Conditions for the start and spread of crown fire

C. E. VAN WAGNER
Canadian Forestry Service, Petawawa Forest Experiment Station, Chalk River, Ont., Canada

Received May 19, 1976[1]
Accepted August 24, 1976

VAN WAGNER, C. E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. **7**: 23–34.

Some theory and observations are presented on the factors governing the start and spread of crown fire in conifer forests. Crown fires are classified in three ways according to the degree of dependence of the crown phase of the fire on the ground surface phase. The crown fuel is pictured as a layer of uniform bulk density and height above ground. Simple criteria are presented for the initiation of crown combustion and for the minimum rates of spread and heat transfer into the crown combustion zone at which the crown fire will spread. The theory is partially supported by some observations in four kinds of conifer forest.

Introduction

A great deal of work has been done on the theoretical problem of how forest fire spreads, both by semiempirical laboratory modeling and by pure physical deduction. Almost all this work, however, has been devoted to single, homogeneous fuel layers in contact with the ground; and yet it could be argued with some reason that the main problem in forest fire behaviour is the interaction of separate fuel layers. The obvious example, of course, is crown fire in conifer stands; without an acceptable solution to it, the science of fire behaviour prediction must remain severely limited. In this paper an attempt is made to develop some physical criteria for crown fire initiation and spread. The approach is elementary and the aim is to deduce simple functions that can be calibrated by field observation. For present purposes the crown layer is described only in terms of foliar bulk density and moisture content and is distinctly separated from the surface fuel layer by an open trunk space. Some theory is presented first, followed by a discussion of the local field evidence and a comparison of the present results with the previous published work on crown fire. A list of equation symbols follows.

Initiation of Crowning

Consider first the ignition of the tree crowns and suppose that it depends merely on the attainment of a certain minimum temperature at the base of the crown layer. An established relation (cf. Thomas 1963) gives the temperature, ΔT above ambient, reached at height z above a line fire of intensity I burning on the surface:

$$[1] \qquad \Delta T \propto I^{2/3}/z,$$

where I is in terms of energy output rate per unit length of fire front. The form of this relation is not really surprising since it is known that crowning requires first a substantial surface fire and is more difficult to initiate as the height of the crown base increases. Flame length, being proportional to $I^{2/3}$, could be substituted here for intensity; however, intensity is the more basic parameter since it is directly calculable from rate of advance and fuel consumption by Byram's (1959) simple equation

$$[2] \qquad I = HWR,$$

where H is net heat of combustion, W is weight of fuel consumed per unit area, and R is rate of advance. The actual temperature needed at the crown base is not important here since the main goal is to deduce a valid criterion that can be calibrated by field observations.

Another obviously important parameter is the foliar moisture content. The heat of ignition, h, depends mainly on the moisture content given, for example, by the following relation (Van Wagner 1968) or a similar one:

$$[3] \qquad h = 460 + 26m,$$

[1]Revised manuscript received August 17, 1976.

TABLE 1. Physical properties of some conifer crown layers

	Trees/ha	Basal area, m^2/ha	Tree height, m	Height to crown base, m	Foliage weight, kg/m^2	Bulk density, kg/m^3	Fire No. (Table 2)
Red pine plantation, Petawawa	3200	50	14	7	1.80	0.26	C4, C6, R1
Jack pine, full stocked, Petawawa	1600	27	20	12	0.80	0.10	GL-A
Jack pine, half stocked, Petawawa	890	15	18	6	0.50	0.042	SC
Jack and red pine, Petawawa	1800	25	18	6	1.22	0.11	GL-B
Balsam fir under pine, Petawawa	27700	12	4.5	1	0.42	0.12	F3
Black spruce, upland, Quebec[a]	7100	41	12	8	0.86	0.22	—
Black spruce, lowland, Alberta[b]	600	1.5	4.4	1.5	0.13	0.045	ADK

[a]From Weetman and Harland (1964).
[b]From Kiil (1975).

TABLE 2. Parameters and crowning criteria for eight fires of various types

Item	Red pine fire C6	Red pine fire C4	Red pine fire R1	Jack pine fire SC	Jack pine fire GL-A	Jack pine fire GL-B	Balsam fir fire F3	Black spruce fire ADK[a]
Foliar moisture content, m, %	95	135	95	100	100	100	120	80
Ignition energy, h, kJ/kg	2930	3970	2930	3060	3060	3060	3580	2540
Crown bulk density, d, kg/m^3	0.23	0.26	0.23	0.04	0.10	0.12	0.14	0.045
Critical surface intensity, I_o, kW/m	2890	4560	2890	2490	6950	1350	210	235
Final intensity, surface phase, I_s, kW/m	10,500	9500	4200	12,100	4800	9200	85	3640
Final intensity, whole fire, I, kW/m	22,500	21,100	7300	15,800	4800	18,300	85	4180
Critical spread rate for active crown fire, R_o, m/s	0.22	0.19	0.22	1.00	0.50	0.45	0.36	1.11
Actual spread rate, R, m/s	0.46	0.28	0.18	0.25	0.20	0.41	0.02	0.11
Intensity criterion for crown ignition	$I_s > I_o$	$I_s > I_o$	$I_s > I_o$	$I_s > I_o$	$I_s < I_o$	$I_s > I_o$	$I_s < I_o$	$I_s > I_o$
Spread rate criterion for active crowning	$R > R_o$	$R > R_o$	$R \leq R_o$	$R < R_o$	$R < R_o$	$R \leq R_o$	$R < R_o$	$R < R_o$
Fire type	Active crown	Active crown	Developing active crown	Passive crown	Intense surface	Active crown	Gentle surface	Passive crown

