds. In other words, the *CFB* function should be scaled such that *CFB* approaches 1.0 at the point where active crowning is expected.

Each of the above implementations has a problem of internal consistency, especially when applied to stands with different surface or canopy fuel characteristics. The problem is the inconsistency between the derivation of *a* and the subsequent formulation of *x* in equation 23.

First, we must determine whether *x* in equation 23 should be $R_{final} - R'_{initiation}$, as in the one-equation model used in the Canadian FFBP System, or $R_{surface} - R'_{initiation}$, which is used in all the other formulations. In the Canadian FFBP System and Van Wagner (1989), the derivation of *a* is said to be based on the difference between $R_{surface}$ and $R'_{initiation}$. Given that, using $x = R_{surface} - R'_{initiation}$ seems reasonable. However, *CFB* in the one-equation model of the Canadian FFBP System, with the same value of *a* as the two-equation model, is instead computed using $x = R_{final} - R'_{initiation}$. Because $R_{final} >\ = R_{surface}$, their one-equation model will over-predict *CFB* relative to the two-equation model.

A more pressing problem for making crown fire hazard assessments is the proper scaling of *a* to correctly represent various stand conditions. Using a single value of *a* implies that progress toward fully active crowning is independent of *CBD*. In contrast, Van Wagner (1977) suggests a critical mass-flow rate through the canopy (a function of *CBD*) must be met before fully active crowning can occur. Van Wagner's (1993) dynamic computation of the parameter *a* accounts for differing canopy characteristics in a way that makes consistency with a critical mass-flow rate possible.

However, because Van Wagner (1993) scaled the coefficient *a* between $R'_{initiation}$ and R'_{active}, consistency is most logically achieved by using $x = R_{final} - R'_{initiation}$ rather than $x = R'_{initiation}$ in the *CFB* equation. For practical purposes the predicted $R_{surface}$ is usually much less than R'_{active} using the standard U.S. Fire Behavior Fuel Models commonly associated with conifer forests fuels.

This inconsistency is best illustrated with an example. Consider a dense forest stand with *CBD* = 0.20 kg m^{-3}, *CBH* = 2 m, *WRF* = 0.15, and surface fuels characterized by FM 10, on level terrain. Such a stand is obviously susceptible to active crown fire. For this stand R'_{active} = 15 m min^{-1} (equation 14), $R'_{initiation}$ = 1.08 m min^{-1} (equation 12), and *a* = 0.184 (equation 26). Even under the most extreme environmental conditions (fine dead fuel moisture 3 percent, live surface fuel moisture 70 percent, open [6.1-m] windspeed 70 km/hr), predicted surface fire spread rate is only 6.0 m/min. Following Van Wagner (1993), with *a* as above, *CFB* would be only 0.60. Following the two-equation *CFB* model of the Canadian FFBP System (equation 23), *CFB* would be only 0.68. Under the extreme conditions specified, we could reasonably expect fully active crowning, so *CFB* should be much closer to 1. Rothermel's (1991a) crown fire correlation predicts that R_{active} will equal R'_{active}, at an open windspeed of only 21 km hr^{-1}. At that windspeed, the Van Wagner (1993) predicts *CFB* = 0.06 and Forestry Canada Fire Danger Group (1992) models predict *CFB* = 0.07. In Van Wagner's model, this problem results because the coefficient *a* is based on $x = R'_{active} - R'_{initiation}$, but *CFB* is scaled by $x = R_{surface} - R'_{initiation}$. In the Canadian FFBP System, the problem is the use of a single value of *a* to represent the wide range of stand conditions we need to evaluate.

We can avoid this inconsistency in two ways. First, we can scale *a* following equation 26 but use $x = R_{final} - R'_{initiation}$ in equation 23. Unfortunately, R_{final} is itself a function of *CFB* (equation 21), resulting in a problem of circularity that can be solved by iteration.

Alternatively, we can keep $x = R_{surface} - R'_{initiation}$ for the *CFB* equation but provide an alternative derivation of *a* that will properly scale *CFB* to equal or approach 1 when the critical mass-flow rate is met. For example,

$$a = \left(\frac{-\ln(0.1)}{\left(R'_{SA} - R'_{initiation}\right)} \right) \tag{27}$$

where R'_{SA} is the predicted surface fire spread rate that corresponds to the environmental conditions for which $R_{active} = R'_{active}$ (see fig. 8 in text). In equation 27 we drop the 0.9 factor so that the point at which $R_{active} = R'_{active}$ corresponds exactly to $CFB = 0.9$. This is satisfying because the Canadian FFBP System defines an active crown fire as one having $CFB > 0.9$. In other words, this approach is consistent with the Van Wagner (1977) and the Canadian FFBP System classifications and will properly predict active crown fire spread rates when the critical mass-flow rate is met (Van Wagner 1977).

All of the above approaches are based on the assumption that the *CFB* transition function should follow the negative exponential form of equation 23. However, no empirical evidence suggests what equation form best represents the transition to active crown fire. Assuming a straight line function for *CFB*, as did Stocks (1987, 1989) when relating canopy fuel consumption to Initial Spread Index, might be better than assuming a more complex shape. The equivalent straight-line CFB equation is

$$CFB = \frac{\left(R_{surface} - R'_{initiation}\right)}{\left(R'_{SA} - R'_{initiation}\right)} \tag{28}$$

In this paper, the purpose of predicting crown fire behavior is to assess the relative crown fire potential of different stand structures. Therefore, we use equation 28 for estimating *CFB* and equation 21 for R_{final} because that approach (1) assumes the simplest shape for the *CFB* function in the absence of empirical evidence to the contrary, (2) correctly bounds *CFB* such that $CFB = 1.0$ where $R_{active} = R'_{active}$, (3) does not require iteration, and (4) varies logically with most surface and canopy fuel characteristics believed to influence crown fire development.

APPENDIX B: GLOSSARY

Active crown fire—A **crown fire** in which the entire **fuel complex** becomes involved, but the crowning phase remains dependent on heat released from the **surface fuels** for continued spread. Also called **running** and **continuous crown fire**.

Available canopy fuel—The mass of **canopy fuel** per unit area consumed in a crown fire. There is no post-frontal combustion in canopy fuels, so only fine canopy fuels are consumed. We assume that only the foliage and a small fraction of the branchwood is available.

Available fuel—The total mass of ground, surface and canopy fuel per unit area consumed by a fire, including fuels consumed in postfrontal combustion of duff, organic soils, and large woody fuels.

Canopy base height—The lowest height above the ground at which there is a sufficient amount of **canopy fuel** to propagate fire vertically into the canopy. Canopy base height is an effective value that incorporates ladder fuels such as shrubs and understory trees. See also **fuel strata gap** and **crown base height**.

Canopy bulk density—The mass of **available canopy fuel** per unit canopy volume. It is a bulk property of a stand, not an individual tree.

Canopy fuels—The live and dead foliage, live and dead branches, and lichen of trees and tall shrubs that lie above the **surface fuels**. See also **available canopy fuel**.

Conditional surface fire—A potential type of fire in which conditions for sustained active crown fire spread are met but conditions for crown fire initiation are not. If the fire begins as a surface fire then it is expected to remain so. If it begins as an **active crown fire** in an adjacent stand, then it may continue to spread as an active crown fire.

Continuous crown fire—See **active crown fire**.

Crown base height—The vertical distance from the ground to the bottom of the live crown of an individual tree. See also **canopy base height**.

Crown bulk density—The mass of available fuel per unit crown volume. In this paper it is a property of an individual tree, not a whole stand. See also **canopy bulk density**.

Crown fire—Any fire that burns in **canopy fuels**.

Crown fire cessation—The process by which a **crown fire** ceases, resulting in a **surface fire**. Crown fire cessation is a different mechanism than crown fire initiation, possibly leading to **hysteresis**.

Crown fire hazard—A physical situation (fuels, weather, and topography) with potential for causing harm or damage as a result of crown fire.

Crowning Index—The open (6.1-m) windspeed at which **active crown fire** is possible for the specified **fire environment**.

Environmental conditions—That part of the **fire environment** that undergoes short-term changes: weather, which is most commonly manifest as windspeed and dead fuel moisture content.

Fire environment—The characteristics of a site that influence fire behavior. In fire modeling the fire environment is described by surface and canopy fuel characteristics, windspeed and direction, relative humidity, and slope steepness.

Fire hazard—A physical situation (fuels, weather, and topography) with potential for causing harm or damage as a result of wildland fire.

Fire intensity—See **frontal fire intensity**. Contrast with **fireline intensity**.

Fireline intensity—The rate of heat release in the **flaming front** per unit length of fire front (Byram 1959).

