HELP WITH MAKING CROWN FIRE HAZARD ASSESSMENTS

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ABSTRACT: This paper offers some suggestions and field guides with respect to the operational application of C. E. Van Wagner's (1977. Can. J. For. Res. 7: 23-34.) theory to calculate the threshold conditions for the start and spread of crown fires in conifer forests. Three categories of crowning are recognized (passive, active, and independent); they are determined by three crown fuel properties (live crown base height, foliar moisture content and bulk density) and two characteristics of fire behavior (spread rate and surface intensity).

INTRODUCTION

Three main types of forest fire are commonly recognized on the basis of the fuel layer(s) involved in the combustion process:

- Ground or Subsurface Fire
- Surface Fire
- Crown Fire

Although they may appear to spread independently, crown fires advance through the crown fuel layer normally in direct conjunction with a surface fire. Crowning forest fires are very exciting natural phenomena but pose a potentially serious threat to life and property in wildland areas (Rothermel and Mutch 1986; Webster 1986; Wilson and Ferguson 1986; Abt and others 1987). The transition from a surface fire to a crown fire is also obviously of great significance to fire managers since crowning generally represents a level of fire behavior that normally precludes any direct suppression action. The conditions under which crown fires are likely to occur have been identified in a general way (Beale and Dieterich 1963; Fahnestock 1970; Rothermel 1983). More fundamental knowledge about the physics of such wildfire phenomena in the wildland/urban interface has recently been identified as a critical fire research need (Davis and Marker 1987). In the meantime, what information is currently available now to assist land managers with the job of objectively appraising the likelihood of crown fire development on an area or site-specific basis? More than 10 years ago, Van Wagner (1977) proposed some simple theory, supported in part by empirical field observations, regarding the conditions for the initiation and sustained propagation of crown fires in conifer forests which could be applied to a variety of fire management issues, including the wildland/urban interface problem. The purpose of this paper is to outline, in practical terms, the possible application of Van Wagner's crown fire classification scheme and model to the task of evaluating crowning potential. This includes the author's synopsis of Van Wagner's theory (with a minimum of equations), supplemented with several graphical and tabular aids to facilitate the interpretation of the theoretical concepts, designed with the fire manager in mind[1]. However, a certain level of familiarity on the part of the reader with the science of wildland fire behavior and the art of its prediction is assumed. Van Wagner's (1977) journal article should of course be consulted for clarification of any technical details given here. The International System of Units (SI) is used throughout; a list of SI-to-English unit conversion factors is included near the end of the paper. However, the English unit equivalents of all equations are given.

BACKGROUND INFORMATION

Fire intensity as used in this paper refers to frontal fire intensity (I), which is synonymous with Byram's (1959) fireline intensity (Merrill and Alexander 1987), defined as "the rate of heat energy release per unit time per unit length of fire front" (Merrill and Alexander 1987). The equation used to compute I (kW/m or Btu/sec/ft) is as follows (after Byram 1959):

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

where, H = net heat of combustion (kJ/kg or Btu/lb), W = quantity of fuel consumed in the active flaming front (kg/m^2 or lb/ft^2), and R = linear rate of spread (m/min or ft/min). Flame length (Alexander 1982, p. 351, figure 1) is generally considered a surrogate measure of frontal fire intensity. The most commonly accepted equations are (from Alexander 1982 and Byram 1959, respectively):

$$L = 0.0775(I)^{0.46} \qquad (2)$$

$$L = 0.45(I)^{0.46} \qquad (3)$$

where, L = flame length (m and ft, respectively) and I = frontal fire intensity (kW/m and Btu/sec/ft, respectively).

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[1]Enlargements and English unit versions of Figures 1 to 5 plus the Appendix are available upon request from the author at the following mailing address: 5320 - 122 Street, Edmonton, Alberta, Canada T6H 3S5.

VAN WAGNER'S CLASSIFICATION SCHEME AND MODEL

Classes of Crown Fire

According to Van Wagner (1977), crown fires in conifer forests can be classified according to their degree of dependence on the surface phase and the criteria could be described by several semi-mathematical statements. Approximate definitions for the three types of crown fires are as follows:

Passive Crown Fire - A fire in which trees "torch" as individuals, but rate of spread is controlled by the surface phase.

Active Crown Fire - A fire that advances with a well-defined wall of flame extending from the ground surface to above the crown fuel layer.

Independent Crown Fire - A fire that advances in the crown fuel layer only; the surface fire of course lags some distance behind the leading edge of the crowning phase.

Other crown fire terminology exists (for example, Brown and Davis 1973; Merrill and Alexander 1987). A passive crown fire is basically not that different from an intense surface fire and probably most crown fires are of the active class (Van Wagner 1983). The class of crown fire to be expected in a conifer forest on any given day, according to Van Wagner (1977), depends on three simple properties of the crown fuel layer and two basic fire behavior characteristics:

- Initial Surface Fire Intensity
- Foliar Moisture Content
- Live Crown Base Height
- Crown Bulk Density
- Rate of Fire Spread

The first three quantities determine whether a surface fire will ignite the coniferous foliage. The last two quantities determine whether or not a continuous flame front can be sustained within the crown fuel layer.

