CROWN FIRE INITIATION AND SPREAD: EXPERIENCE IN CANADIAN FORESTS AND RELEVANCE TO AUSTRALIAN EXOTIC PINE PLANTATIONS[1]

by

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Background Information

Between 1980 and 1989, some 10 000 wildfires burned over about 2.5 million ha of forest land (Stocks 1990). Probably 95% of the area burned was the result of less than 5% of the fires, largely by high-intensity crowning. The vast majority of Canada's forests are especially prone to crown fire development over vast areas. Because the transition from a surface fire to a crown fire represents such a critical phase in wildfire suppression, a great deal of effort has been expended by Forestry Canada fire researchers on identifying the conditions required for crowning and formulating methods for predicting the subsequent fire behaviour given the fact that a few fires escaping initial attack is inevitable.

The federal forestry service in Canada has been conducting experimental forest fires for upwards to six decades now. The main purpose of these fires has been the study of free-burning fire behaviour. The practical output of this continuing research programme has been the development of the Canadian Forest Fire Danger Rating System (Stocks et al. 1989). Beginning in 1931, some 20 000 2-minute point-source test fires (Wright 1932; Macleod 1948) were eventually carried out at about 12 different locations in most of the major forest and fuel types found across Canada (Paul 1969; Simard 1970). Although an additional 1600 such fires were undertaken in east-central British Columbia during 1966-68 (Russell and Pech 1968), the 2-minute test fire programme effectively ended in 1961. Since the early 60s, the tend has been to burn increasingly larger plots in order to achieve equilibrium fire behaviour as opposed to investigating ignition potential and initiating fire growth (Alexander and Quintilio 1990).

The first "official" experimental crown fire reported on in the literature occurred on June 8, 1961, at the Petawawa Forest Experiment Station at Chalk River, Ontario, on a 0.06 ha plot of red pine plantation (Van Wagner 1964). Since that time, some 55 experimental crown fires have been conducted in several different kinds of conifer forest with variable stocking levels and mean stand heights of up to 20 m, in both eastern and western Canada (Van Wagner 1968, 1977a; Kiil 1975; Quintilio et al. 1977; Newstead and Alexander 1983; Stocks 1987a, 1987b, 1989; Weber et al. 1987; Alexander and De Groot 1988; Alexander and Lanoville 1989; Alexander, Stocks and Lawson 1990). Plot sizes have ranged up to 3.0 ha. Head fire spread rates and frontal intensities have varied from ~ 5 m/min (300 m/h) to 82 m/min (4920 m/h) and ~ 3000 kW/m to nearly 70 000 kW/m, respectively. There have been only two major "escapes"; one for 73 ha (1981) and the other for 1430 ha (1982) (Stocks 1987a; Alexander, Stocks and Lawson 1990). There have of course been about 75 experimental surface fires as well (Van Wagner 1963; Lawson 1973). A concerted effort has also been made to investigate and document the behaviour of major wildfires (Van Wagner 1965; Stocks and Walker 1973;

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Stocks 1975, 1988; Alexander et al. 1983; Alexander and Lanoville 1987; Stocks and Flannigan 1987). The amount of laboratory-based fire research related to crowning phenomena has been quite limited (e.g., Quintilio 1977). The crown fire behaviour research undertaken by Forestry Canada now spans a period of 30 years. Two major accomplishments have thus far emerged from this work -- some theoretical considerations about the conditions necessary for the start and spread of crown fire and a semi-empirical system for quantitative prediction of surface and crown fire behavior in major Canadian forest fuel types. The experimental crown fires have also made it possible to evaluate a physical-based model for predicting crown fire rate of spread developed by the U.S. Forest Service (Albini and Stocks 1986). A review on the subject of crown fire initation and spread has recently been prepared, and is based to large extent on Canadian experience (Alexander et al. 1990).

Van Wagner's Crown Fire Theory

Classification of Crown Fires

Although they may appear to spread independently, crown fires advance through the crown fuel layer normally in direct conjunction with a surface fire. Van Wagner (1977a) proposed that crown fires in conifer forests could be classified according to their degree of dependence on the surface phase and the criteria could be described by several semi-mathematical statements. The three classes of crown fire are (after Merrill and Alexander 1987; Alexander 1988):

> Passive crown fire.-- a fire in which trees "torch" individually but rate of spread is controlled by the surface fire; basically not that different from a high-intensity surface fire.
>
> 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 (i.e., the surface and crown phases must travel together as a linked unit); most crown fires are of the active class.
>
> Independent crown fire.-- a fire that advances in the crown fuel layer only, running ahead and some what independent of the surface phase (i.e., the surface fire of course lags some distance behind the leading edge of the crowning phase).

High-intensity wildfires do in fact exhibit all three classes of crowning in time and space.

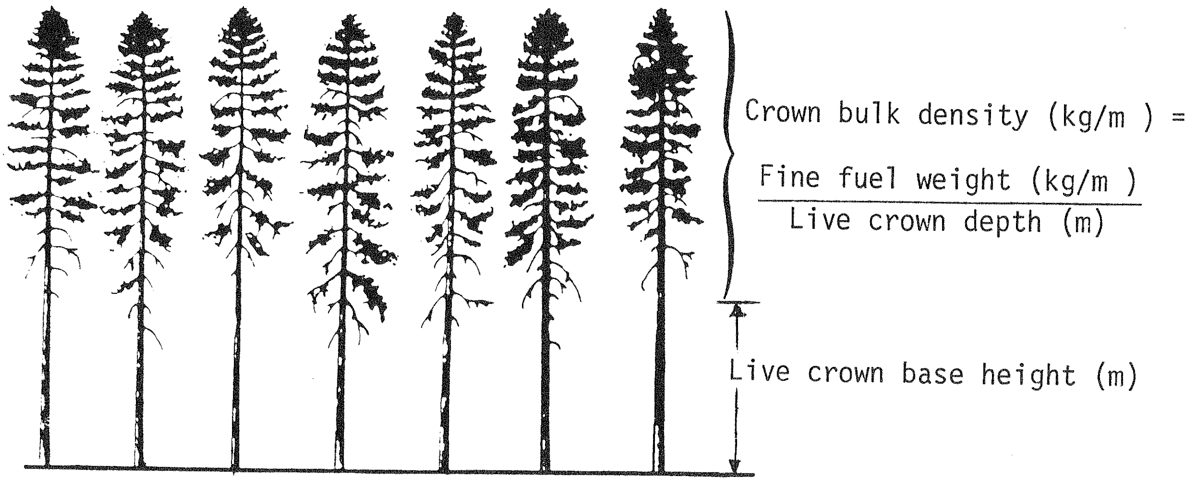

Figure 1. Two of the three crown fuel properties of a conifer forest identified in Van Wagner's (1977a) crown fire theory.

The class of crown fire to be expected in a conifer forest on any given day, according to Van Wagner (1977a), 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 coniferous foliage. The last two determine whether or not a continuous flame front can be sustained within the crown fuel layer. A dichotomous key to a forest fire classification scheme incorporating Van Wagner's (1977a) three classes of crown fire and the corresponding theory has been prepared (Fig. 2).

Criteria for the Initiation of Crowning

Van Wagner (1977a) considered that the onset of crowning would occur in a conifer forest stand when the surface fire intensity (I_s) attained or exceeded a certain "critical surface intensity for crown combustion" (I_o) value. In other words:

if $I_s \geq I_o$, crowning can occur <u>or</u> if $I_s < I_o$, a surface fire will result

Ladder or bridge fuels must presumably be present in sufficient quantity to intensify the surface burning as well as to extend the height of flames. The equation used to calculate I_o is as follows:

$$I_o = [0.010 \cdot \mathrm{LCBH}(460 + 26 \cdot \mathrm{FMC})]^{1.5} \tag{1}$$

where I_o is the critical surface intensity for crown combustion (kW/m), LCBH is the live crown base height (m), and FMC is the foliar moisture content (% oven-dry weight basis). A graphical representation of Equation 1 is presented in Figure 3; sample interpretation: the surface fire intensity required to initiate crowning in a conifer stand with a LCBH of 5.0 m and a 130% FMC is about 2660 kW/m. Note that the surface fire intensity required for the intiation of crowning increases with FMC and LCBH.