Flaming front—The zone at a fire's edge where solid flame is maintained.

Foliar moisture content—Moisture content (dry weight basis) of live foliage, expressed as a percent. Effective foliar moisture content incorporates the moisture content of other canopy fuels such as lichen, dead foliage, and live and dead branchwood.

Foliar moisture effect—A theoretical effect of **foliar moisture content** on active crown fire spread rate (Van Wagner 1974, 1979, 1983).

Frontal fire intensity—Similar to **fireline intensity**, it is the rate of heat release per unit length of fire front, including the additional heat released from postfrontal flaming and smoldering combustion (Forestry Canada Fire Danger Group 1992).

Fuel complex—The combination of ground, surface, and canopy fuel strata.

Fuel model—A set of surface fuel bed characteristics (load and surface-area-to-volume-ratio by size class, heat content, and depth) organized for input to a fire model. Standard fuel models (Anderson 1982) have been stylized to represent specific fuel conditions.

Fuel strata gap—The vertical distance between the top of the **surface fuel** stratum and the bottom of the **canopy fuel** stratum.

Fuel stratum—A horizontal layer of fuels of similar general characteristics. We generally recognize three fuel strata: ground, surface, and canopy.

Full-range fire behavior simulation—The simulated behavior of a wildland fire whether it is a surface fire, passive crown fire, or active crown fire. Ground fire behavior is usually not included.

Ground fire—A slow-burning, smoldering fire in **ground fuels**. Contrast with **surface fire**.

Ground fuels—Fuels that lie beneath surface fuels, such as organic soils, duff, decomposing litter, buried logs, roots, and the below-surface portion of stumps. Compare with **surface fuels**.

Hysteresis—The failure of a property that has been changed by an external agent to return to its original value when the cause of the change is removed. In crown fire, hysteresis is expressed in the persistence of active crowning after the fire environment has changed such that a crown fire could no longer initiate.

Independent crown fire—A **crown fire** that spreads without the aid of a supporting **surface fire**.

Intermittent crown fire—A **crown fire** that alternates in space and time between active crowning and surface fire or passive crowning. See also **passive crown fire**.

Mass-flow rate—The rate of fuel consumption (kg m^{-2} s^{-1}) through a vertical plane (oriented parallel with the fireline) within the fuel bed. It is the product of spread rate (m s^{-1}) and fuel bed bulk density (kg m^{-3}).

Passive crown fire—A crown fire in which individual or small groups of trees torch out, but solid flaming in the canopy cannot be maintained except for short periods. Passive crown fire encompasses a wide range of crown fire behavior from the occasional torching of an isolated tree to a nearly active crown fire. Also called torching and candling. See also **intermittent crown fire**.

Plume-dominated fire-—A fire for which the power of the fire exceeds the power of the wind, leading to a tall convection column and atypical spread patterns. The models used in this paper do not address plume-dominated fire behavior. Contrast with **wind-driven fire**.

Running crown fire—See **active crown fire**.

Site characteristics—The characteristics of a location that do not change with time: slope, aspect, elevation.

Surface fire—A fire spreading through **surface fuels**.

Surface fuels—Needles, leaves, grass, forbs, dead and down branches and boles, stumps, shrubs, and short trees.

Surfacing Index—The higher of O'_{active} and $O'_{cessation}$. The Surfacing Index is the open windspeed at which an **active crown fire** can be expected to drop to the surface, either due to insufficient **mass-flow rate** through the canopy or insufficient contribution of **surface fuels** to **fireline intensity**.

Torching Index—The open (6.1-m) windspeed at which crown fire activity can initiate for the specified **fire environment**.

Total biomass—The mass per unit area of all living and dead vegetation at a site.

Total fuel load—The mass of fuel per unit area that could possibly be consumed in a hypothetical fire of the highest intensity in the driest fuels.

Wind-driven fire—A wildland fire in which the power of the wind exceeds the power of the fire, characterized by a bent-over smoke plume and a high length-to-width ratio.

Wind reduction factor—The ratio of the midflame windspeed to the open (6.1-m) windspeed. For convenience of measurement eye-level winds are usually substituted for midflame winds.

APPENDIX C: ENGLISH/METRIC UNIT CONVERSION FACTORS

Multiplication factors

weight

from	to=>	g	oz	lb	kg	ton	Mg
g		1	0.035	2.205E-03	0.001	1.102E-06	1.000E-06
oz		28.35	1	0.06251	2.835E-02	3.125E-05	2.835E-05
lb		453.6	16	1	0.4536	5.000E-04	4.536E-04
kg		1000	35.30	2.205	1	1.10E-03	0.001
ton		9.072E+05	3.202E+04	2000	907.2	1	0.9072
Mg		1.E+06	3.530E+04	2205	1000	1.102	1

length

from	to=>	mm	cm	inch	feet	yard	meter	chain	km	mile
mm		1	0.1	3.937E-02	3.281E-03	1.094E-03	0.001	4.971E-05	1.E-06	6.214E-07
cm		10	1	0.3937	3.281E-02	1.094E-02	0.01	4.971E-04	1.E-05	6.214E-06
inch		25.40	2.540	1	0.08333	0.02778	0.02540	0.001	2.540E-05	1.578E-05
feet		304.8	30.48	12	1	0.3333	0.3048	0.01515	3.048E-04	1.894E-04
yard		914.4	91.44	36	3	1	0.9144	4.545E-02	9.144E-04	5.682E-04
meter		1000	100	39.37	3.281	1.094	1	0.04971	0.001	6.214E-04
chain		2.012E+04	2.012E+03	7.920E+02	66	22	20.12	1	2.012E-02	1.250E-02
km		1.E+06	1.E+05	3.937E+04	3.281E+03	1.094E+03	1000	49.71	1	0.6214
mile		1.609E+06	1.609E+05	6.336E+04	5280	1760	1.609E+03	80	1.609	1

area

from	to=>	cm2	in2	ft2	yd2	m2	acre	ha	km2	mi2
cm2		1	0.1550	1.076E-03	1.196E-04	0.0001	2.471E-08	1E-08	1E-10	3.861E-11
in2		6.452	1	6.944E-03	7.716E-04	6.452E-04	1.594E-07	6.452E-08	6.452E-10	2.491E-10
ft2		929.0	144	1	0.1111	0.09290	2.296E-05	9.290E-06	9.290E-08	3.587E-08
yd2		8361	1296	9	1	0.8361	2.066E-04	8.361E-05	8.361E-07	3.228E-07
m2		1.E+04	1550	10.76	1.196	1	2.471E-04	1.E-04	1E-06	3.861E-07
acre		4.047E+07	6.273E+06	4.356E+04	4840	4047	1	0.4047	4.047E-03	1.563E-03
ha		1.E+08	1.550E+07	1.076E+05	1.196E+04	1.E+04	2.471	1	0.010000045	3.861E-03
km2		1.E+10	1.550E+09	1.076E+07	1.196E+06	1.E+06	247.1	100	1	0.3861
mi2		2.590E+10	4.014E+09	2.788E+07	3.098E+06	2.590E+06	640.0	259.0	2.590	1

bulk density

from	to=>	ton/(ac-ft)	kg/m3	ton/(ac-in)	lb/ft3	gm/cm3
ton/(ac-ft)		1	0.7355	0.08333	0.04591	7.355E-04
kg/m3		1.360	1	0.1133	0.06243	0.001
ton/(ac-in)		12	8.826	1	0.5510	8.826E-03
lb/ft3		21.78	16.02	1.815	1	0.01602
gm/cm3		1360	1000	113.3	62.43	1

area intensity

from	to=>	kJ/(m2-min)	kW/m2	BTU/(ft2-s)	cal/(cm2-s)
kJ/(m2-min)		1	0.01667	1.469E-03	3.984E-04
kW/m2		60	1	0.08811	0.02390
BTU/(ft2-s)		680.9	11.35	1	0.2712
cal/(cm2-s)		2510	41.84	3.687	1

heat content

from	to=>	kJ/kg	BTU/lb	cal/gm
kJ/kg		1	0.4303	0.2390
BTU/lb		2.324	1	0.5555
cal/gm		4.184	1.800	1