Conditions for the Onset of Crowning

Van Wagner (1977) postulated that vertical fire spread will occur in coniferous forest stands when the surface fire intensity (I_s) attains or exceeds a certain critical surface intensity for crown combustion (I_o) value (kW/m or Btu/sec/ft). That is, when $I_s \geq I_o$, torching or crowning is quite possible. Whereas, when $I_s < I_o$, a surface fire is likely to be the result. Ladder or bridge fuels must presumably be present in sufficient quantity to intensify the surface fire appreciably as well as to extend the height of the flames (Quintilio and others 1977). The SI or metric unit version of the equation to calculate I_o (kW/m or Btu/sec/ft) is as follows (after Van Wagner 1977):

$$I_o = [0.010\ \mathrm{LCBH}(460 + 26\ \mathrm{FMC})]^{1.5} \qquad (4)$$

$$I_o = [0.0030976\ \mathrm{LCBH}(197.90 + 11.186\ \mathrm{FMC})]^{1.5} \qquad (5)$$

where, LCBH = live crown base height (m or ft, respectively) and FMC = foliar moisture content (% oven-dry weight or ODW basis). LCBH refers to the distance from the ground surface to the base of the live conifer tree crowns and FMC refers to the moisture content of coniferous tree foliage. Equations (4) and (5) define the amount of energy required to preheat the unburned coniferous foliage to ignition temperature. Graphical representations of equation (4) are given in figures 1A and 1B. Note that the surface fire intensity required for ignition of coniferous tree crowns increases with FMC and HLCB. The importance of moisture content with respect to the ignitability of coniferous tree foliage has been demonstrated many times in the laboratory (see, for example, Fuglem and Murphy 1979; Cohen and others 1987). If the FMC is high, combustion efficiency is reduced and greater amounts of energy are required to bring the foliage to ignition temperature. However, it appears from figure 1A that the natural variation in LCBH would allow for a much greater effect on the flammability of coniferous tree foliage than would the observed variation in FMC (cf. Fuglem and Murphy 1980, p. 35, figure 10). Since frontal fire intensity and flame length are known to be directly related, it is possible, by combining equations (2) and (4) [or (3) and (5)], to infer a critical or minimum flame length for crown combustion L_o (fig. 2). According to figure 2, the flames of a surface fire do not have to necessarily reach into the tree crowns to initiate crowning; flame height and length are only equal in the case of no wind or slope (Alexander 1982).

Conditions for Sustained Crown Fire Spread

Presumably some conifer stands are simply not prone or susceptible to sustained crowning because of their low tree density and/or crown fuel density (that is, there is insufficient coniferous tree foliage to support continuous horizontal fire spread in the crown fuel layer). Passive or intermittent crown fires are common, for example, in sparsely-stocked black spruce stands even though the tree crowns extend to the ground surface (Norum 1982). The torching which occurs in a passive or intermittent crown fire simply reinforces the spread rate (that is, the crowning phase of the fire is dependent on the surface phase, the spread of which will control the fire's spread rate as a whole).

What kind of forest is most likely then to support an active crown fire? Presumably there must be sufficient surface fuel to support a substantial surface fire in order to induce crown combustion. Thereafter the surface and crown fire phases advance as a linked unit, but are dependent on each other (Van Wagner 1977). In an active crown fire, both phases contribute significantly to the spread rate. Intuitively one would think that there must be a more or less critical value or threshold condition which must be exceeded in order to sustain a continuous flame front within the trunk and crown space. Van Wagner (1977) theorized that the bulk density of the crown fuel layer must have a lower limit below which active crowning cannot be maintained (fig. 3). This thought has been formulated into the following relation (after Van Wagner 1977):