Criteria for Continuous Crown Fire Spread

Obviously certain conifer stands are more prone or susceptible to sustained crowning simply because their crown fuel characteristics (i.e., in addition to low LCBH, fine fuels such as needles and small twigs are in sufficient quantity to support continuous horizontal fire spread in the tree crowns). Van Wagner (1977a) theorized that the bulk density of the crown fuel layer must have a lower limit below which active crowning would not be possible and suggested the following relationship:

$$R_o = \frac{3.0}{\mathrm{CBD}} \tag{2}$$

where R_o is the critical minimum spread rate for an active crown fire (m/min) and CBD is the crown bulk density (kg/m^3). To compute R_o in m/h, the coefficient in Equation 2 becomes 180, rather than 3.0. A graphical representation of Equation 2 is presented in Figure 4; sample interpretation: assuming $I_s \geq I_o$, an active crown fire would not be possible in a conifer stand with a CBD of 0.25 kg/m^2 until the rate of spread after crowning exceeded 12 m/min or 720 m/h.

Type of Forest Fire: A Summary Key

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-EXTINQUISHING 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.***

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

Figure 2. A dichotomous key to a type of forest fire classification scheme based in part on Van Wagner's (1977a) crown fire theory (from Alexander 1988).

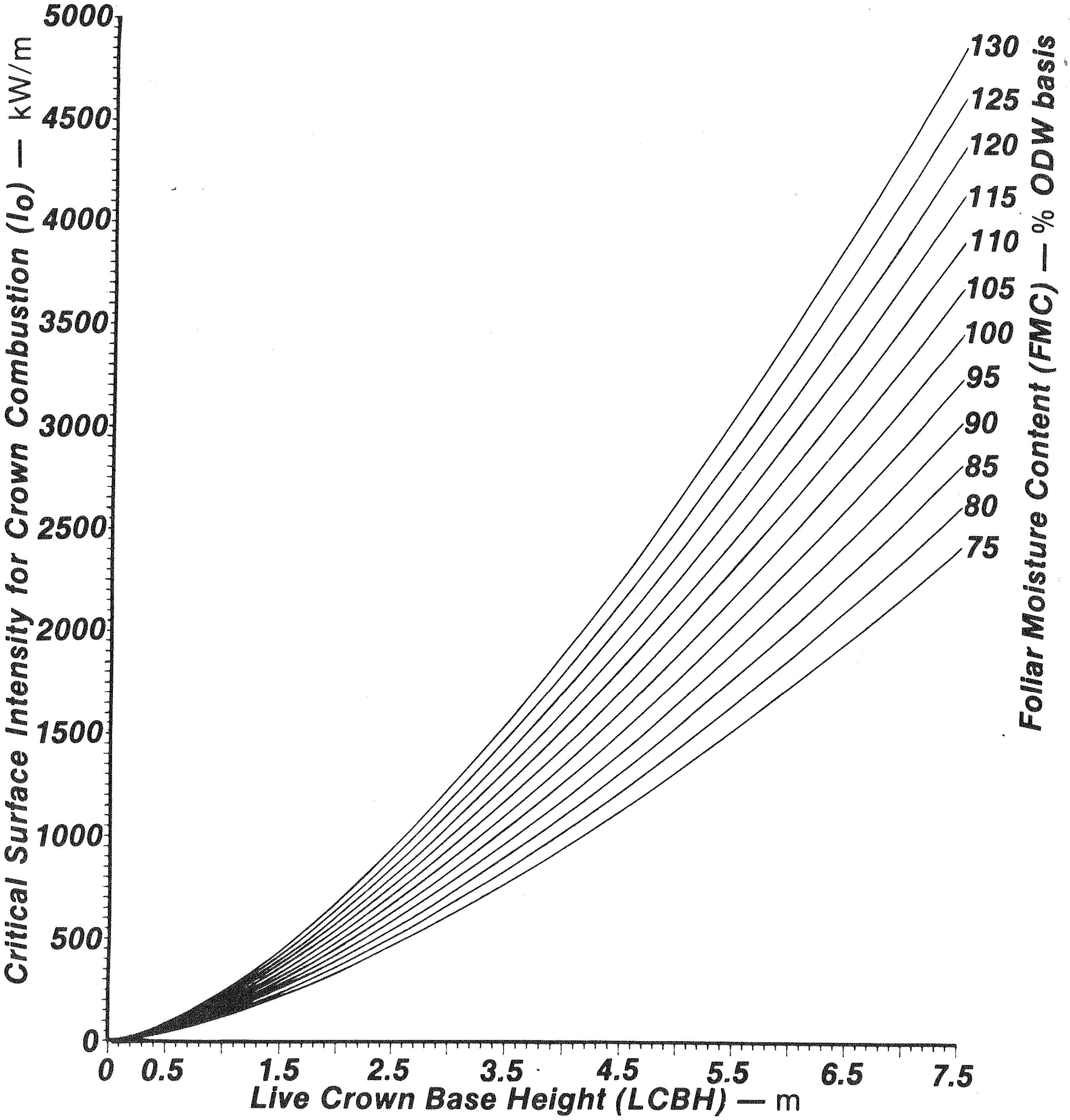

Figure 3. Critical surface intensity for crown combustion in coniferous forest stands as a function of live crown base height and foliar moisture content according to Van Wagner's (1977a) crown fire theory (from Alexander 1988).