rate of spread, speed

from	to=>	ft/min	ch/hr	cm/s	m/min	km/hr	ft/sec	mi/hr	knot	m/sec
ft/min		1	0.9091	0.5080	0.3048	0.01829	0.01667	0.01136	9.875E-03	5.080E-03
ch/hr		1.100	1	0.5588	0.3353	0.02012	0.01833	0.01250	0.01086	5.588E-03
cm/s		1.968	1.790	1	0.6000	0.03600	0.03281	0.02237	0.01944	0.01
m/min		3.281	2.983	1.667	1	0.06000	0.05468	0.03728	0.03240	0.01667
km/hr		54.68	49.71	27.78	16.67	1	0.9113	0.6214	0.5400	0.2778
ft/sec		60	54.55	30.48	18.29	1.097	1	0.6818	0.5925	0.3048
mi/hr		88	80	44.70	26.82	1.609	1.467	1	0.8690	0.4470
knot		101.3	92.06	51.44	30.87	1.852000037	1.688	1.151	1	0.5144
m/sec		196.8	179.0	100	60	3.6	3.281	2.237	1.944	1

fireline intensity

from to=>	J/(ft-sec)	cal/(cm-sec)	kW/m	BTU/(ft-sec)	kcal/(m-sec)
J/(ft-sec)	1	7.841E-03	3.281E-03	9.485E-04	7.841E-04
cal/(cm-sec)	127.5	1	0.4184	0.1210	0.1
kW/m	304.8	2.390	1	0.2891	0.2390
BTU/(ft-sec)	1054	8.268	3.459	1	0.8268
kcal/(m-sec)	1275	10	4.184	1.210	1

heat, energy

from to=>	J	cal	kJ	BTU
J	1	0.2390	0.001	9.485E-04
cal	4.184	1	4.184E-03	3.968E-03
kJ	1000	239.0	1	0.9485
BTU	1054	252.0	1.054	1

fuel load

from to=>	g/m2	Mg/ha	tons/ac	kg/m2	lbs/ft2
g/m2	1	0.01	4.461E-03	0.001	2.048E-04
Mg/ha	100	1	0.4461	0.1	0.02048
tons/ac	224.2	2.242	1	0.2242	0.04591
kg/m2	1000	10	4.461	1	0.2048
lbs/ft2	4882	48.82	21.78	4.882	1

basal area

from to=>	ft2/ac	m2/ha
ft2/ac	1	0.2296
m2/ha	4.356	1

angles

from to=>	degrees	radians
degrees	1	0.01745
radians	57.30	1

heat per unit area

from to=>	J/ft2	kJ/m2	BTU/ft2	kcal/m2	cal/cm2
J/ft2	1	0.01076	9.479E-04	2.572E-03	2.572E-04
kJ/m2	92.96	1	0.08811	0.2391	0.02391
BTU/ft2	1055	11.35	1	2.713	0.2713
kcal/m2	388.9	4.183	0.3686	1	0.1
cal/m2	3889	41.83	3.686	10	1

APPENDIX D: NOMOGRAMS

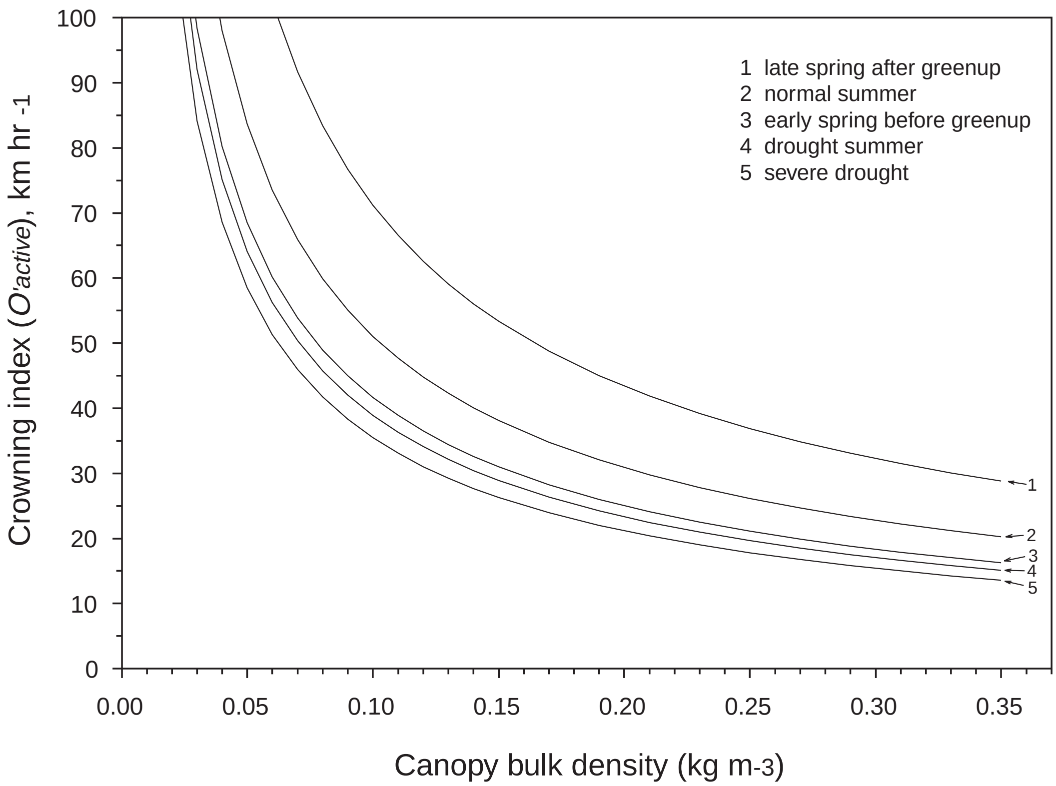

Figure D-1—Chart for determining Crowning Index from canopy bulk density and stylized surface fuel moisture. Level ground is assumed. Fuel moisture conditions are described in table 4.

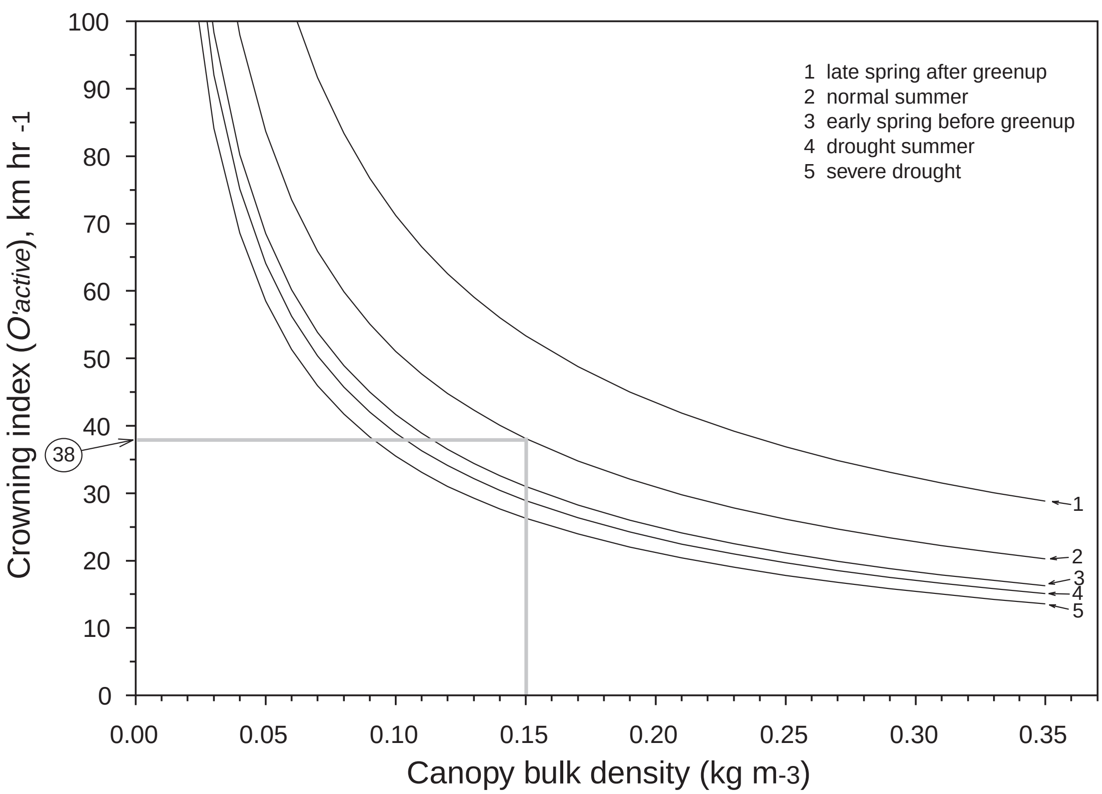

Figure D-2—Example use of figure D-1. For normal summer fuel moisture condition (Rothermel 1991a) and canopy bulk density = 0.15 kg m^{-3}, the Crowning Index is 38. That is, an open windspeed of at least 38 km hr^{-1} is needed to sustain active crowning.