$$R_o = 3.0/\mathrm{CBD} \qquad (6)$$

where, R_o = critical minimum spread rate for active

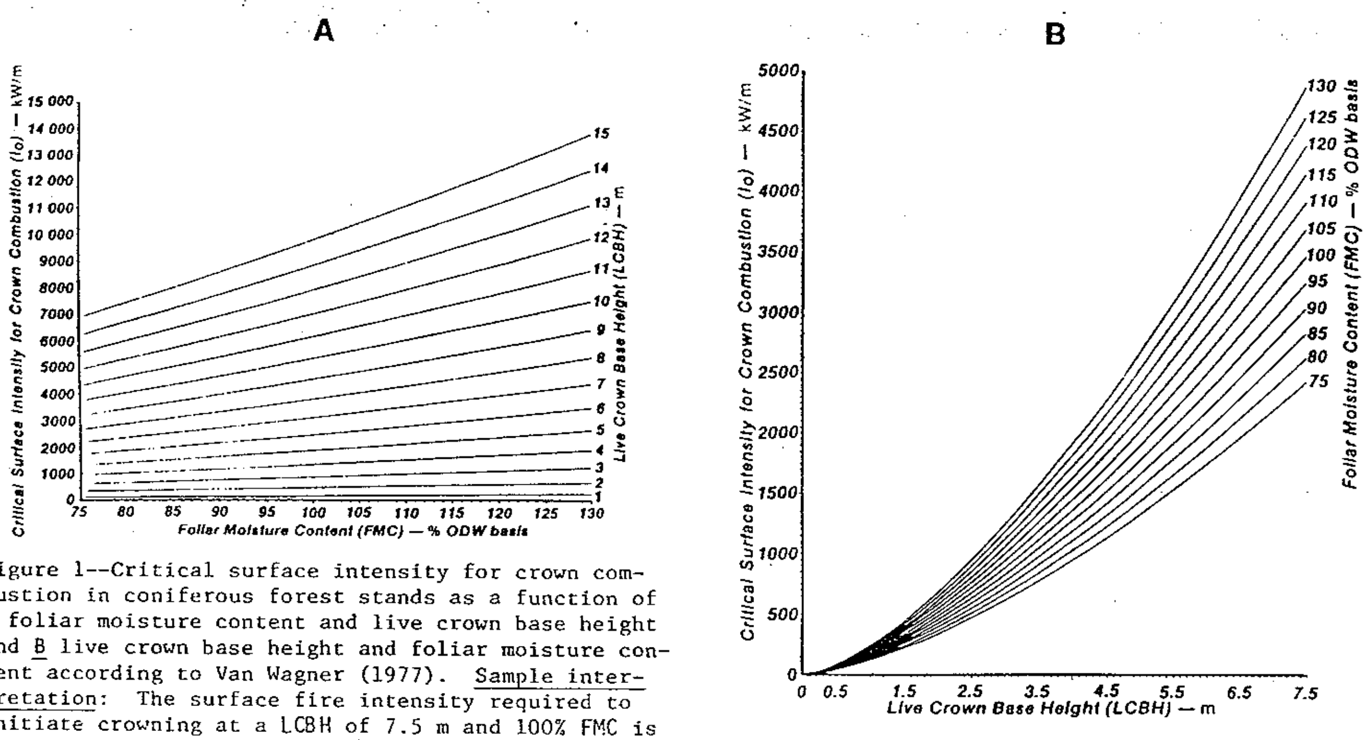
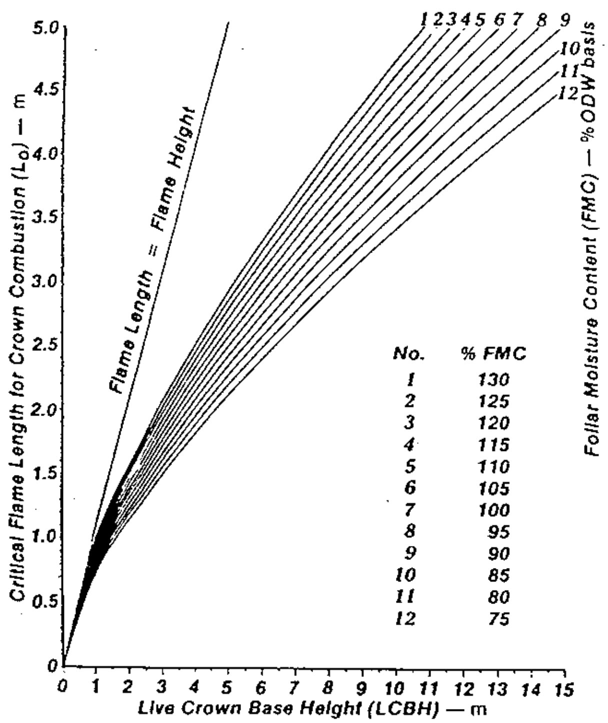
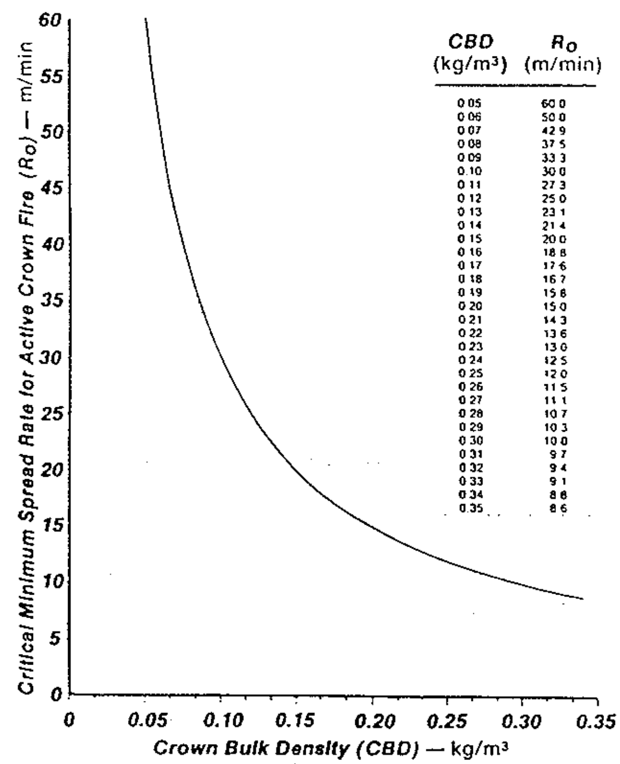


Figure 1--Critical surface intensity for crown combustion in coniferous forest stands as a function of A foliar moisture content and live crown base height and B live crown base height and foliar moisture content according to Van Wagner (1977). Sample interpretation: The surface fire intensity required to initiate crowning at a LCBH of 7.5 m and 100% FMC is about 3500 kW/m.



No.	% FMC
1	130
2	125
3	120
4	115
5	110
6	105
7	100
8	95
9	90
10	85
11	80
12	75

Figure 2--Minimum flame length for crown combustion in coniferous forest stands as a function of live crown base height and foliar moisture content based on Van Wagner (1977) and Byram (1959). The line of exact agreement between flame length and flame height is noted for reference purposes. Note that the key to the family of FMC curves is given in the accompanying tabulation. Sample interpretation: At a LCBH of 5 m and 100% FMC, crowning would commence once the surface fire began to generate flame lengths of 2.5 m.



CBD (kg/m³)	R_o (m/min)
0 05	60 0
0 06	50 0
0 07	42 9
0 08	37 5
0 09	33 3
0.10	30 0
0 11	27 3
0 12	25 0
0 13	23 1
0 14	21 4
0 15	20 0
0 16	18 8
0 17	17 6
0 18	16 7
0 19	15 8
0 20	15 0
0 21	14 3
0 22	13 6
0 23	13 0
0 24	12 5
0 25	12 0
0 26	11 5
0 27	11 1
0 28	10 7
0 29	10 3
0 30	10 0
0 31	9 7
0 32	9 4
0 33	9 1
0 34	8 8
0.35	8 6

Figure 3--Theoretical relation between the critical minimum spread rate for active crown fire and crown bulk density in coniferous forest stands according to Van Wagner (1977). A tabulation of CBD and the corresponding R_o values in also given for the convenience of field users. Sample interpretation: The development of an active crown fire would not be possible at a CBD of 0.23 kg/m³ until the rate of spread after crowning exceed 13 m/min.