[a]From Kiil (1975).

where m is moisture content percentage based on dry fuel and h is in kilojoules per kilogram. Heat of ignition, h, must now be worked into [1]. Assume that [1] gives the ΔT required for crown ignition only at an arbitrary value of h called h_o and that the actual required temperature rise at the crown base varies with the ratio h/h_o. The left-hand side of [1] thus becomes $\Delta T \cdot h/h_o$. Replacing $\Delta T/h_o$ by an empirical quantity C then yields

[4] $$I_o = (Czh)^{3/2},$$

where I_o is now the critical surface intensity needed to initiate crowning. According to this relation, the onset of crown combustion should take place when the intensity of the surface fire exceeds I_o. The quantity C is best regarded as an empirical constant of complex dimensions whose value is to be found from field observations.

Two further assumptions are implicit in the above argument: first, that variation in ambient temperature is unimportant in view of the much greater value of ΔT and, second, that the vertical spread of fire into the crowns is for practical purposes independent of crown bulk density.

The most available basis for estimating C comes from three previously reported experimental crown fires in a red pine plantation (Van Wagner 1964, 1968). The physical description of the plantation appears in Table 1 and the fires' behaviour in Table 2. The best estimate of the minimum surface intensity at the time of crowning was about 2500 kW/m. For a crown base height of 6 m and a foliar moisture content of 100%, [4] then yields a value of 0.010 for C.

According to Thomas's (1963) expression for flame length, L, in terms of line-fire intensity, I, the flame from such a surface fire should be just about 6 m, in other words equivalent to the crown base height, z. Since this matches the visual impression of people observing those fires, [4] may well represent the intensity of a surface fire whose tip is just reaching into the crown layer. The additional dependence of I_o on ignition energy, h, remains an assumption since data are too few to demonstrate it.

Presumably, patchy incomplete combustion of the crown layer could take place without a full-fledged crown fire. Further information, then, is needed to judge whether a full solid crown flame will develop with associated horizontal spread.

Criteria of Crown Spread

The simplest general statement of how fire spreads through a fuel layer is the basic heat balance linking rate of spread, R, with the fuel bulk density, d, the heat of ignition, h, and the net horizontal heat flux, E, into the unburned fuel ahead of the fire:

$$Rdh = E. \tag{5}$$

The first clear explanation of this process was by Thomas *et al.* (1964), and in modified or more complex form it forms the basis of most published theories and models of fire spread through a porous fuel complex. In the present argument, d and h refer to the effective crown fuel (primarily live foliage) and to the whole crown space, not just the individual tree crown volumes. E is the required heat flux that must be supplied to the crown fuel at the specified values of R, d, and h and is designated E_o when used in this critical sense. Obviously E_o is one basic criterion of crown spread; it is, however, insufficient by itself.

Another basic criterion is needed because [5] specifies no limits on R or d. Yet it is obvious that the crown spread process must fail if either R or d falls below a certain practical level. The required second criterion can also be obtained from [5] by rearranging thus:

$$Rd = E/h = S, \tag{6}$$

where S is the mass flow rate of fuel into the crown space in terms of mass per unit cross-sectional area per unit time. This mass flow is best visualized by imagining a stationary fire front into which fuel is flowing horizontally through a vertical cross section. Furthermore, suppose that a solid flame in the crowns requires that a certain minimum mass of fuel be burned per unit time in each successive unit of crown space. It follows, then, that S has, for practical purposes, a critical value, S_o, that according to [6] is independent of foliar moisture content and below which a solid flame cannot form in the crown space. Given this limiting mass flow rate, S_o, it further follows that for any specified value of bulk density, d, the spread rate, R, must have a lower limit below which crowning cannot be sustained. That is,

$$R_o = S_o/d, \tag{7}$$

where R_o is the critical spread rate that must be achieved to make crown spread possible. S_o is the required second basic criterion, but the derived form R_o is perhaps more convenient for practical use.

The value of S_o must presumably be determined from field observations. Again the red pine plantation fire data (Table 2) provide one estimate, namely 0.05 kg/m²·s. This is just above the lowest of three red pine mass flow rates and is close to the minimum value given for solid flames in experimental fuel beds (0.06 — 0.08 kg/m²·s) by Thomas (1967), who also derived a similar value for a crown fire reported by Van Wagner (1965).