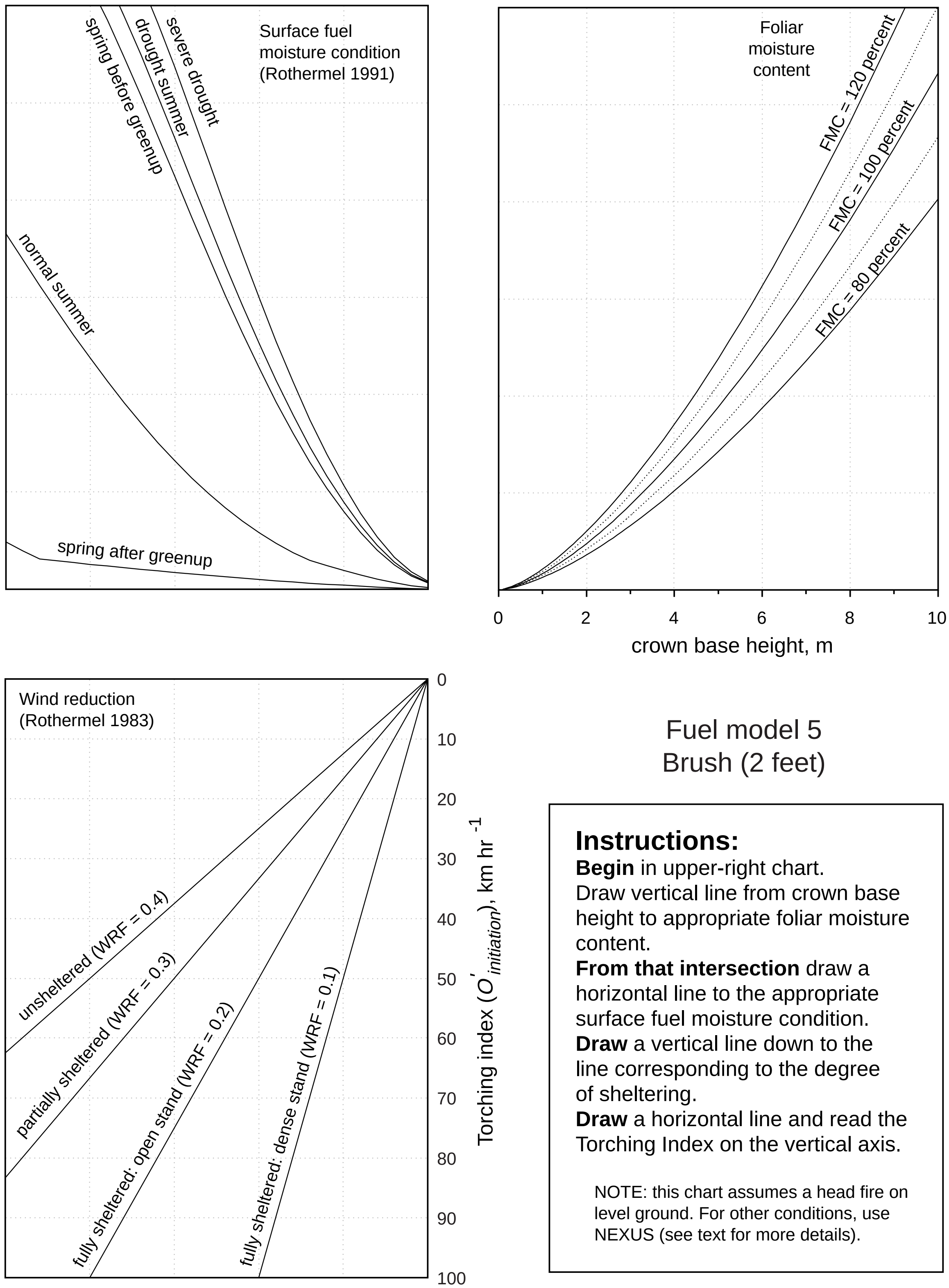

Figure D-3—Nomogram for determining the Torching Index for fuel model 5 (Brush 2 feet).

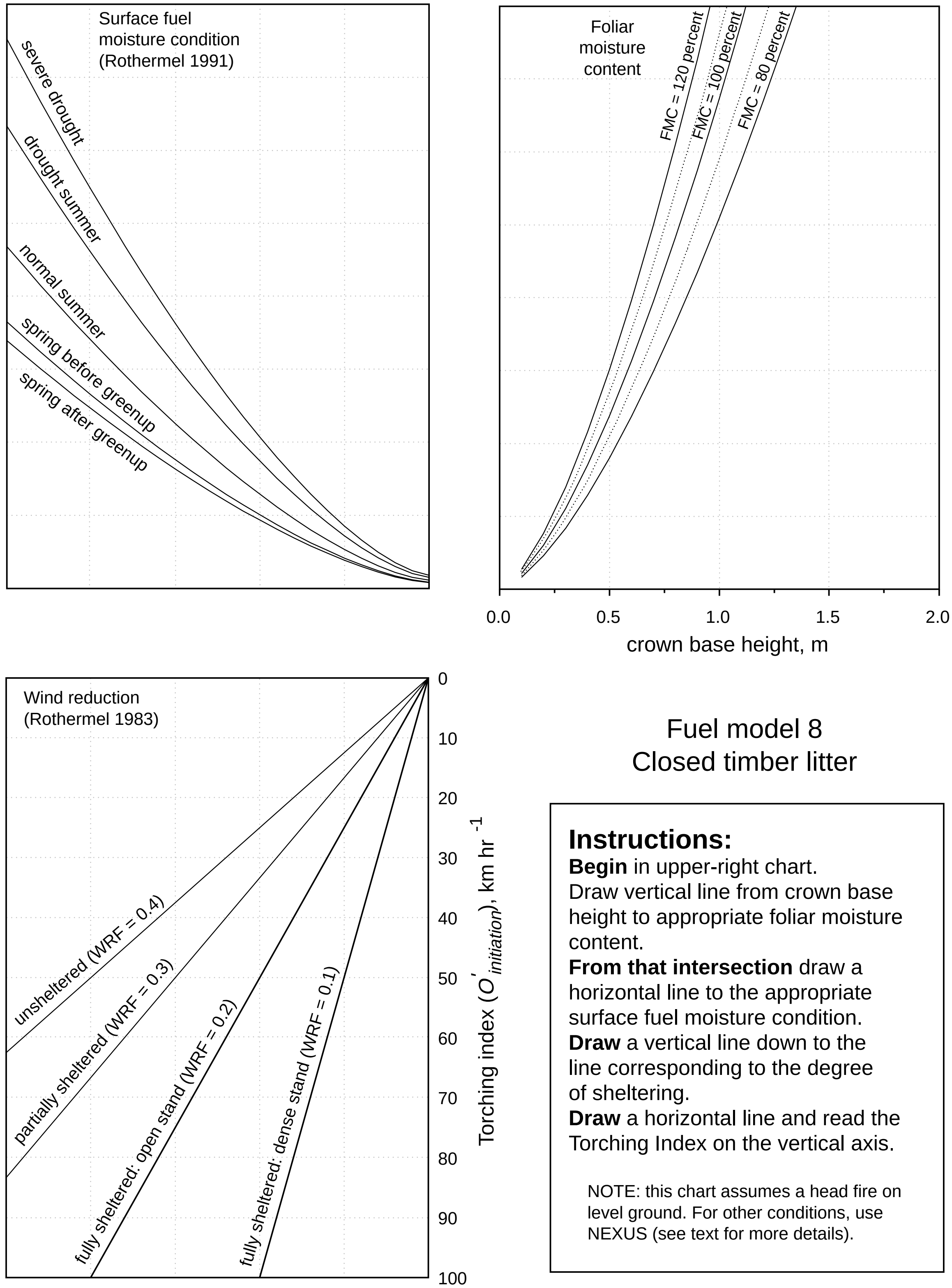

Figure D-4—Nomogram for determining the Torching Index for fuel model 8 (closed timber litter).