crown fire (m/min) and CBD = crown bulk density (kg/m^3). To compute R_o in either ch/hr or ft/min and CBD in lb/ft^3, the coefficient in equation (6) becomes 0.55861 or 0.61446 respectively, rather than 3.0. Note that the minimum spread rate required for active crowning increases as the bulk density of the crown fuel layer decreases (fig. 3). In the simplest case, the bulk density of the crown fuel layer in a coniferous forest stand is determined by dividing the foliage weight (kg/m^2 or lb/ft^2) by the average live crown length (m or ft). This assumes that only the conifer needles are involved in the crown fire propagation process and that they are uniformly distributed throughout the overstory canopy. The CBD determination is obviously somewhat more complex in immature and disease/insect-killed stands (Stocks 1987a, 1987b) since dead twigs and some branchwood may also become available for combustion. The development of an active crown fire does not occur in a single vertical lift but climbs progressively into the crown with its forward spread as illustrated, for example, by Geddes and Pfeiffer (1981, p. 10). Once the fire crowns, the flame front will be nearly vertical within the trunk space. Deflection by the wind field may begin within the crown fuel layer and be most pronounced above the tree crowns (see, for example, Van Wagner 1968, p. 16, figure 11). Active crowning will then continue provided that the rate of spread is fast enough to maintain a continuous flame in the crown phase (that is, when $R > R_o$) and the fire can transfer enough heat to the unburned tree crowns ahead to maintain continuous ignition.

Development of a truely independent crown fire on flat topography most certainly must require strong surface winds. This is necessary in order to achieve the direct flame contact and forward radiation heat transfer through the crown foliage, that is required to continue the propagation in a horizontal dimension, more or less independent of the surface fire energy output rate. In mountainous terrain, slope steepness no doubt compensates for the reduced wind flow; as for example, a 60% slope would result in about a 7-fold increase in rate of fire spread (see, for example, Lawson and others, 1985, p. 12, figure 6), and at least a corresponding increase in fire intensity compared to the same fuel and weather conditions on level terrain. Instances of independent crown fires have been reported (Rothermel and Mutch 1986). Sustained "runs" are undoubtedly a very rare event due to the natural variations in wind velocity, fuels and terrain. In certain forest cover types with very light surface fuel loads, such as the Ocala sand pine forests of north-central Florida, wildfires would appear to spread as an independent crown fire or not at all (Cooper 1973).

FIELD APPLICATION

On the basis of Van Wagner's (1977) crown fire model, a set of graphs and tables that relate I_o and L_o to LCBH and FMC were prepared following the present author's attendance at the S-590 Fire Behavior Officer (FBO) [now Fire Behavior Analyst or FBA] training course held at the USDA Forest Service's National Advanced Resource Technology Center (NARTC), Marana, Arizona, in December 1979 (Rothermel 1983, p. 107). One of the graphs was then included in Appendix F of Rothermel (1983, p. 142, figure F-1) but no adequate credit was given to the original Van Wagner (1977) contribution. This graph was subsequently reproduced by Keown (1985) and included, along with the tables, in the FBO or FBA and Fire Behavior for Managers (FBM) Field References issued by NARTC since 1983. Tabulated versions of figures 1 and 2, for quick reference in the field, are appended to this paper (Appendix). These decision aids are based on equations (2) and (4). Some guidelines with respect to satisfying the five input requirements in the field application of Van Wagner's (1977) crown fire theory follow. Two worked-out examples of Van Wagner's (1977) model, based on data given in Quintilio and others (1977) and Newstead and Alexander (1983), are also summarized in table 1 for reference check purposes.

Spread Rate (R) and Surface Fire Intensity (I_s)

The prediction of R and I_s would consider most of the known variables that influence fire behavior (i.e., air temperature, relative humidity, wind, fuel load, fuel moisture, slope, fuel arrangement, condition of herbaceous vegetation, etc.). There are basically five approaches to obtaining decent estimates of these two parameters:

- mathematical model such as the BEHAVE system or similar method (Rothermel 1983; Andrews 1986);
- empirical-based system (Hough and Albini 1978; Lawson and others 1985);
- comparison with known wildfire case histories (Geddes and Pfeiffer 1981; Simard and others 1983; Rothermel and Mutch 1986) or experimental fire case studies (Quintilio and others 1977; Newstead and Alexander 1983; Stocks 1987a, 1987b; Alexander and De Groot 1988);
- recent on-site observations of fire behavior (e.g., Norum 1982); and/or
- experienced judgement.

Although the intensity of the surface fire required to support a crown fire can be specified, the prediction of surface fire rate of spread and frontal intensity is, in fact, probably more difficult to predict than the level of crown fire behavior, given the most infinite variety of possible forest floor and understory fuel complexes. The rate of spread after crowning must exceed R_o, or nearly so, in order to maintain an active crown fire. Van Wagner's (1977) model does not predict the spread rate after crowning has taken place. However, the recent work by Albini and Stocks (1986) suggests that a physical model for the prediction of crown fire rate of spread may soon be available for adaptation to field use. The effect of crowning on the overall fire spread rate is accounted for directly in the rate of spread component equations of the Canadian Forest Fire Behavior Prediction System (Lawson and others 1985). One possible approximation that could be applied to the various methods of quantitative fire behavior prediction used in the U.S. (Andrews 1986), which are technically restricted to fire spread in surface fuels, is to fully or partially adjust the mid-flame wind to the standard 6.1-m [or 20-ft] open wind speed value if crowning is anticipated on basis of the predicted initial I_s (Anderson 1983; Simard and others 1983).

Table 1--Application of Van Wagner's (1977) crown fire model to two contrasting situations

Item	Unit	Case A	Case B
Fuel type	-	Pine stand	Spruce stand
Predicted spread rate (R)	m/min	1.0	7.5
Predicted fire intensity (I)	kW/m	620	4230
Foliar moisture content (FMC)	%	117	109
Live crown base height (LCBH)	m	4.4	1.4
Crown bulk density (CBD)	kg/m^3	0.15	0.38
Critical surface intensity for crown combustion (I_o)	kW/m	1913	313
Critical minimum spread rate for active crown fire (R_o)	m/min	20.0	7.9
Type of fire	-	surface	active crown[1]

[1]Developing.