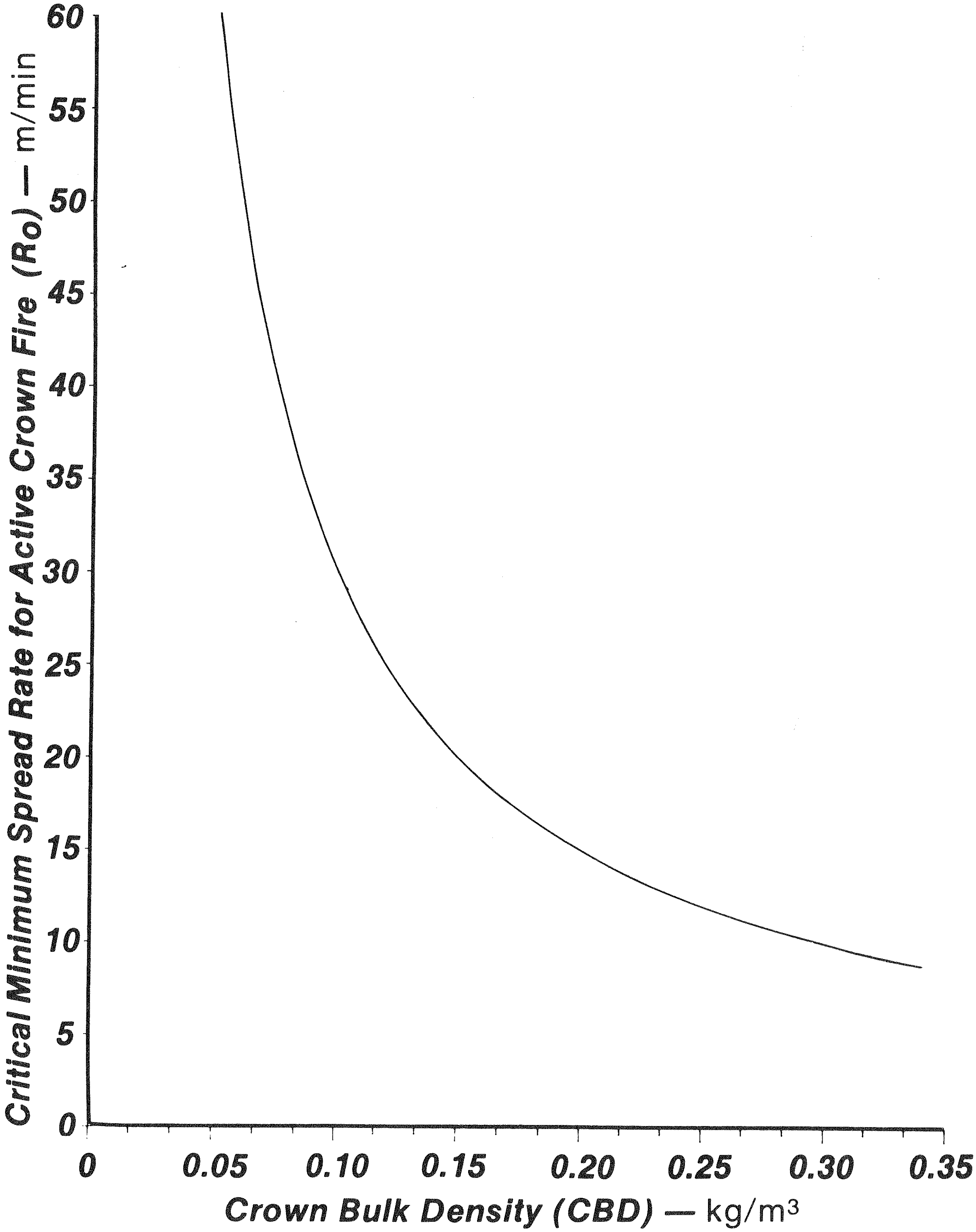

Figure 4. Theoretical relation between the critical minimum spread rate for active crown fire and crown bulk density in coniferous forest stands according to Van Wagner's (1977a) crown fire theory (from Alexander 1988).

Note that the minimum spread rate (R) required for crowning increases as the bulk density of the crown fuel layer increases. Once a fire crowns, active crowning will continue provided the rate of spread is fast enough (i.e., $R \geq R_o$) to maintain a continuous flame front in the trunk space and crown fuel layer and thereby transfer enough heat to the unburned tree crowns in order to maintain continuous ignition and flaming combustion (Fig. 5).

Development of a truely independent crown fire on flat topography most certainly must require very strong 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. Slope steepness can no doubt compensate for reduced wind flow; for example, a 60% or 31° slope can result in about a 7 to 8.5 fold increase in rate of fire spread (Fig. 6), and at least a corresponding increase in fire intensity compared to the same fuel and weather conditions on level terrain. Sustained independent crown fire runs are undoubtedly a very rare event, if in fact they occur at all, given the natural variation in wind velocity, fuels and terrain. It's unlikely that the crown phase can advance ahead of the surface fire by more than about 150 m (and generally considerably less) (Alexander et al. 1990). However, these represent short bursts of limited duration. The concept of the crowning phase of a forest fire racing ahead of the surface phase by several metres or even kilometres for hours on end is a myth which has been perpetuated by not only the media but to a certain extent in the technical and scientific literature as well.

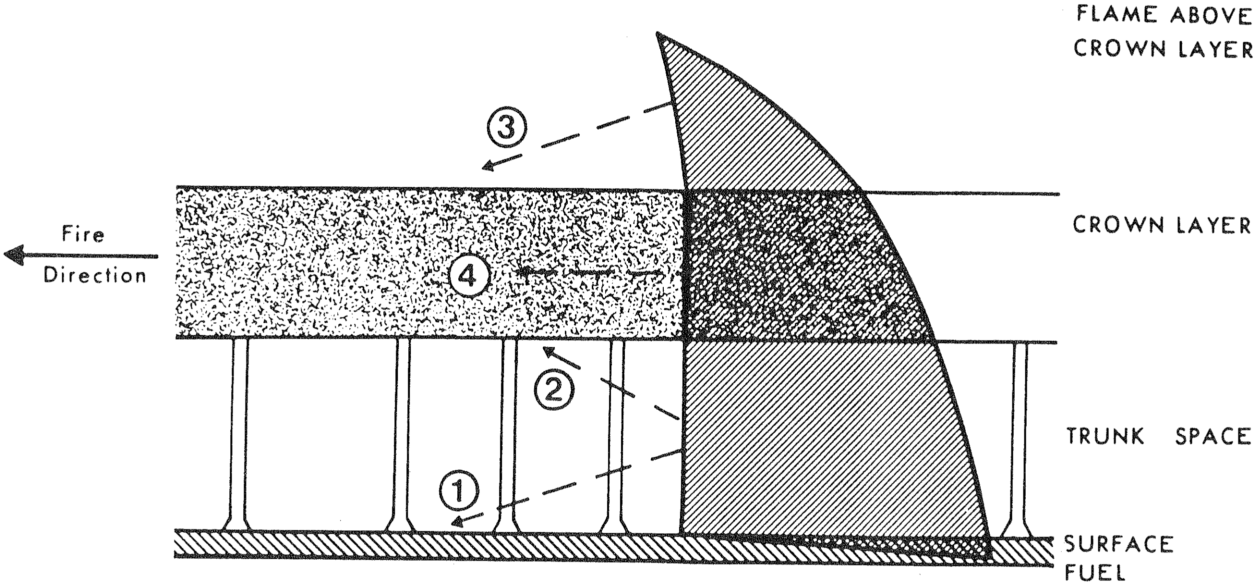

Figure 5. Schematic diagram illustrating the four components of forward radiation heat transfer in a fully-developed crown fire spreading through an idealized conifer forest stand (from Van Wagner 1968): trunk space flame radiates to ① surface and ② crown fuels; flame above the canopy radiates to ③ crown fuels; and flame within the crown fuel layer radiates ④ throughout the layer.