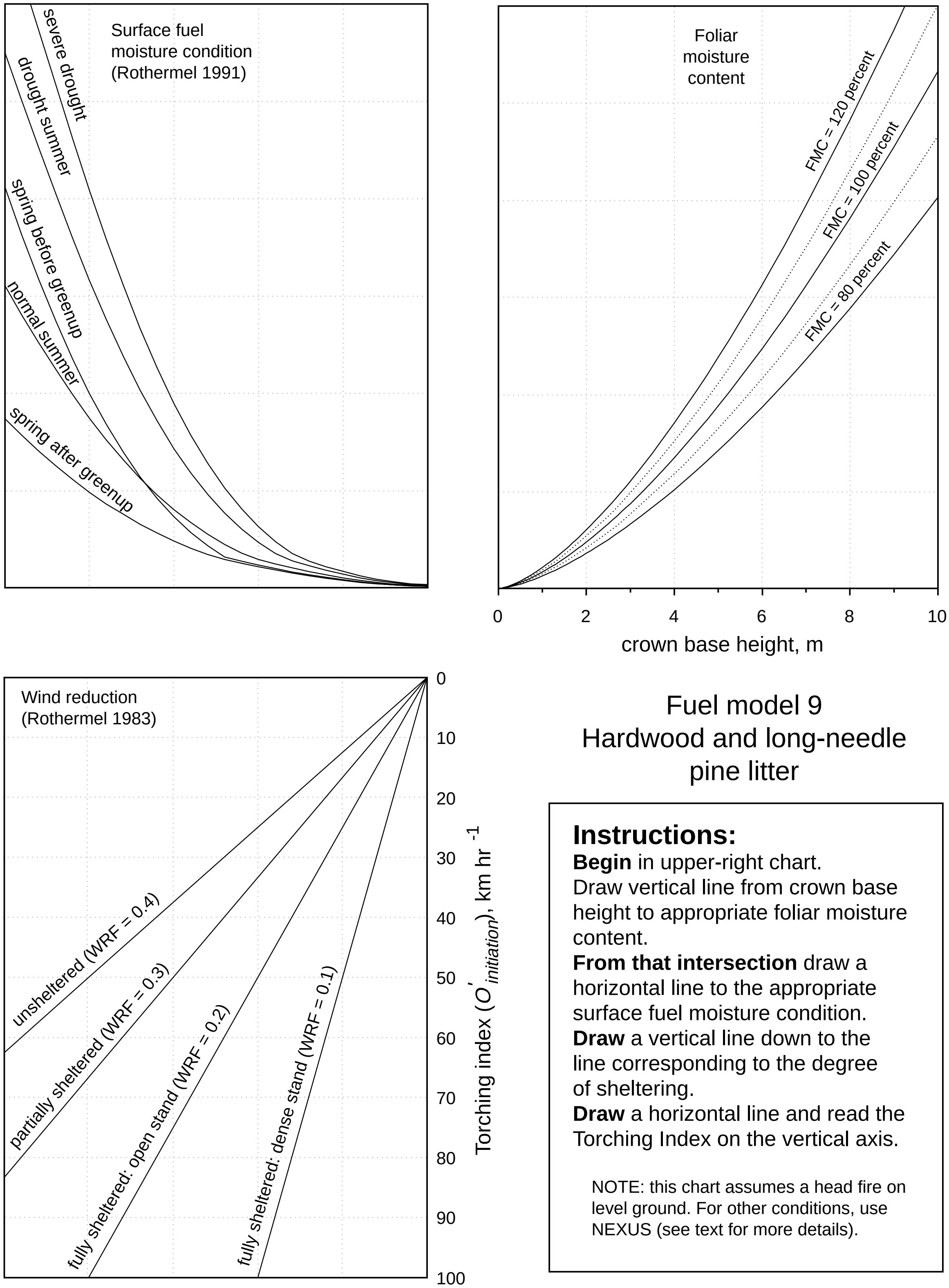

Figure D-5—Nomogram for determining the Torching Index for fuel model 9 (hardwood and long-needle pine litter).

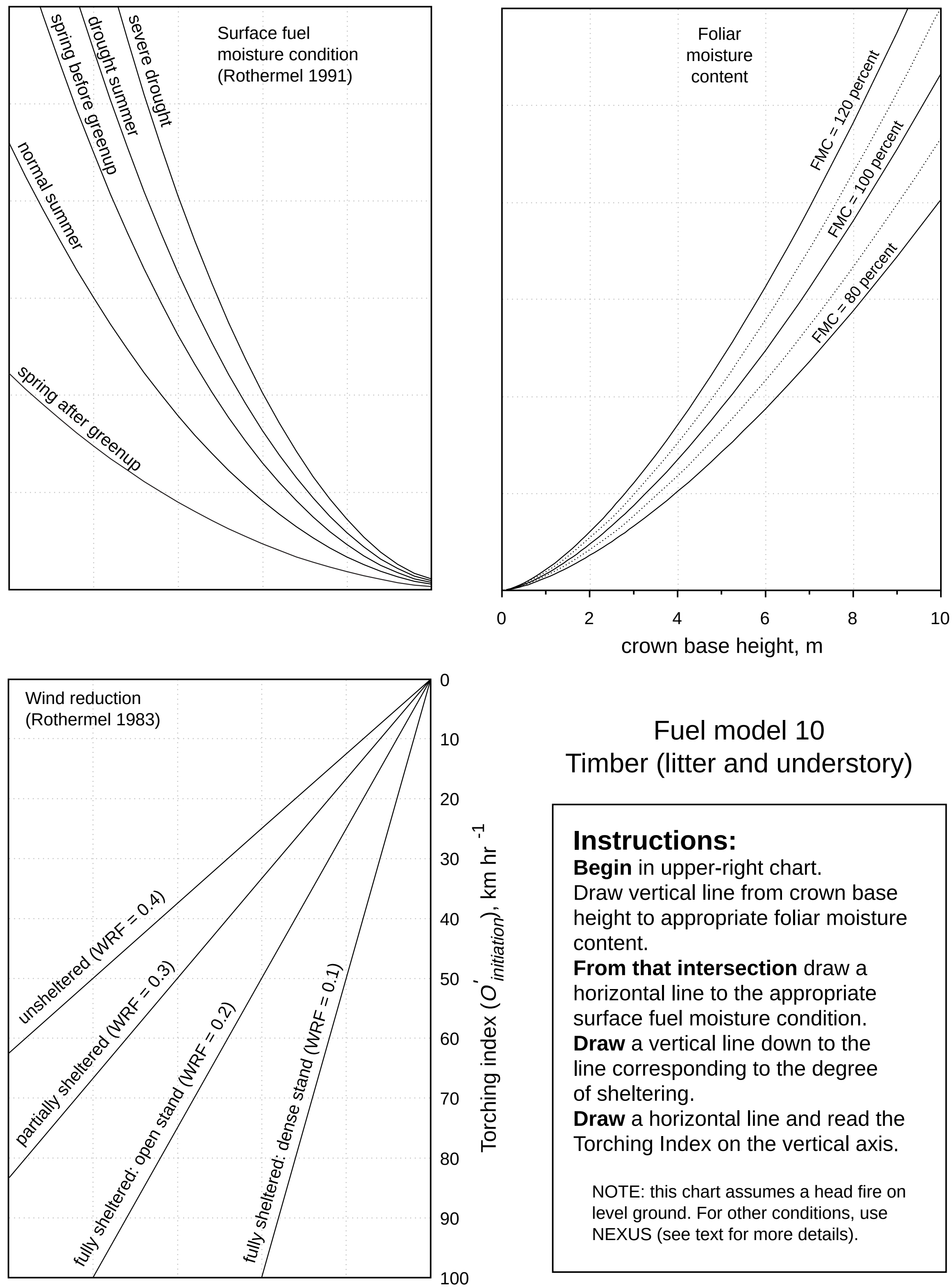

Figure D-6—Nomogram for determining the Torching Index for fuel model 10 (timber litter and understory).