Foliar Moisture Content (FMC)

A seasonal cycle in the moisture content of coniferous tree foliage has been identified by several investigators (table 2). Twenty to 40-percentage point differences, within a range of about 75 to 130%, have been documented. Diurnal variation in FMC is also known to exist (Philpot 1965), but is probably insignificant in terms of real noticeable differences in fire behavior. At least in eastern and northern North America, a marked moisture decrease in the moisture content of 1+ year-old needles, which constitutes the bulk of a tree's foliar dry weight, is evident in the spring just before flushing of the new growth. As this new growth continues to develop, the moisture content of the older foliage gradually increases. FMC is generally highest in the late summer or early fall when all the new growth has fully developed. Similar trends have also been reported in northern Siberia (Kurbatskii 1972). The low spring moisture content of the 1+ year-old needles is felt to contribute in a significant way to the probability of crown fire occurrences during the spring fire season in many areas (Fuglem and Murphy 1980; Simard and others 1983; Norum and Miller 1984), including the northern Rocky Mountains (Norum 1975), although other fuel and weather factors are no doubt involved. The reason for this spring decrease in FMC is not entirely a reduction in the amount of water in the needles but also, in part, a corresponding increase in starch content (Little 1970). This is not so much a weather-caused phenomenon as a physiological one; there are, however, field reports which suggest that occasionally severe drought conditions lead to abnormal moisture stress in trees growing on sandy, well-drained sites. The exact timing of the normal "spring dip" varies with elevation and latitude (Philpot 1963; Fuglem and Murphy 1980). Significant differences in the moisture content of coniferous foliage between tree species and needle age do exist. There is substantial evidence to suggest that the annual trend probably does not vary greatly from year to year. The possibilities for obtaining a reasonable FMC value are:

- general rules-of-thumb (typical value(s) for time of year and/or stage of plant growth) in a manner similar to the way in which estimation of moisture content in minor vegetation is handled by Rothermel (1983, p. 13, table II-2);
- on-site, near real-time measurement (Sackett 1980; Norum and Miller 1984);
- rely on published curves (table 2) or data (Brown 1978, p. 28-29) in the literature; or
- conduct independent study for species and locale of interest (Agee and Huff 1988).

Roussopoulos (1978a, 1978b), for instance, simply used a standard FMC value of 100% in his nomogram guide to the prediction of crown fires as "a common midsummer moisture content" in northeastern Minnesota.

Live Crown Base Height (LCBH)

The proportion of live tree crown does of course vary with tree height, stand density, etc. For example, in central British Columbia, Muraro (1971) found that the ratio of LCBH to tree height in lodgepole pine to be about 0.6:1. The distance from the ground surface to the base of the live crowns in a coniferous forest stand could be determined by:

- actual physical measurement;
- field observation ("guess-timate"); and/or
- infer from known relationship (for example, stand height and perhaps some measure of tree density) as illustrated in figure 4.

Examples of the latter method are also given in Anderson (1974), Cole and others (1982), Holdaway (1986), and Ritchie and Hann (1987).

Crown Bulk Density (CBD)

Determination of CBD requires: (1) crown foliage weight vs. diameter-at-breast height (dbh) relationship for the species of interest (Muraro 1971; Anderson 1974; Brown 1978; Roussopoulos 1978b; Freeman and others 1982); (2) number of stems per hectare (or acre) by dbh size class (based on stand exam or cruise data); and (3) the average stand crown length (this could of course be inferred from the mean stand height and mean live crown base height). There are basically two approaches available for determining crown bulk densities:

- calculate from stand inventory data and computer program, such as HAZARD (Puckett and others 1979) or related system (Radloff and others 1982) for a specific area.
- derive representative or stylized value(s) for various forest cover type/structure complexes (for example, "mature lodgepole pine") on a stand basis in a manner analogous to the way in which average individual tree crown bulk densities are quoted by Brown (1978, p. 25-28).

Note that bulk density does vary throughout the crown fuel layer as pointed out, for example, by Muraro (1971), Brown (1978) and others. Such a consideration could in fact result in a more refined estimate of the "effective" LCBH (Sando and Wick 1972; Roussopoulos 1978b).

Table 2--List of foliar moisture content studies conducted on conifer tree species in North America to date