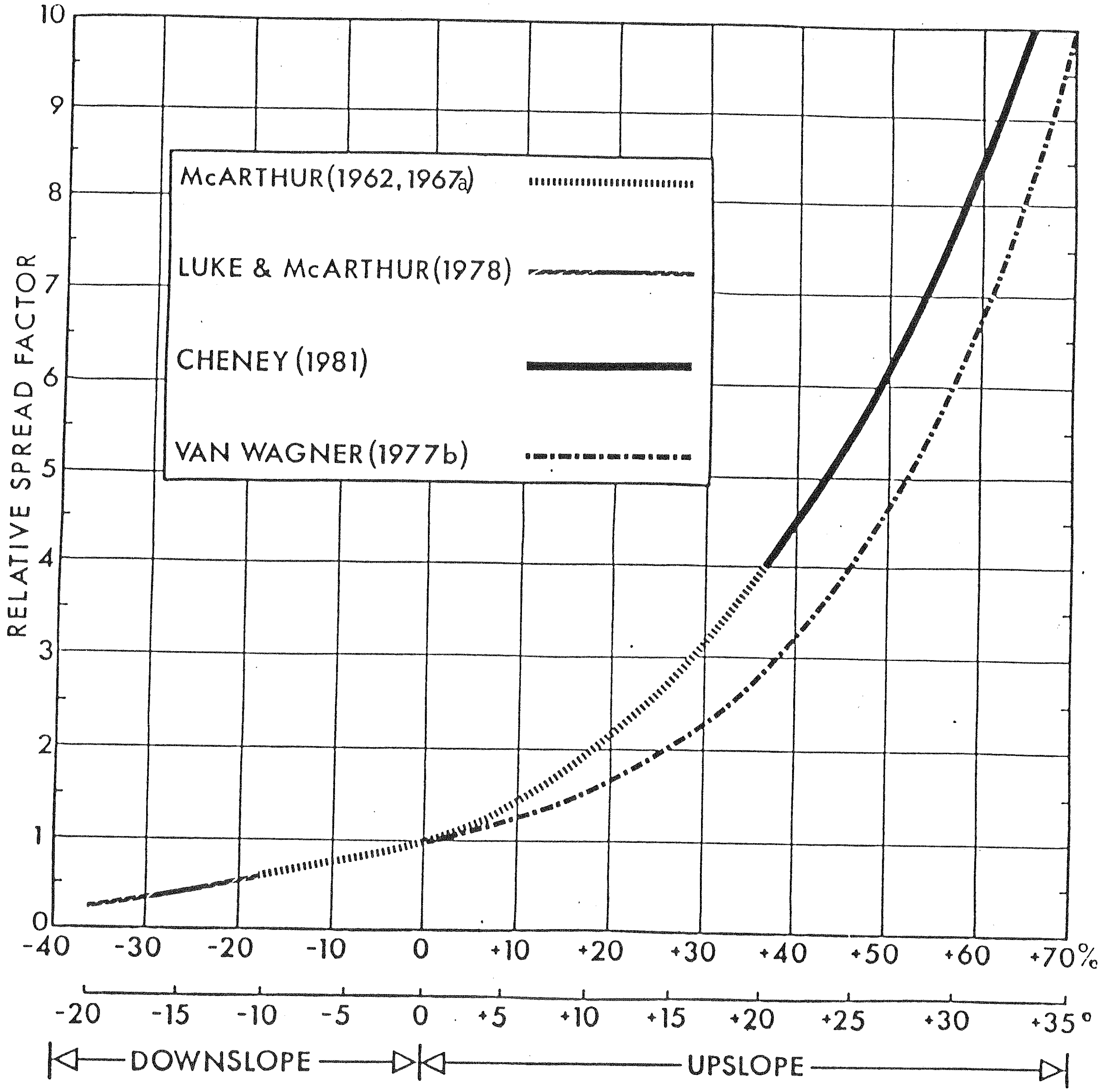

Figure 6. The effect of ground slope on increasing or decreasing the forward spread rate of wildland fires according to to Canadian (Van Wagner 1977b) and Australian (McArthur 1962, 1967a; Luke and McArthur 1978; Cheney 1981) sources.

The Canadian Forest Fire Behavior Prediction (FBP) System

Simply stated, the aim of forest fire behaviour research is to describe, explain and predict fire behaviour for any kind of fuel complex/topographic situation under any weather conditions. This is a daunting objective indeed. Consider Jemison's (1939) statement:

> *Rates of spread vary in a bewildering way. It would be easy to yield to the temptation to throw up our hands and say that it is useless to try for anything but good guesses at the rate a given fire will spread under given conditions of fuel, weather, and topography. The sanner attitude is to keep digging away at the effect of this or that factor on rate of spread in the belief that in time the intricate puzzle will be solved by the creation of something that can rightfully be called the science of rate of spread.*

Although a great deal of progress has been made in the last 50 years, the development of a completely generalized, physical theory-based fire behaviour model, with universal acceptance and applicability, remains a continuing research challenge. Scientifically, the choices of approach to fire behaviour research are between (i) small-scale laboratory test fires coupled with mathematical modelling and (ii) field observation of real forest fires. To date, this has resulted in "two solitudes" to fire behaviour research as evident, for example, by the fire behaviour prediction systems currently used in Canada and the United States. A combination of both approaches will no doubt provide the best progress in the future. Quite likely the data from field experiments will be useful in making the inputs for theoretical models more accurate.

The general consensus within Forestry Canada has been that a purely laboratory/modelling approach to the development of quantitative models for predicting fire behavior is too difficult and intractable. We have therefore opted to observe and gather data from outdoor experimental fires and well-documented wildfires (which burned through several fuel types), analyzed statistically and backed up by as much simple theory and logic as deemed reasonable. The incorporation of high-intensity wildfires in our empirical database (currently about 35) has been particularily useful towards the extreme end of the fire behaviour scale where experimental fires have been difficult to arrange.

The national fire danger rating system used in Canada consists of two major sub-systems. The Canadian Forest Fire Weather Index (FWI) System provides relative numerical ratings of fire potential in a standard fuel type on level terrain, based solely on weather observations. The other major sub-system, the FBP System, allows for the prediction of certain fire behavior characteristics in quantitative terms for specific fuel types and topographic situations. In 1984, the rate of spread (ROS) and elliptical fire growth components were released on an interim basis for field testing and evaluation by various user groups in Canada (Alexander et al. 1984; Lawson et al. 1985); simple quantitative models and guides to fire behavior prediction had been available prior to this time (e.g., Lawson 1973; Van Wagner 1973; B.C. Ministry of Forests 1983). At that time, surface-crown fire thresholds were simply delineated on the basis of the Initial Spread Index (ISI) component of the FWI System for fires burning on level ground, or in terms of head fire ROS for fires spreading upslope. Eight of the 14 fuel types (includes hardwood and mixedwood stands, slash and grass) were considered to be susceptible to crowning (two fuel types have since been added). Verified after-the-fact predictions of crown fire rate of spread have shown quite good agreement between observed versus predicted values (Lawson et al. 1985; De Groot and Alexander 1986; Lawson 1986; Stocks and Flannigan 1987; De Groot and Schisler 1989; Stocks 1988; Hirsch 1988, 1989a, 1989b; Alexander 1990).

The first completion edition of the FBP System, which will be published in 1991 (Forestry Canada Fire Danger Group, in prep.), provides for the prediction of fire behaviour in terms of spread rate (m/min), frontal intensity (kW/m), and type of fire (surface, intermittent crown and continuous crown) of both point-source ignitions, using a simple elliptical fire growth model (Alexander 1985) with consideration for acceleration to a steady-state condition, and line source ignitions; this includes spread distances and the elliptical fire shape, area and perimeter length based on elapsed time since ignition. The degree of ground/surface fuel consumption and crown fuel consumption is also an output; the former item is determined by the Buildup Index (BUI) component of the FWI System. In addition to the effects of slope, fine fuel moisture and wind (represented by the ISI) on rate of spread, the effect of variable fuel consumption on the spread rate has also been taken into account (Van Wagner 1989). Furthermore, a computational scheme for estimating FMC based on calendar date, geographical location (i.e., latitude and longitude) and elevation has been developed in order to take the FMC into account when predicting crowning tendency and crown fire spread rates; the development of this scheme was based on previous FMC studies conducted by Forestry Canada fire researchers and others (e.g, Van Wagner 1967; Chrosciewicz 1986).

Van Wagner's (1977a) I_o concept has now been incorporated into the FBP System (Van Wagner 1989) which has meant that representative LCBH values have now been assigned to those fuel types judged to be capable of crowning, although there is provision for varying the LCBH for the red pine plantation fuel type based on stand height or stand height and tree spacing (Fig. 7). Representative crown fuel loads have also been added in order to compute the frontal intensity of crown fires. Some judgements have had to be made about the degree of crown fuel involvement in relation to expected level of fire behaviour, however. Because of the empirical nature of the basic ISI-spread rate relationships embodied in the FBP System, it's not possible yet to directly incorporate the R_o concept as the criteria for determining the type of crown fire to be expected. The importance of the ISI-head fire ROS relationships (Fig. 8) cannot be overemphasized and the same can be said for the ground/surface fuel consumption-BUI relationships. Together, they permit an estimate of I_s to be made, thereby enabling an assessment of crowning potential provided the FMC and LCBH are known or can be approximated.

The FBP System is unique in that it is based on the most extensive crown fire data set in existence. As a matter of interest, a plot of crown fire spread rates in conifer forests obtained from experimental fires and wildfires showed a relatively strong correlation ($r^2 = 0.68$) with wind velocity although there was considerable scatter due to fuel type differences and fuel moisture levels (from Alexander et al. 1990):

$$R_c = -8.28 + 1.814 \cdot W \qquad (3)$$

where R_c is the crown fire rate of spread (m/min) and W is the 10-m open wind speed (km/h). Equation 3 does include observations of wildfires spreading at nearly 110 m/min or 6600 m/h with winds of almost 50 km/h. A comparison of predicted values with observations from wildfires in Australian pine plantations of comparable height shows remarkably good agreement (e.g., Anon. 1981; Geddes and Pfeiffer 1981). However, the above relation would result in a considerable underprediction of the 12.5 km/h spread rate of the 1983 Mount Muirhead Fire in southeastern SA (Keeves and Douglas 1983) based on a wind of 83 km/h recorded at Mt. Burr just 10 minutes prior to ignition (Anon. 1984, p. 108).