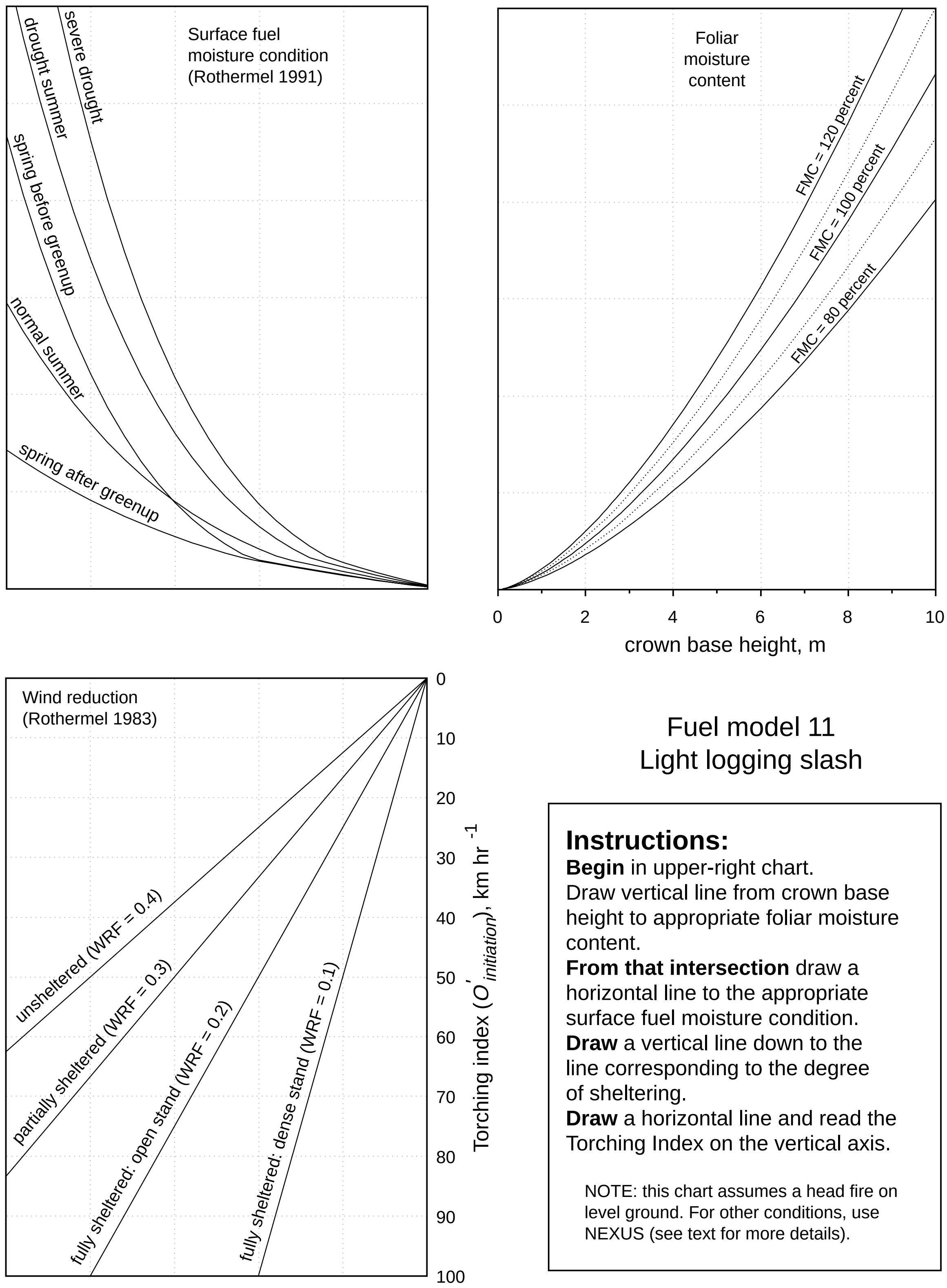

Figure D-7—Nomogram for determining the Torching Index for fuel model 11 (light logging slash).

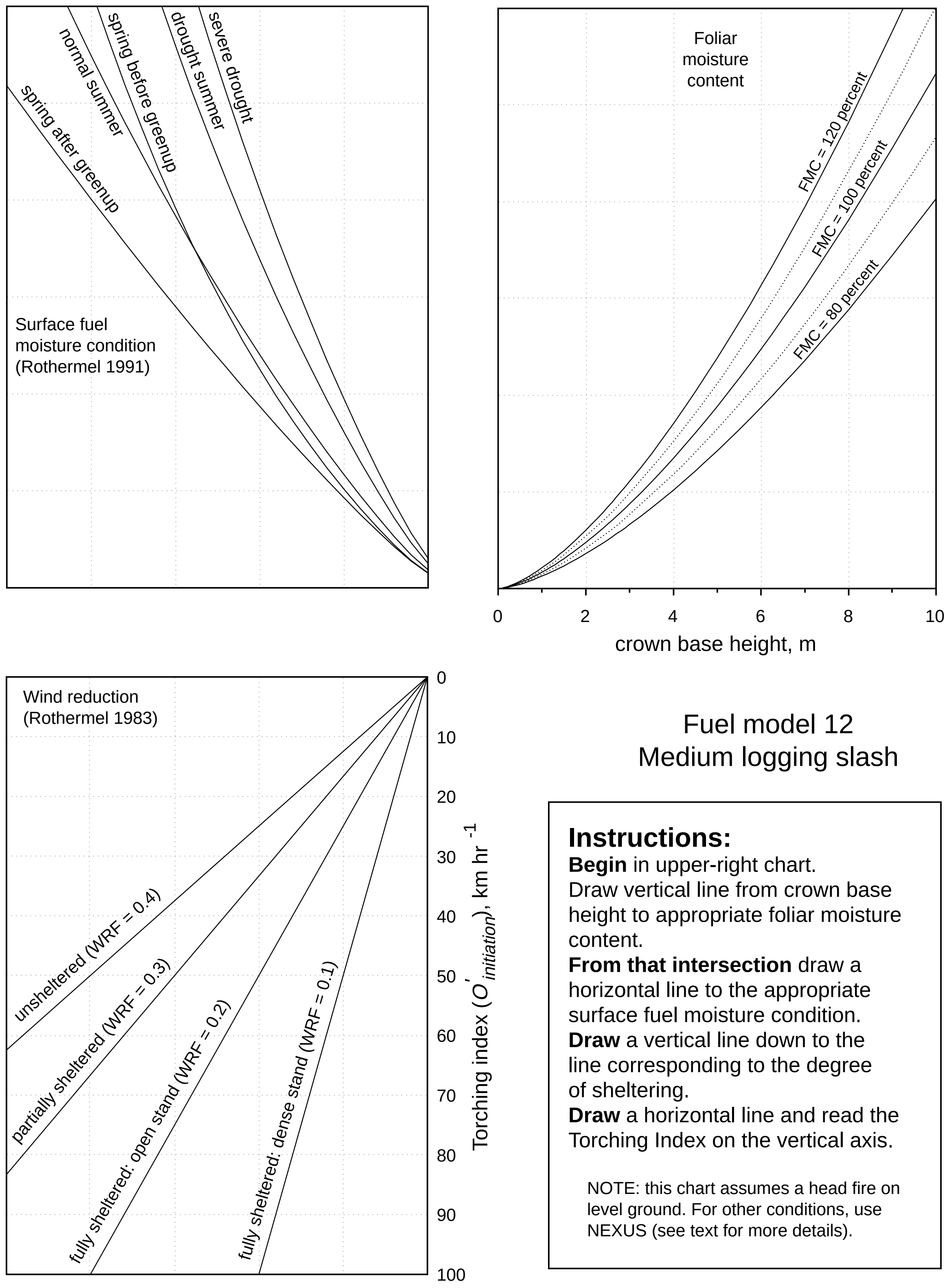

Figure D-8—Nomogram for determining the Torching Index for fuel model 12 (medium logging slash).