No.	Reference(s)	Species[1]	Location
1.	Bunting, Stephen C.; Wright, Henry A.; Wallace, Walter H. 1983. Seasonal variation in the ignition time of redberry juniper. Journal of Range Management. 36(2): 169-171.	RJ	north-central Texas
2.	Chrosciewicz, Z. 1986. Foliar moisture content variations in four coniferous trees of central Alberta. Canadian Journal of Forest Research. 16(1): 157-162.	BS, WS, BF, JP	central Alberta
3.	Fingland, Randy D. 1987. Seasonal foliar moisture trends in Banff National Park. Vancouver, BC: University of British Columbia. 64 p. B.Sc.F. Thesis.	LP, WS	southwestern Alberta
4.	Fuglem, Peter L. 1979. Foliar moisture content of central Alberta conifers and its implication in crown fire occurrence. Edmonton, AB: University of Alberta. 148 p. M.Sc. Thesis. [*see* also Fuglem and Murphy 1980 in REFERENCES].	LP, BS, WS-ES	central Alberta
5.	Gary, Howard L. 1971. Seasonal and diurnal changes in moisture contents and water deficits of Engelmann needles. Botanical Gazette. 132(4): 327-332.	ES	north-central New Mexico
6.	Hough, W.A. 1973. Fuel and weather influences wildfires in sand pine forests. Res. Pap. SE-106. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 11 p.	SP	north-central Florida
7.	Jameson, Donald A. 1966. Diurnal and seasonal fluctuations in moisture content of pinyon and juniper. Res. Note RM-67. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 7 p.	UJ, AJ, OJ, P	central Arizona
8.	Johnson, Von J. 1966. Seasonal fluctuation in moisture content of pine foliage. Res. Note NC-11. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.	RP, JP	central Minnesota and Michigan
9.	Kiil, A.D. 1968. Changes in the physical characteristics and moisture content of pine and spruce-fir slash during the first five years after logging. Int. Rep. A-14. Edmonton, AB: Canada Department of Forestry and Rural Development, Forestry Branch, Forest Research Laboratory. 40 p.	LP, WS	west-central Alberta
10.	Kozlowski, Theodore T.; Clausen, J. Johanna. 1965. Changes in moisture contents and dry weights of buds and leaves of forest trees. Botanical Gazette. 126(1): 20-26.	WP, RP, BF, EH	northern Wisconsin
11.	Little, C.H.A. 1970. Seasonal changes in carbohydrate and moisture content in needles of balsam fir (Abies balsamea). Canadian Journal of Botany. 48(11): 2021-2028. [*see* also Little 1970 in REFERENCES].	BF	central New Brunswick
12.	Philpot, Charles W. 1963. Vegetation moisture trends in the central Sierra Nevada. Berkeley, CA: University of California. 53 p. M.Sc. Thesis. [*see* also Philpot 1963 in REFERENCES].	PP	central California
13.	Philpot, Charles W.; Mutch, Robert W. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. Res. Pap. INT-112. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 21 p.	PP, DF	northwestern Montana
14.	Russell, R.N.; Turner, J.A. 1975. Foliar moisture content during bud swelling and needle flush in British Columbia. Bi-monthly Research Notes. Ottawa, ON: Canadian Forestry Service; 31(4): 24-25.	GF, WH, DF, NS	Vancouver Island, British Columbia
15.	Springer, E.A.; Van Wagner, C.E. 1984. The seasonal foliar moisture trend of black spruce at Kapuskasing, Ontario. Canadian Forestry Service Research Notes. 4(3): 39-42.	BS	northeastern Ontario
16.	Van Wagner, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Dep. Publ. No. 1204. Ottawa, ON: Canada Department of Forestry and Rural Development, Forestry Branch. 15 p.	WP, RP, JP, BF, WS	eastern Ontario
17.	Van Wagner, C.E. 1974. A spread index for crown fires in spring. Inf. Rep. PS-X-55. Chalk River, ON: Canadian Forestry Service, Petawawa Forest Experiment Station. 12 p.	RP	eastern Ontario

[1]WP = eastern white pine; PP = ponderosa pine; RP = red pine; JP = jack pine; LP = lodgepole pine; SP = sand pine; P = pinyon pine; WS = white spruce; ES = Engelmann spruce; BS = black spruce; NS = Norway spruce; EH = eastern hemlock; WH = western hemlock; BF = balsam fir; GF = grand fir; DF = Douglas- fir; RJ = redberry juniper; UJ = Utah juniper; AJ = alligator juniper; OJ = one-seeded juniper.

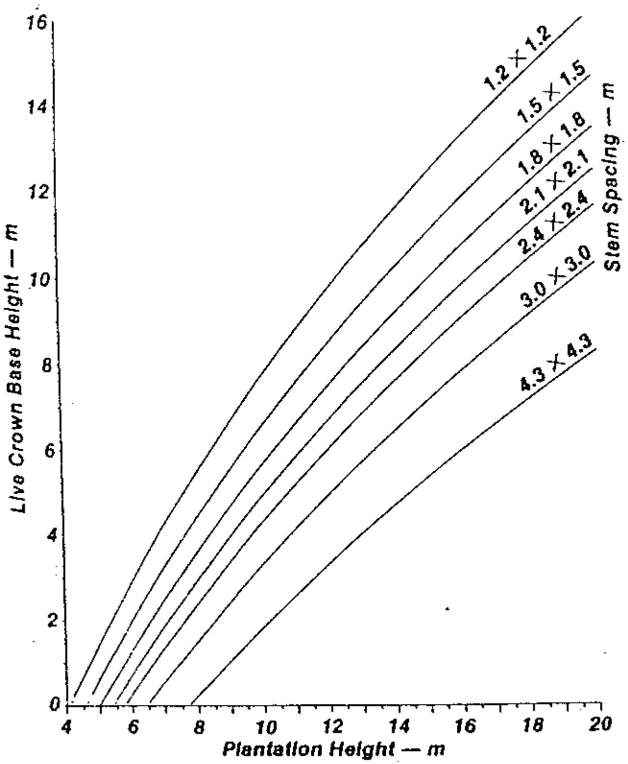


Figure 4--Relation between live crown base height and stand height in unthinned red pine plantations in eastern Ontario according to Stiell (1980).

I. Surface Fire Intensity (I_S) is predicted to be less than 10 kW/m.
   - A. A firebrand has caused an ignition to occur *SELF-EXTINGUISHING FIRE; FAILS TO SPREAD.*
   - B. Going fire . . . . *GROUND or SUBSURFACE FIRE.**

II. Surface Fire Intensity (I_S) is predicted to be greater than 10 kW/m but less or nearly equal to the Critical Surface Intensity for Crown Combustion (I_O).
   - A. I_S is substantially less than I_O . . *SURFACE FIRE.*
   - B. I_S is nearly equal to I_O *Developing PASSIVE CROWN FIRE.*

III. Surface Fire Intensity (I_S) is predicted to be equal to or greater than the Critical Surface Intensity for Crown Combustion (I_O).
   - A. Rate of Fire Spread (*R*) is predicted to be less than or nearly equal to the Critical Minimum Spread Rate for Active Crown Fire (R_O).
     1. *R* is substantially less than R_O *PASSIVE CROWN FIRE.*
     2. *R* is nearly equal to R_O *Developing ACTIVE CROWN FIRE.*
   - B. Rate of Fire Spread (*R*) is predicted to be equal to or greater than the Critical Minimum Spread Rate for Active Crown Fire (R_O).
     1. Forward heat transfer through the crown fuel layer relies upon surface fire phase *ACTIVE CROWN FIRE.*
     2. Energy requirements for the continued propagation through the crown fuel layer supplied entirely by the crown fire phase *INDEPENDENT CROWN FIRE.*

*Assuming there is a forest floor layer of significant depth and dryness.