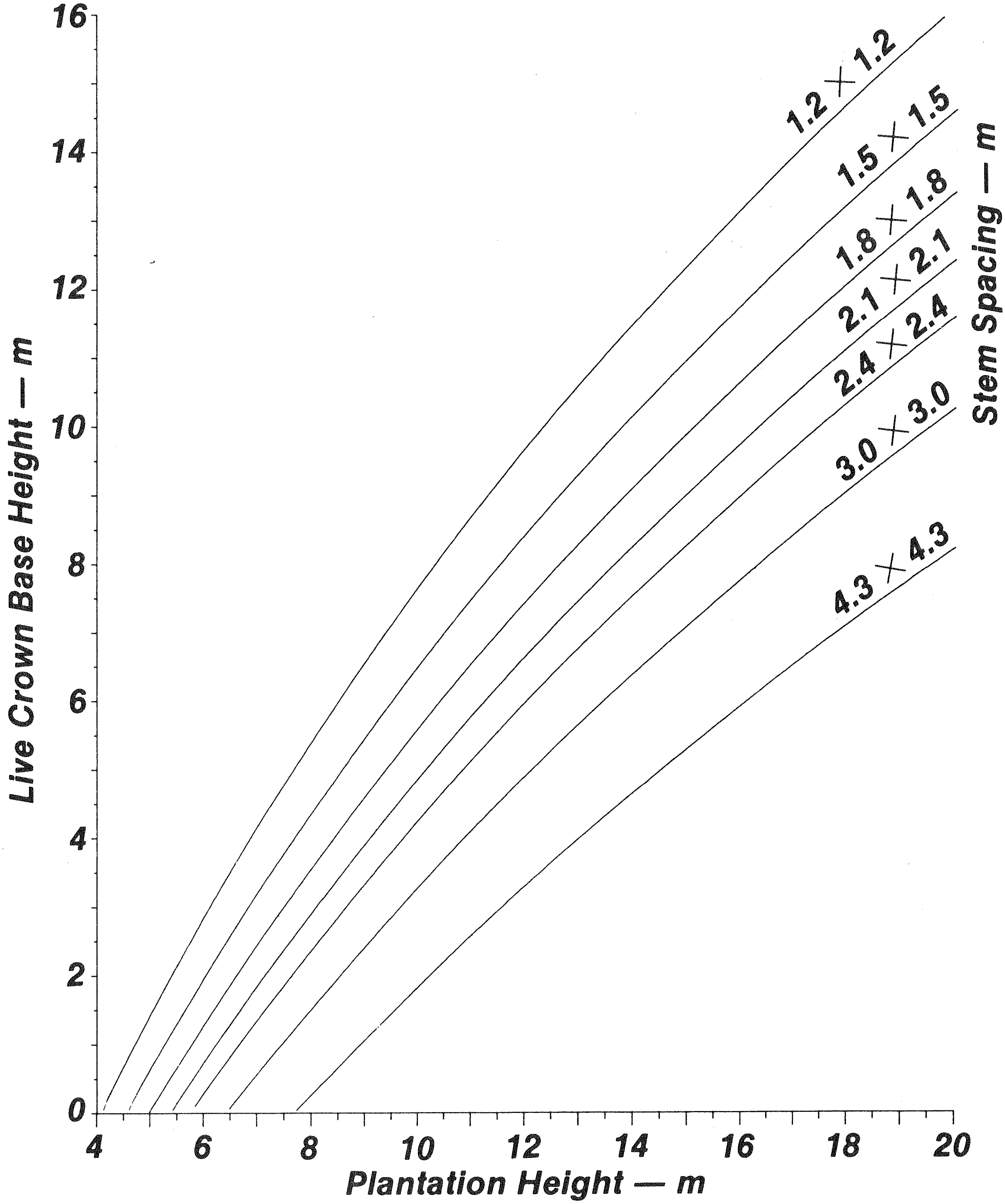

Figure 7. Relation between live crown base height and stand height in unthinned red pine plantations in eastern Ontario at seven different spacings (from Alexander 1988).

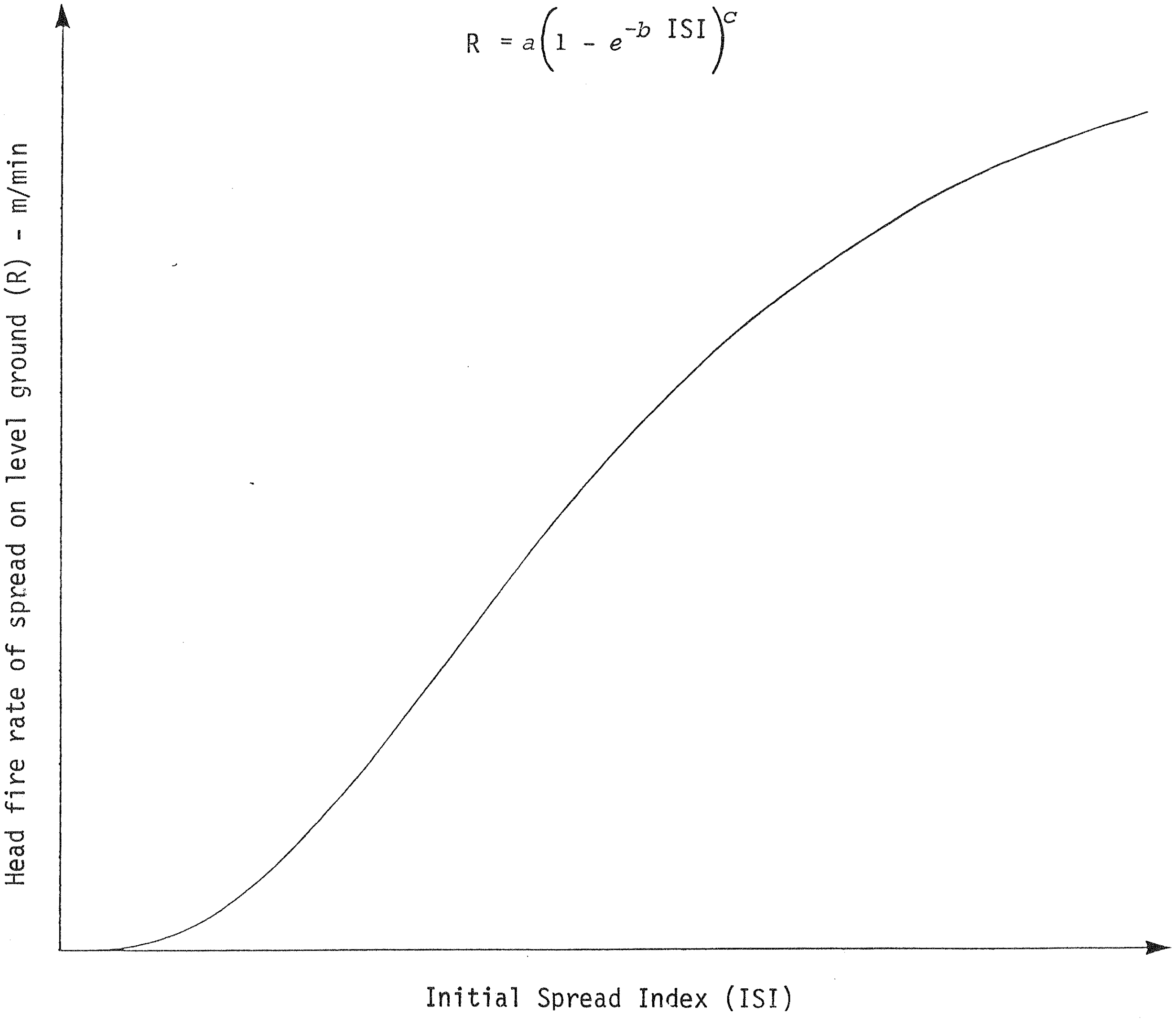

Figure 8. Schematic diagram illustrating the generalized relationship between the ISI component of the Canadian Forest Fire Weather Index System and head fire rate of spread on level ground for conifer forests as embodied in the Canadian Forest Fire Behavior Prediction System. Typically, the lower section of the S-shaped curve represents surface fires, the upper flattening section represents fully-developed crown fires, and the relatively steep intermediate section a transition zone characterized by very high-intensity surface fires with significant torching and intermittent crown fires. Separate coefficients (a, b, c) in the regression equation are generally required for a specific fuel type based on an analysis of experimental fires conducted at low to moderal ISI levels and a few well-documented wildfires at very high to extreme ISI values.