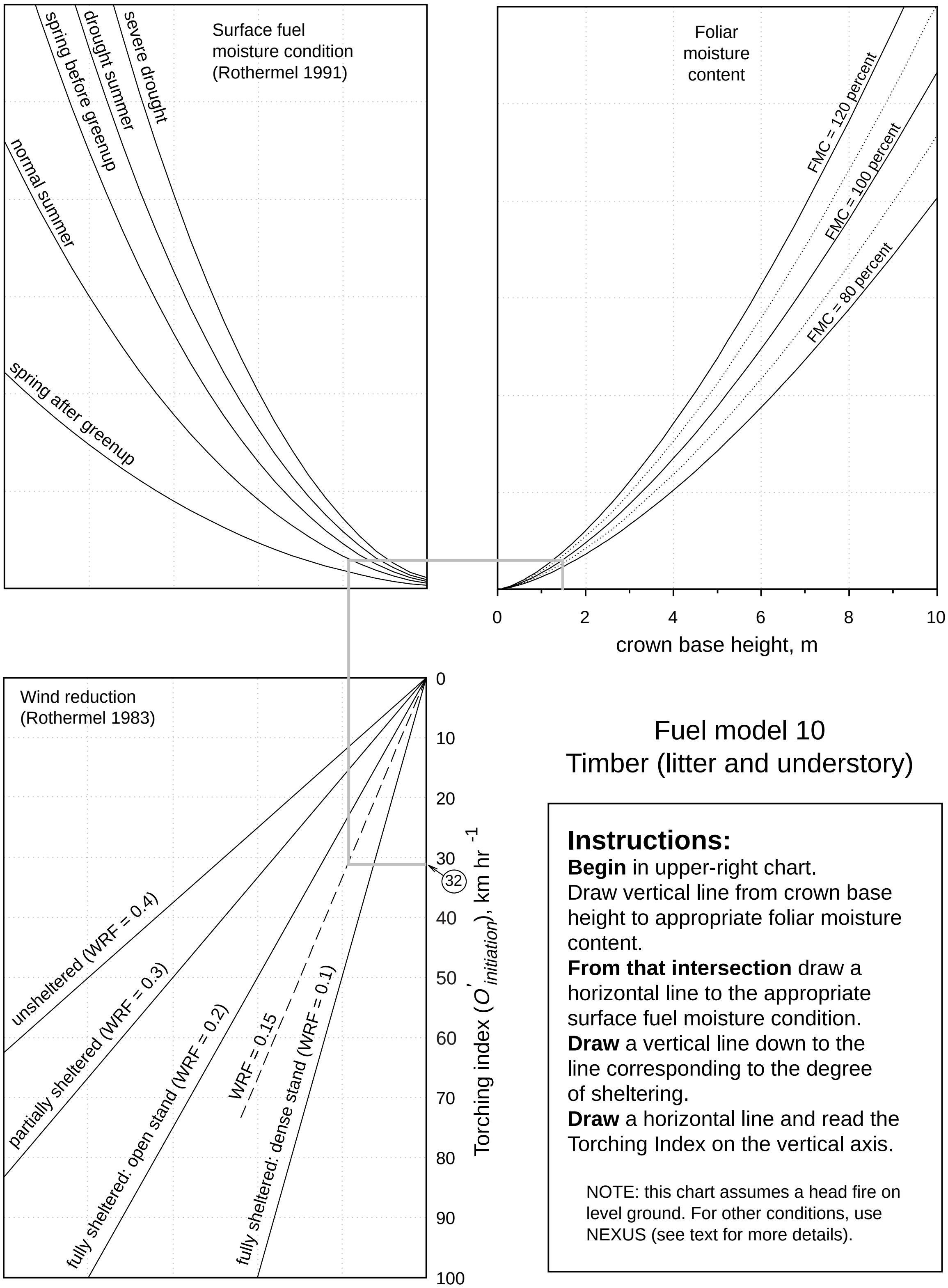

Figure D-9—Example nomogram for determining the Torching Index. **Inputs**: fuel model 10 (timber litter and understory), slope = 0, canopy base height = 1.5 m, foliar moisture content = 100 percent, normal summer fuel moisture condition (Rothermel 1991a), and wind adjustment factor = 0.15. The Torching Index is 32, indicating that an open windspeed of at least 32 km hr^{-1} is needed to initiate crown fire activity in the stand.

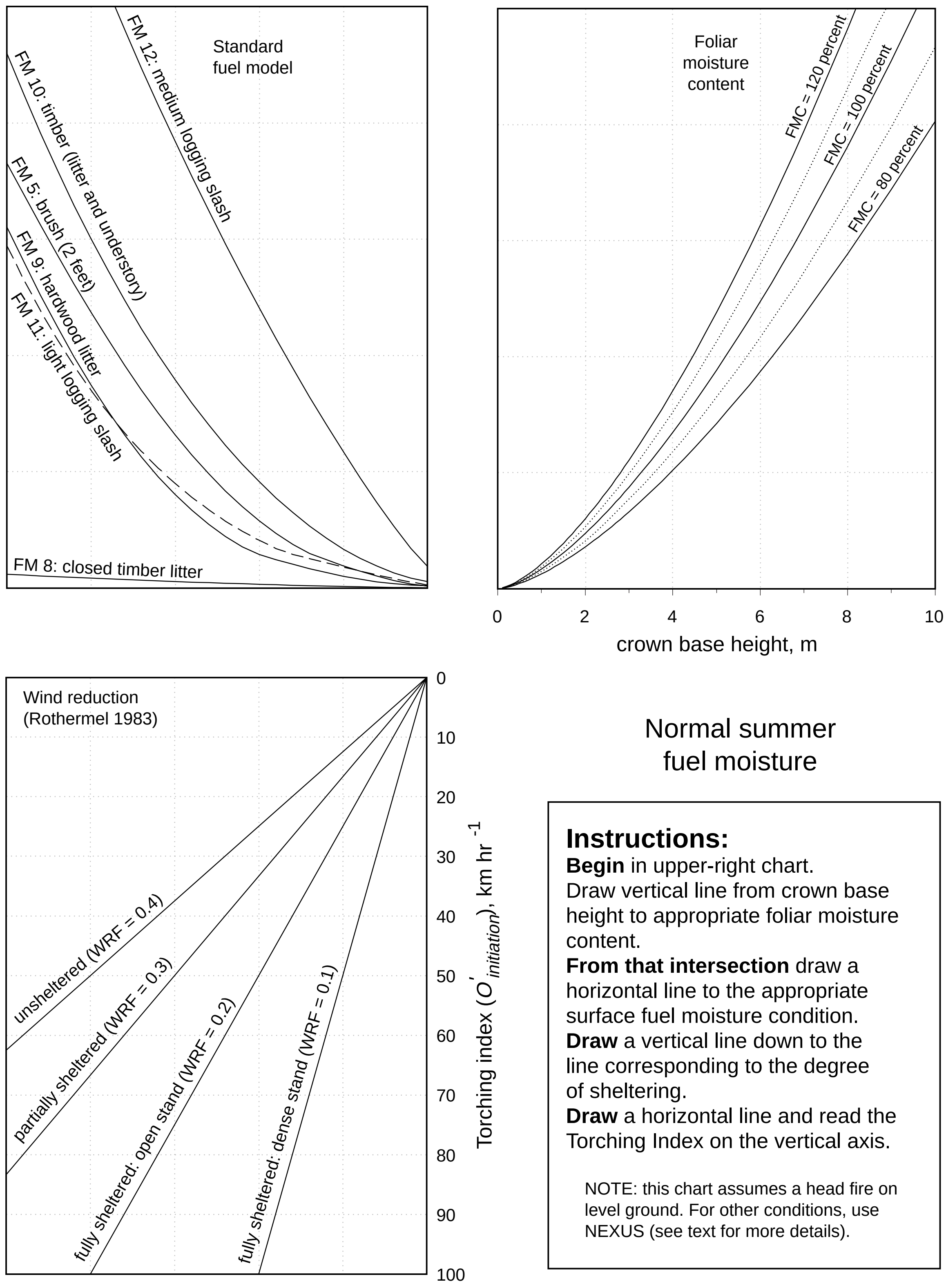

Figure D-10—Nomogram for determining the Torching Index for normal summer fuel moisture condition (Rothermel 1991a).