Figure 5--A dichotomous key to a type of forest fire classification scheme based in part on Van Wagner's (1977) crown fire theory.

CLOSING REMARKS

Van Wagner's (1977) crown fire theory has received a fair amount of exposure in the wildland fire science literature (for example, Chandler and others 1983; Rothermel 1983; Pyne 1984) but implementation has been limited (see, for example, Roussopoulos 1978a, 1978b). His semi-physical model does remain largely untested. There certainly is a very strong need for further basic and applied research on crown fire modelling, especially with respect to spread rate prediction. Nevertheless, Van Wagner's approach, which is based on certain fundamental principles of fire physics, can be immediately applied to the systematic assessment of crown fire hazard (or at least supplement expert opinion) for use, at least on an interim basis, as an aid or tool in fire and fuel management planning today, particularly in even-aged conifer stands (fig. 5). For example, alternate strategies for manipulating the overstory stand structure and composition to limit the possibility and extent of crowning could be simulated (Sando and Wick 1972); this analysis could be coupled with a consideration of an area's "fire behavior climatology" (Salazar and Bradshaw 1986). Application of Van Wagner's model as a field guide and/or computer-assisted program for near real-time prediction of crown fire potential would, however, require some compilation and synthesizing of available information.

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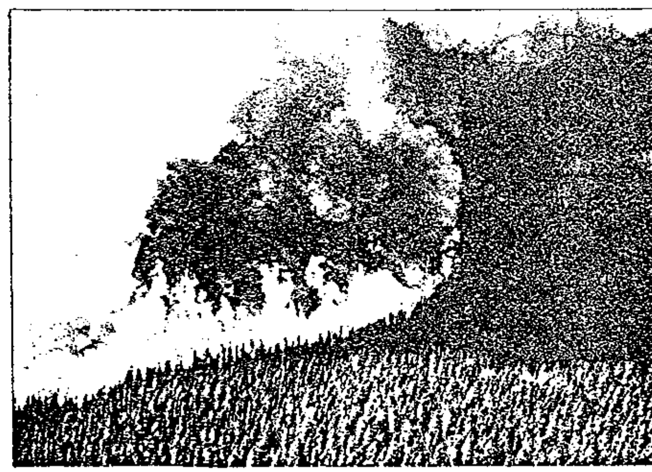

A free-burning active crown fire in the boreal forest region of central Alberta (photo by author).

INTERNATIONAL SYSTEM (SI)-TO-ENGLISH UNIT CONVERSION FACTORS

If the SI units are:	Multiply by:	To obtain:	Inverse Factor
kilograms per cubic metre (kg/m^3)	0.062428	pounds per cubic foot (lb/ft^3)	16.018
kilograms per square metre (kg/m^2)	0.20482	pounds per square foot (lb/ft^2)	4.8824
kilojoules per kilogram (kJ/kg)	0.43021	Btu per pound (Btu/lb)	2.3244
kilowatts per metre (kW/m)	0.28909	Btu per second per foot (Btu/sec/ft)	3.4592
metres (m)	3.2808	feet (ft)	0.3048
metres per minute (m/min)	3.2808	feet per minute (ft/min)	0.3048
metres per minute (m/min)	2.9826	chains per hour (ch/hr)	0.33528

Note: All factors are given to five significant digits. If fewer, the value is exact. To convert English unit values to SI multiply by the inverse factor given in the right-hand column. A "Btu" is a British thermal unit.

APPENDIX: Critical Surface Intensity (I_o) and Flame Length (L_o) for Crown Combustion in Coniferous Forest Stands versus Live Crown Base Height (LCBH) and Foliar Moisture Content (FMC) based on Van Wagner (1977) and Byram (1959). Units: kilowatts per metre (kW/m) and metres (m).

LCBH (m)	FMC (% ODW basis)											
	75	80	85	90	95	100	105	110	115	120	125	130
	I_o (kW/m)											
0.5	42	45	49	52	56	60	64	68	72	76	80	84
1.0	118	128	138	148	159	169	180	191	203	214	226	238
1.5	217	235	253	272	291	311	331	351	372	393	415	437
2.0	335	362	390	419	449	479	510	541	573	606	639	673
2.5	468	506	545	586	630	669	712	756	801	847	893	941
3.0	615	665	717	770	824	880	936	994	1,053	1,113	1,174	1,236
3.5	775	838	903	970	1,038	1,108	1,180	1,253	1,327	1,403	1,480	1,558
4.0	946	1,024	1,104	1,185	1,269	1,354	1,441	1,530	1,621	1,714	1,808	1,904
4.5	1,129	1,222	1,317	1,414	1,514	1,616	1,720	1,826	1,934	2,045	2,157	2,271
5.0	1,323	1,431	1,542	1,656	1,773	1,892	2,014	2,139	2,266	2,395	2,526	2,660
5.5	1,526	1,651	1,780	1,911	2,046	2,183	2,324	2,467	2,614	2,763	2,915	3,069
6.0	1,739	1,881	2,028	2,177	2,331	2,488	2,648	2,811	2,978	3,148	3,321	3,497
6.5	1,961	2,121	2,286	2,455	2,628	2,805	2,986	3,170	3,358	3,550	3,745	3,943
7.0	2,191	2,371	2,555	2,744	2,937	3,135	3,337	3,543	3,753	3,967	4,185	4,407
7.5	2,430	2,629	2,834	3,043	3,258	3,477	3,701	3,929	4,162	4,400	4,641	4,887
8.0	2,677	2,897	3,122	3,352	3,589	3,830	4,077	4,328	4,585	4,847	5,113	5,384
8.5	2,932	3,172	3,419	3,672	3,930	4,195	4,465	4,741	5,022	5,308	5,600	5,897
9.0	3,194	3,456	3,725	4,000	4,282	4,570	4,865	5,165	5,471	5,783	6,101	6,425
9.5	3,464	3,748	4,040	4,338	4,644	4,956	5,276	5,601	5,933	6,272	6,617	6,968
10	3,741	4,048	4,363	4,685	5,015	5,353	5,697	6,049	6,408	6,774	7,146	7,525
11	4,316	4,670	5,033	5,405	5,786	6,175	6,573	6,979	7,393	7,815	8,244	8,681
12	4,918	5,321	5,735	6,159	6,593	7,036	7,490	7,952	8,424	8,904	9,394	9,892
13	5,545	6,000	6,467	6,945	7,434	7,934	8,445	8,966	9,498	10,040	10,592	11,153
14	6,197	6,706	7,227	7,761	8,308	8,867	9,438	10,021	10,615	11,221	11,837	12,465
15	6,873	7,437	8,015	8,607	9,214	9,834	10,467	11,113	11,772	12,444	13,128	13,824