Examples of Potential Application

Case No. 1: Pinus radiata

Cheney (1971) has indicated that "Experiments in Australia have shown that there is little difference between the behaviour of eucalypt and pine fires except in the very high to extreme category when spotting becomes an important factor in the spread of eucalypt fires." There is collaborative evidence for this statement (Luke 1962; Douglas 1964; McArthur 1965, 1967b; Cheney 1968). Cheney (1975, 1985) and his co-workers (Loane and Gould 1986; Gould 1987) have continued to base their estimates of head fire rate of spread in radiata pine on McArthur's (1967a, 1973) Forest Fire Danger Meter. This fire behaviour guideline is deemed to be most relevant to intermediate to middle-aged plantations which have been prunned and thinned and carry ground and surface fuel loads of 10 to 15 t/ha.

On the basis of the above information, it's possible to estimate the likelihood of crowning according to the Forest Fire Danger Index (FFDI) given the knowledge of stand conditions and terrain. In the following tabulation a FMC of 130% has been used based on existing data from ACT and SA (A.M. Giil and D.N. Fife, pers. comms.) and a Keetch-Byram Drought Index (metric scale) of 100+ which would ensure 100% fuel consumption (McArthur 1966; McArthur and Cheney 1966):

FFDI	Threshold LCBH (m) for Crowning	
	Level ground	10% or 6° slope
10	2.5	3.3
12	2.8	3.7
14	3.1	4.1
16	3.4	4.5
20	4.0	5.2
24	4.5	5.9

The mechanical effect of slope on fire spread rates applied to the above was according to the established relationship used throughout Australia as given in Figure 6.

Case No. 2: Pinus elliottii

According to information contained in Byrne (1980), a 10 y.o. slash pine plantation might average 10 m, have a LCBH of around 5 m, and a surface fuel load of 11-12 t/ha. The weight of needle foliage would be about 17 t/ha (S.M. Hunt, unpubl.). For a FMC of 117.5% (S.M. Hunt, unpubl.), such a stand would require a surface fire intensity of 2330 kW/m to induce crowning. Assuming complete surface fuel consumption, this translates into a head fire spread rate of 6.75 m/min or 405 m/h. Incidentally, the spread rate required for a fully developed crown fire, based on a CBD of 0.34 kg/m^3 is only 8.8 m/min or 528 m/h.

McArthur (1971) developed a guide for predicting head fire rate of spread in slash pine plantations with surface fuel loads of about 22.5 t/ha. Assuming a litter moisture content of 6%, crowning would be expected to occur in stand described above when the 10-m open winds exceed 18 km/h. Furthermore, if we assume that the spread rate will double after crowning, there's every indication that a fully-developed crown fire can be sustained within the tree crowns provided the threshold wind speed is maintained or exceeded.

Case No. 3: Pinus pinaster

The operations headquarters for the Department of Conservation and Land Management (CALM) in Western Australia is located at Como within a 63 y.o. maritime pine plantation exhibiting the following mean stand and fuel characteristics in May 1990 (N.D. Burrows, pers. comm.):

Tree density: 107 stems/ha
Dbhob: 60.1 cm
Tree height: 25.2 m
Crown width: 6.2 m
LCBH: 14.6 m
Surface fuel load: 3.1 t/ha

The foliage weight for the stand is estimated to be approximately 1.3 t/ha using the tree biomass equations of Turton and Keay (1970). It should be noted that the plantation area is prescribed burned annually as a fire hazard abatement measure. Assuming a FMC of 150% (N.D. Burrows, pers. comm.), the critical surface intensity for crown combustion (I_o) for this stand is calculated to be 16 060 kW/m which would require a surface fire spread rate of 173 m/min or 10 361 m/h! Furthermore, for a CBD of only 0.012 kg/m^3 the development of an active crown fire would require a spread rate in excess of 250 m/min or 15 000 m/h! What sort of burning conditions would be required to achieve this level of fire behaviour? According to the CALM "Red Book" (Sneeuwjagt and Peet 1985), even with surface and profile moisture contents of 3% and <25%, respectively, and open winds of 35-40 km/h, the maximum predicted rate of spread would only be 165 m/min or 9920 m/h. This represents the extreme limit of tabulated values in the WA fire behaviour guide, although for the pine fuel types, the maximum rates of spread in the associated data base would be less than 1000 m/h (J.A. Beck, unpubl.).

CONCLUSIONS

Is the Canadian research on crown fire behaviour applicable to Australia's exotic pine plantations? The simply answer is "yes" given the structural similarity with many of the conifer forest types found in Canada, although the specifics are not directly transferable (i.e., the FBP System would not be appropriate because it was designed for a different range of weather and fuel moisture conditions), but certainly many of the basic principles are believed to be worth considering. In fact, their relevancy is currently being explored as part of a Ph.D. thesis project by the author at the Australian National University in cooperation with the CSIRO Division of Forestry & Forest Products, and with the assistance of the various state forestry organizations which is gratefully acknowledged. Particular attention is being placed on the initiation of crowning (i.e., identifying the surface-crown fire thresholds) as opposed to predicting crown fire rate of spread. This appears to be a major knowledge gap in all existing wildfire behaviour guides (e.g., Burrows 1984; Anon. 1988, p. 38). There is of course the direct application to analyzing strategies for the creation and maintenance of "crown fire-free zones". In closing, it's worth emphasizing that the prediction of surface fire behaviour is, in fact, probably much more difficult than the prediction of crown fire potential, given the infinite number of possible forest floor and understory fuel complexes. As a result, any model predictions for the start and spread of crowning forest fires will utimately be dependent, at least in part, on the predicted surface fire behaviour characteristics.

References Cited

Albini, F.A.; Stocks, B.J. 1986. Predicted and observed rates of spread of crown fires in immature jack pine. Combust. Sci. and Technol. 48(1+2): 65-76.

Alexander, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pages 287-304 in Proc. Eighth Conf. Fire and For. Meteor. (Apr. 29-May 2, Detroit, Michigan). Soc. Am. For., Bethesda, Maryland. SAF Publ. 85-04.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. Pages 147-156 in Protecting People and Homes from Wildfire in the Interior West: Proc. Symp. and Workshop (Oct. 6-8, 1987, Missoula, Montana). USDA For. Serv., Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-251.

Alexander, M.E. 1990. The 1985 Butte Fire in central Idaho: a Canadian perspective on the associated burning conditions. in Proc. Fire and the Environment: Ecological & Cultural Perspectives Interl. Symp. (Mar. 20-24, Knoxville, Tennessee). Univ. Tenn., Knoxville, Tennessee. (in press.)

Alexander, M.E.; De Groot, W.J. 1988. Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Poster (with text).