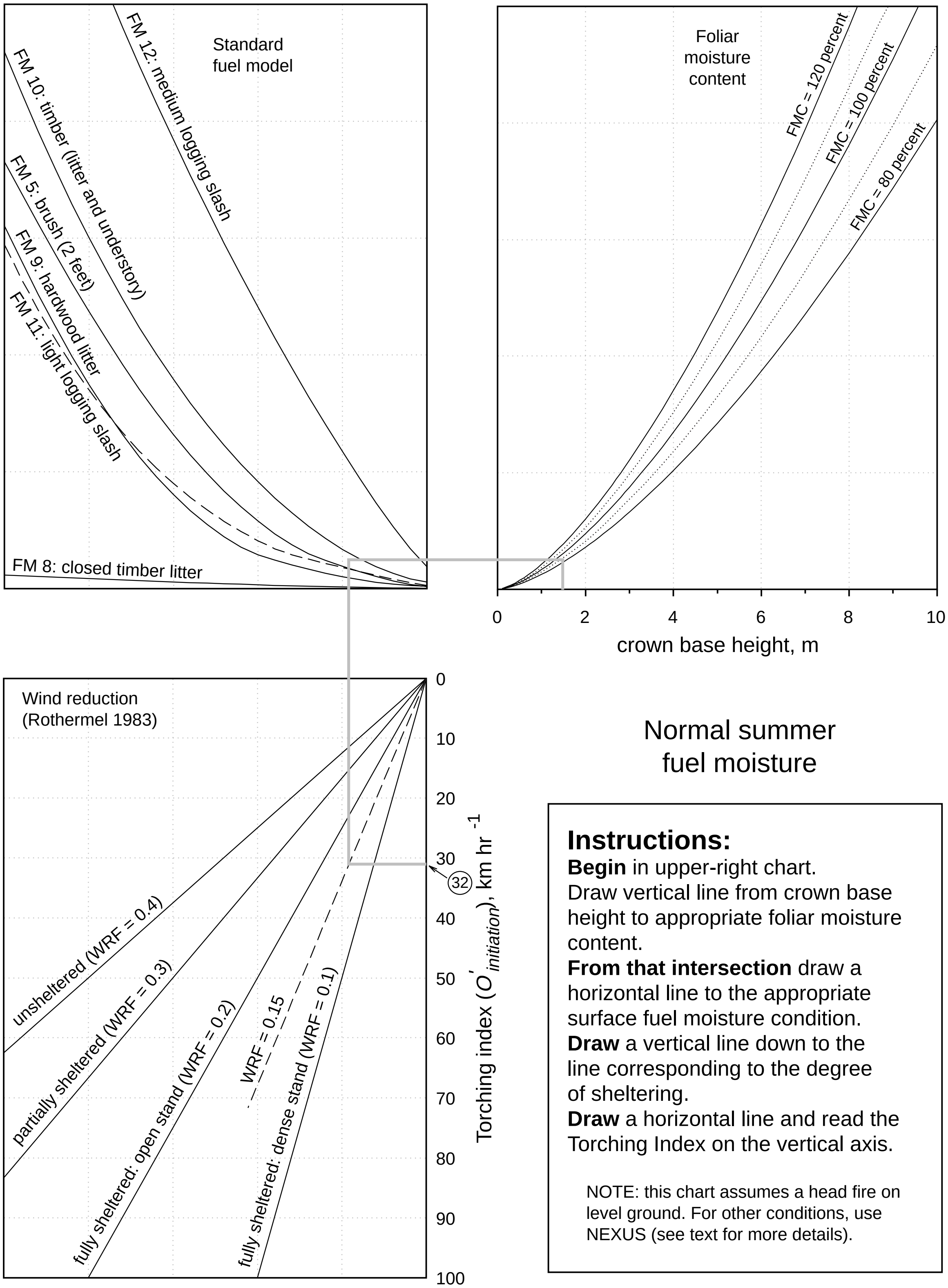

Figure D-11—Example nomogram for determining the Torching Index for normal summer fuel moisture condition (Rothermel 1991a). Inputs: fuel model 10 (Timber litter and understory), slope = 0, canopy base height = 1.5 m foliar moisture content = 100 percent, normal summer fuel moisture condition (Rothermel 1991a), and wind adjustment factor = 0.15. The Torching Index is 32, indicating that an open windspeed of at least 32 km hr^{-1} is needed to initiate crown fire activity in the stand.

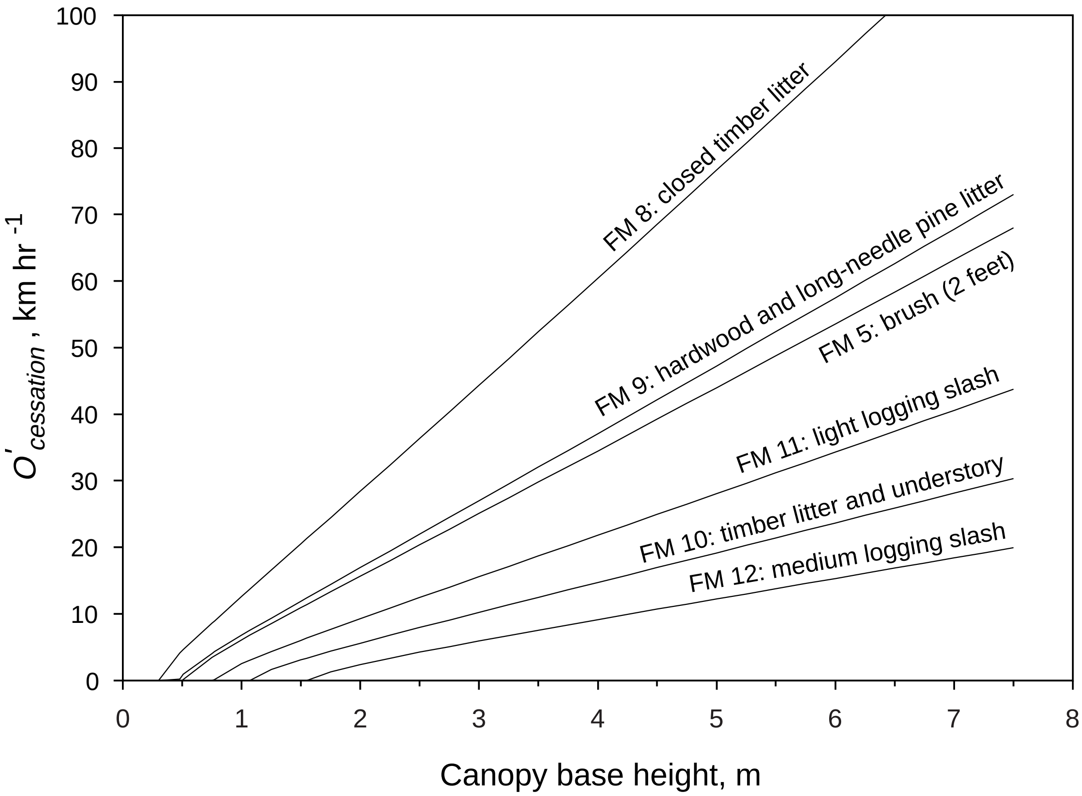

Figure D-12—Chart for determining the open windspeed ($O'_{cessation}$) at which the contribution of surface fuels to fireline intensity is too low to maintain crown fire spread, for a variety of surface fuel models. The contribution of surface fuels to fireline intensity is computed as the product of $HPA_{surface}$ and R_{active}. Normal summer fuel moisture condition (Rothermel 1991a) is assumed.

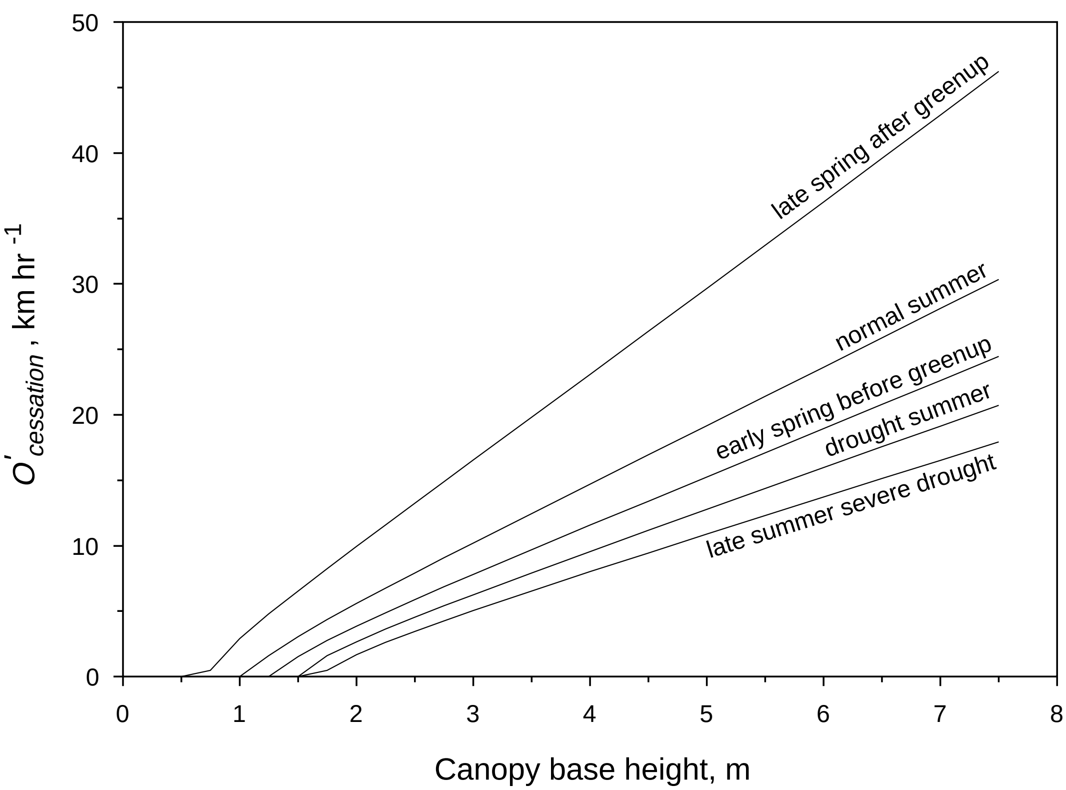

Figure D-13—Chart for determining the open windspeed ($O'_{cessation}$) at which the contribution of surface fuels to fireline intensity is too low to maintain crown fire spread, for a variety of fuel moisture conditions (Rothermel 1991a). Surface fuel model 10 was used in this chart. The contribution of surface fuels to fireline intensity is computed as the product of $HPA_{surface}$ and R_{active}.

Rocky Mountain Research Station
240 W. Prospect Road
Fort Collins, CO 80526

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