LCBH (m)	FMC (% ODW basis)											
	75	80	85	90	95	100	105	110	115	120	125	130
	L_o (m)											
0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
1.0	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.0
1.5	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.3
2.0	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.5
2.5	1.3	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8
3.0	1.5	1.5	1.6	1.6	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.0
3.5	1.7	1.7	1.8	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.2	2.3
4.0	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.3	2.3	2.4	2.4	2.5
4.5	2.0	2.0	2.1	2.2	2.2	2.3	2.4	2.5	2.5	2.6	2.6	2.7
5.0	2.1	2.2	2.3	2.3	2.4	2.5	2.6	2.6	2.7	2.8	2.8	2.9
5.5	2.3	2.3	2.4	2.5	2.6	2.7	2.7	2.8	2.9	3.0	3.0	3.1
6.0	2.4	2.5	2.6	2.7	2.7	2.8	2.9	3.0	3.1	3.2	3.2	3.3
6.5	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.2	3.3	3.4	3.5
7.0	2.7	2.8	2.9	3.0	3.1	3.1	3.2	3.3	3.4	3.5	3.6	3.7
7.5	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
8.0	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0
8.5	3.0	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2
9.0	3.2	3.3	3.4	3.5	3.6	3.7	3.8	4.0	4.1	4.2	4.3	4.4
9.5	3.3	3.4	3.5	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5
10	3.4	3.5	3.7	3.8	3.9	4.0	4.1	4.3	4.4	4.5	4.6	4.7
11	3.6	3.8	3.9	4.0	4.2	4.3	4.4	4.5	4.7	4.8	4.9	5.0
12	3.9	4.0	4.2	4.3	4.4	4.6	4.7	4.8	5.0	5.1	5.2	5.3
13	4.1	4.2	4.4	4.5	4.7	4.8	5.0	5.1	5.2	5.4	5.5	5.6
14	4.3	4.5	4.6	4.8	4.9	5.1	5.2	5.4	5.5	5.7	5.8	5.9
15	4.5	4.7	4.8	5.0	5.2	5.3	5.5	5.6	5.8	5.9	6.1	6.2

October 6-8,
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Protecting People and Homes From Wildfire in the Interior West:

Proceedings of the Symposium and Workshop

Compilers:

William C. Fischer, Research Forester
Stephen F. Arno, Research Forester

Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

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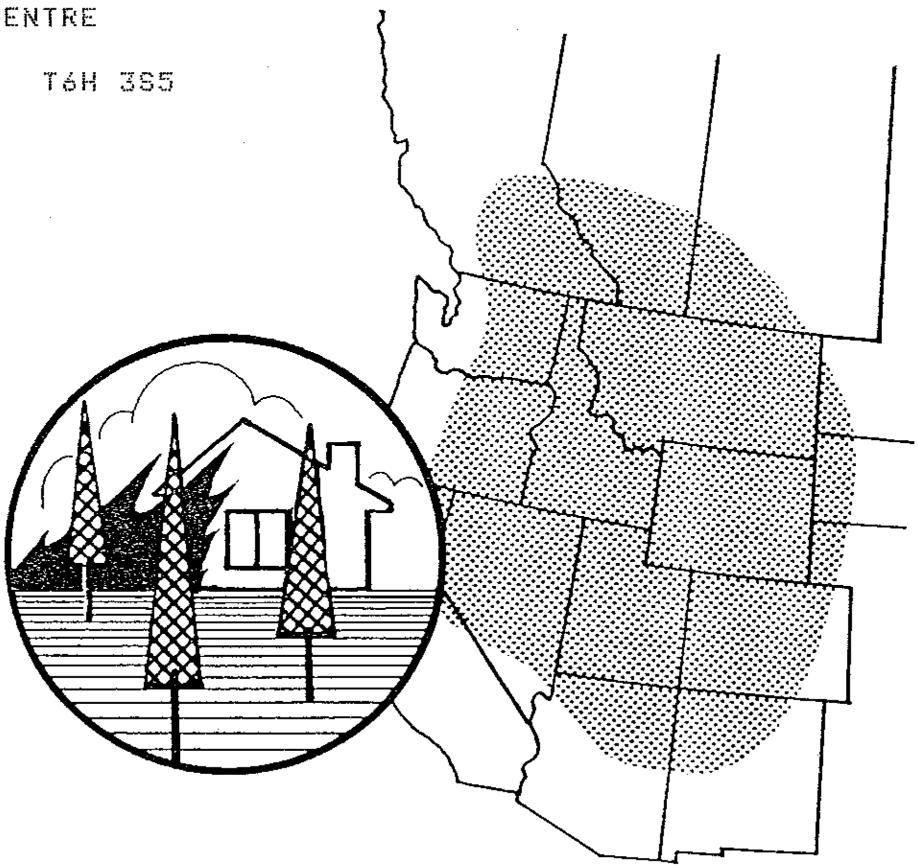

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