Alexander, M.E.; Janz, B.; Quintilio, D. 1983. Analysis of extreme wildfire behavior in east-central Alberta: a case study. Pages 38-46 in Preprint Vol. Seventh Conf. Fire and For. Meteor. (Apr. 25-29, Fort Collins, Colorado). Am. Meteor. Soc., Boston, Massachusetts.

Alexander, M.E.; Lanoville, R.A. 1987. Wildfires as a source of fire behavior data: a case study from Northwest Territories, Canada. Pages 86-93 in Postprint Vol. Ninth Conf. Fire and For. Meteor. (Apr. 21-24, San Diego, California). Am. Meteor. Soc., Boston, Massachusetts.

Alexander, M.E.; Lanoville, R.A. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. For. Can., North. For. Cent., Edmonton, Alberta and Govt. Northwest Territ., Dep. Renewable Resour., Territ. For. Fire Cent., Fort Smith, Northwest Territories. Poster (with text).

Alexander, M.E.; Lawson, B.D.; Stocks, B.J.; Van Wagner, C.E. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim ed. Environ. Can., Can. For. Serv., Fire Danger Group, Ottawa, Ontario. 73 p. + Supplements (1st printing - July 1984; revision & second printing Sept. 1984)

Alexander, M.E.; Quintilio, D. 1990. Perspectives on experimental fires in Canadian forestry research. Mathl. and Computer Modelling 13: (in press.)

Alexander, M.E.; Stocks, B.J.; Lawson, B.D. 1990. Fire behavior in black spruce-lichen woodland: the Porter Lake project. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-310. (in press.)

Alexander, M.E.; Stocks, B.J.; Lawson, B.D.; McAlpine, R.S. 1990. Crown fire initiation and spread. in Patterns and Process in Crown Fire Ecosystems. Princeton Univ. Press, Princeton, New Jersey. (in press.)

Anon. 1981. Case history of the Kelly Range Fire, Toolara State Forest, 1981. Qld. Dep. For., Brisbane, Queensland. 8 p. + Appendices.

Anon. 1984. Report on the meteorological aspects of the Ash Wednesday fires - 16 February 1983. Dep. Sci., Bureau Meteor., Melbourne, Victoria. 143 p.

Anon. 1988. Fire school notes. Qld. Dep. For., Brisbane, Queensland. 126 p.

British Columbia Ministry of Forests. 1983. Fire weather indices, decision aids for forest operations in British Columbia. B.C. Min. For., Prot. Branch, Victoria, British Columbia. For. Prot. Handb. 12. 57 p.

Burrows, N.D. 1984. Protection pyrotechnics for pine plantation protection - a review of research into fuel reduction burning under P. radiata. For. Dep. W.A., Manjimup, Western Australia. Unpubl. rep. 46 p. + Appendices.

Byrne, P.J. 1980. Prescribed burning in Queensland exotic pine plantations. Paper prepared for the Eleventh Commonw. For. Conf., Trinidad. Qld. Dep. For., Brisbane, Queensland. 58 p.

Cheney, N.P. 1968. Predicting fire behaviour with fire danger tables. Aust. For. 32: 71-79.

Cheney, N.P. 1971. Forest industries feasibility study, Zambia: Fire protection of industrial plantations. Food and Agric. Organ. U.N., Rome, Italy. FO:SF/ZAM 5 Tech. Rep. 4. 71 p.

Cheney, N.P. 1975. Industrial forestry plantations, Turkey: Forest fire protection. Food and Agric. Organ. U.N., Rome, Italy. FO:DP/TUR/71/521 Working Document No. 14. 59 p.

Cheney, N.P. 1981. Fire behaviour. Pages 151-175 in Fire and the Australian Biota, A.M. Gill and others (editors). Aust. Acad. Sci., Canberra, Australian Capital Territory.

Cheney, N.P. 1985. Fire protection of small private forests. Paper presented at the Instit. For. Aust. Conf., Hobart. 11 p.

Chrosciewicz, Z. 1986. Foliar moisture content variations in four coniferous tree species in central Alberta. Can. J. For. Res. 16: 157-162.

De Groot, W.J.; Alexander, M.E. 1986. Wildfire behavior on the Canadian Shield: a case study of the 1980 Chachukew Fire, east-central Saskatchewan. Pages 23-45 in Proc. Third Cent. Reg. Fire Weather Comm. Sci. and Tech. Seminar (Apr. 3, Winnipeg, Manitoba). Can. For. Serv., West. and North. Reg., North. For. Cent., Edmonton, Alberta.

De Groot, W.J.; Schisler, J.M. 1989. Fire behavior on the 1987 Elan Fire, Saskatchewan. Pages 26-40 in Proc. Fifth Cent. Reg. Fire Weather Comm. Sci. and Tech. Seminar (Apr. 6, 1988, Winnipeg, Manitoba). For. Can., Northwest Reg., Sask. Dist. Off., Prince Albert, Saskatchewan.

Douglas, D.R. 1964. Some characteristics of major fires in coniferous plantations. Aust. For. 28: 119-124.

Forestry Canada Fire Danger Group. 1991. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can., Ottawa, Ont. For. Tech. Rep. (in prep. for publ.).

Geddes, D.J.; Pfeiffer, E.R. 1981. The Caroline Forest Fire, 2nd February, 1979. Woods and For. Dep. S.A., Adelaide, South Australia. Bull 26. 52 p.

Gould, J.S. 1987. The cost-effectiveness of airtankers in the south-east region of South Australia and the south-west region of Victoria. CSIRO Div. For. Res., Canberra, Australian Capital Territory. DFR User Ser. No. 9. 45 p.

Hirsch, K.G. 1988. An overview of the 1987 Wallace Lake Fire, Manitoba. Fire Manage. Notes 49(2): 26-27.

Hirsch, K.G. 1989a. Documenting wildfire behavior: an example from the 1988 Brereton Lake Fire, Manitoba. Fire Manage. Notes 50(1): 45-48.

Hirsch, K.G. 1989b. Analysis of the fire behavior associated with three 1988 spring wildfires in central Canada. in Proc. Tenth Conf. Fire and For. Meteor. (Apr. 17-21, Ottawa, Ontario). For. Can., Ottawa, Ontario. (in press.)

Jemison, G.M. 1939. Determination of the rate of spread of fire in the southern Appalachians. Fire Contr. Notes 3(1): 4-7.

Keeves, A.; Douglas, D.R. 1983. Forest fires in South Australia on 16 February 1983 and consequent future forest management aims. Aust. For. 46: 148-162.

Kiil A.D. 1975. Fire spread in a black spruce stand. Can. For. Serv. Bi-mon. Res. Notes 31: 2-3.

Lawson, B.D. 1973. Fire behavior in lodgepole pine stands related to the Canadian Fire Weather Index. Environ. Can., Can. For. Serv., Pac. For. Res. Cent., Victoria, British Columbia. Inf. Rep. BC-X-76. 26 p.

Lawson, B.D. 1986. Prescribed fire behavior and control problems on Vancouver Island in 1985 related to decision aids and components of the Canadian Forest Fire Danger Rating System. Paper prepared for Fire Management Seminar sponsored by CIP Tahsis Pacific Region (Apr. 8, Qualicum, British Columbia). 7 p.

Lawson, B.D.; Stocks, B.J.; Alexander, M.E.; Van Wagner, C.E. 1985. A system for predicting fire behavior in Canadian forests. Pages 6-16 in Proc. Eighth Conf. Fire and For. Meteor. (Apr. 29-May 2, Detroit, Michigan). Soc. Am. For., Bethesda, Maryland. SAF Publ. 85-04.

Loane, I.T.; Gould, J.S. 1986. Project Aquarius -- aerial suppression of bushfires - cost-benefit study for Victoria. CSIRO Div. For. Res., Natl. Bushfire Res. Unit, Canberra, Australian Capital Territory. 213 p. + Appendices.

Luke, R.H. 1962. Meeting protection objectives in difficult years. Pages 971-978 in Proc. Fifth World For. Congr. (Aug. 29-Sep. 10, 1960, Seattle, Washington). USDA For. Serv., Washington, D.C.

Luke, R.H.; McArthur, A.G. 1978. Bushfires in Australia. Aust. Govt. Publ. Serv., Canberra, Australian Capital Territory. 359 p. (revised 1986.)

McArthur, A.G. 1962. Control burning in eucalypt forests. Commonw. Aust., For. and Timber Bureau, Canberra, Australian Capital Territory. Leafl. No. 80. 31 p.

McArthur, A.G. 1965. Fire behaviour characteristics of the Longford Fire. Commonw. Aust., For. and Timber Bureau, Canberra, Australian Capital Territory. Leafl. No. 91. 19 p.

McArthur, A.D. 1966. The application of a drought index system to Australian fire control. Commonw. Aust., For. and Timber Bureau, For. Res. Instit., Canberra, Australian Capital Territory. 18 p.

McArthur, A.G. 1967a. Fire behaviour in eucalypt forests. Commonw. Aust., For. and Timber Bureau, Canberra, Australian Capital Territory. Leafl. No. 107. 36 p.

McArthur, A.G. 1967b. Fire protection of man-made forests. Paper presented at World Symp. on Man-made Forests and Their Industrial Importance (Apr. 14-25, Canberra, Australian Capital Territory).

McArthur, A.G. 1971. Aspects of fire control in the P. caribaea & P. ellioittii plantations of northwestern Viti Levu, Fiji Islands. Commonw. Aust., For. and Timber Bureau, For. Res. Instit., Canberra, Australian Capital Territory. 52 p.

McArthur, A.G. 1973. Forest Fire Danger Meter. Mk. 5. Commonw. Aust., For. and Timber Bureau, For. Res. Instit., Canberra, Australian Capital Territory. Slide-rule (with text).

McArthur, A.G.; Cheney, N.P. 1966. The characterization of fires in relation to ecological studies. Aust. For. Res. 2(3): 36-45.

Macleod, J.C. 1948. The effect of night weather on forest fire danger. Can. Dep. Mines and Resour., Mines, For. and Sci. Serv. Branch, Dom. For. Serv., Ottawa, Ontario. For. Fire Res. Note No. 14. 29 p.

Merrill, D.F.; Alexander, M.E. (editors). 1987. Glossary of forest fire management terms. Fourth ed. Natl. Res. Counc. Can., Can. Comm. For. Fire Manage., Ottawa, Ontario. Publ. NRCC No. 26516. 91 p.

Newstead, R.G.; Alexander, M.E. 1983. Short-term fire retardant effectiveness in a lowland black spruce fuel complex. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. For. Rep. No. 28: 3-4.

Paul, P.M. 1969. Field practices in forest fire danger rating. Can. Dep. Fish. and For., Can. For. Serv., For. Fire Res. Instit., Ottawa, Ontario. Inf. Rep. FF-X-20. 17 p. + Appendices.

Quintilio, D. 1977. Lodgepole pine flammability. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. For. Rep. 5(2): 7.

Quintilio, D.; Fahnestock, G.R.; Dube, D.E. 1977. Fire behavior in upland jack pine: the Darwin Lake project. Fish. and Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-174. 49 p.

Russell, R.N.; Pech, Gy. 1968. Development of burning index tables for white spruce-alpine fir and lodgepole pine forest covertypes in the Prince George Forest District (an establishment and progress report). Can. Dep. For. and Rural Develop., For. Branch, For. Res. Lab., Victoria, British Columbia. Int. Rep. BC-8. 35 p.

Simard, A.J. 1970. Reference manual and summary of test fire, fuel moisture and weather observations made by forest fire researchers between 1931 and 1961. Can. Dep. Fish. and For., Can. For. Serv., For. Fire Res. Instit., Ottawa, Ontario. Inf. Rep. FF-X-25. 113 p.

Sneeuwjagt, R.J.; Peet, G.B. 1985. Forest fire behaviour tables for western Australia. Third ed. Dep. Conserv. and Land Manage. W.A., Perth, Western Australia. 59 p.

Stocks, B.J. 1975. The 1974 wildfire situation in northwestern Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-232. 27 p.

Stocks, B.J. 1987a. Fire potential in the spruce budworm-damaged forests of Ontario. For. Chron. 63: 8-14.

Stocks, B.J. 1987b. Fire behavior in immature jack pine. Can. J. For. Res. 17: 80-86.

Stocks, B.J. 1988. Forest fire close to home: Terrace Bay Fire #7/86. Pages 189-193 <u>in</u> Protecting People and Homes from Wildfire in the Interior West: Proc. Symp. and Workshop (Oct. 6-8, 1987, Missoula, Montana). USDA For. Serv., Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-251.

Stocks, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res. 19: 783-790.

Stocks, B.J. 1990. The extent and impact of forest fires in northern circumpolar countries. <u>in</u> Proc. Chapman Conf. Global Biomass Burning - Atmospheric, Climatic, and Biospheric Implications (Mar. 19-23, Williamsburg, Virginia). (in press.)

Stocks, B.J.; Flannigan, M.D. 1987. Analysis of the behavior and associated weather for a 1986 northwestern Ontario wildfire: Red Lake No. 7. Pages 94-100 <u>in</u> Postprint Vol. Ninth Conf. Fire and For. Meteor. (Apr. 21-24, San Diego, California). Am. Meteor. Soc., Boston, Massachusetts.

Stocks B.J.; Lawson, B.D.; Alexander, M.E.; Van Wagner, C.E.; McAlpine, R.S.; Lynham, T.J.; Dube, D.E. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65: 450-457.

Stocks, B.J.; Walker, J.D. 1973. Climatic conditions before and during four significant forest fire situations in Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-187. 37 p.

Turton, A.G.; Keay, J. 1970. Changes in dry-weight and nutrient distribution in maritime pine after fertilization. Aust. For. 34: 84-96.

Van Wagner, C.E. 1963. Prescribed burning experiments: red and white pine. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Publ. No. 1020. 27 p.

Van Wagner, C.E. 1964. History of a small crown fire. For. Chron. 40: 202-205, 208-209.

Van Wagner, C.E. 1965. Story of an intense crown fire at Petawawa. Pulp and Pap. Mag. Can., Woodl Rev. Sec. 66(8): 358-361.

Van Wagner, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Can. Dep. For. and Rural Develop., For. Branch, Ottawa, Ontario. Dep. Publ. No. 1204. 15 p.

Van Wagner, C.E. 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Can. Dep. For. and Rural Develop., For. Branch, Ottawa, Ontario. Dep. Publ. No. 1229. 30 p.

Van Wagner, C.E. 1973. Rough predictions of fire spread rates by fuel type. Environ. Can., Can. For. Serv., Petawawa For. Exp. Stn., Chalk River, Ontario. Inf. Rep. PS-X-42. 5 p. (revised 1980.)

Van Wagner, C.E. 1977a. Conditions for the start and spread of crown fire. Can. J. For. Res. 7: 23-34.

Van Wagner, C.E. 1977b. Effect of slope on fire spread rate. Can. For. Serv. Bi-mon. Res. Notes 33: 7-8.

Van Wagner, C.E. 1989. Prediction of crown fire behavior in conifer stands. in Proc. Tenth Conf. Fire and For. Meteor. (Apr. 17-21, Ottawa, Ontario). For. Can., Ottawa, Ontario. (in press.)

Weber, M.G.; Hummel, M.; Van Wagner, C.E. 1987. Selected parameters of fire behavior and Pinus banksiana Lamb. regeneration in Ontario. For. Chron. 63: 340-346.

Wright, J.G. 1932. Forest-fire hazard research as developed and conducted at the Petawawa Forest Experiment Station. Can. Dep. Interior, For. Serv., Ottawa, Ontario. For.-Fire Hazard Pap. 2.