The discussion to this point has dealt with the crown phase of the fire alone without concern for the surface phase. However, there is no reason why some of the mass flow into the crown space could not be supplied from the surface fire below as partly burned gaseous fuel in the form of flame reaching up into the crown layer. Similarly, there is no reason why some of the required forward heat flux, E_o, could not also be supplied by the surface fire below in the form of supplementary energy for the continuous ignition of fuel at the base of the crown. It is true that the combination of vertical (rising) and horizontal vectors in the energy and mass balances introduces a conceptual difficulty. Strictly speaking, these two vectors are more logically combined on the basis of flux per unit width of fire front than as flux per unit of cross-sectional area. This would entail multiplying E_o

and S_o by the depth of the crown layer. However, if E_o and S_o are thought of as averages over the depth of the crown layer, then the difficulty is eased, and the theory is easier to present.

The equations 5 and 7 describe two separate limitations on crown spread, the required heat flux, E_o, and either the critical mass flow rate, S_o, or spread rate, R_o. The interactions of these two criteria together with the critical surface intensity, I_o, are examined next.

Classes of Crown Fire

Based on the three limiting factors just described, namely surface intensity, horizontal heat flux, and spread rate, it is possible to imagine three different classes of crown fire behaviour, the stage reached on a given day depending on the properties of the crown layer. Brown and Davis (1973) refer briefly to two kinds of crown fire, 'running' and 'dependent'; the following classification goes a step further.

Passive Crown Fire

Suppose that as surface intensity, I, rises above I_o, the crowns begin to burn, but the spread rate remains less than R_o so that the minimum mass flow rate, S_o, cannot be attained within the crown phase alone. Suppose further that the surface intensity continues to increase until a substantial proportion of the surface flame reaches into the crowns. In other words, the surface fire now contributes to the mass flow into the crown space. Once the combined flow of unburned solid and gaseous fuel into the crown space exceeds S_o, then a solid flame will form there. The intensity of the whole fire will be reinforced by the crown combustion, but as long as Rd remains less than S_o, the crown phase will remain completely dependent on the surface phase, whose spread rate will control the whole fire.

Such a 'passive crown fire' is, according to [4] and [6], most likely under two conditions. First, if the crown base is low, then the required surface intensity, I_o, is easily developed at a fairly low spread rate, so that a surface fire of intensity greater than I_o will reinforce the mass flow into the crown space long before the critical rate, R_o, is reached. Second, for a sparse crown layer of low bulk density, d, R_o may be very difficult to attain, and the surface phase may simply engulf the scattered tree crowns without true crown spread becoming possible.

Active Crown Fire

Suppose that as the critical surface intensity, I_o, is reached, the spread rate also exceeds R_o. Of course, as crown combustion begins, heat transfer to the surface fuel may be enhanced and the spread rate may take a decided sudden jump above R_o. The crown phase thus becomes independent in terms of mass flow rate and can develop a solid flame on its own. It is, however, much easier to achieve the minimum spread rate, R_o, than to meet the requirement for horizontal heat flux, E_o, through the crown layer. Consider the case of a typical red pine plantation crown fire with $R = 0.4$ m/s, $d = 0.25$ kg/m^3, and $h = 3060$ kJ/kg (at foliar moisture content 100%). By equation 5, E_o is 305 kW·m^{-2}. However, at the usual temperature of not more than 1000 °C, the crown flame is capable of radiating at most about 125 kW/m^2 from a vertical front. The horizontal mass flow rate of crown fuel alone in such a fire, on the other hand, is 0.1 kg/m^2·s, easily exceeding the minimum 0.05. The surface fire must presumably make up the deficit in E_o by supplying some of the energy needed to raise the crown fuel to the ignition state. The question remaining is what factor controls the spread rate of such a fire?

The basic proviso is that the surface and crown phases must travel together as a linked unit. The crown phase supplies all of its own fuel but depends on the surface phase for a part of its ignition energy; the surface phase in turn depends on the crown phase for the opportunity to develop a solid, deep flame within the trunk space, thus greatly increasing its rate of heat transfer (mainly by radiation) to the surface fuel ahead. The surface-phase flame front, however, remains fairly vertical as a result of the reduced wind speed under the crown canopy and the very strong upward convection from the surface. A possible answer to how the spread rate is controlled then has two parts. (1) Suppose that the spread rate has a distinct upper limit, R_s, that is reached when the surface phase flame is solid and deep, that is, when heat transfer to the surface fuel reaches a maximum rate. (2) Suppose that the actual spread rate varies within the limits R_o and R_s, controlled by the crown properties d and h. Although the crown phase thus exerts partial control over the behaviour of the whole fire, such an 'active crown fire' remains unable to supply its whole required forward heat transfer, E_o, without help from the surface phase.

Absolute calculation of the spread rate of an active crown fire would be difficult, but comparisons should be possible. For example, given the spread rate at one d and h combination and assuming E constant, the effect of varying bulk density or foliar moisture might be estimated. An estimate of the limiting rate, R_s, on a given day would also be required from knowledge of how surface fire behaves in the conifer forest type in question.

An active crown fire should be most likely in forests that have (*a*) ground fuel that permits development of a substantial surface fire, (*b*) a crown base moderately high aboveground, and (*c*) a fairly continuous crown layer of moderate to high bulk density and low to normal foliar moisture content.

Independent Crown Fire

Suppose that in some way the crown phase acquires the ability to supply the whole required horizontal heat flux, E_o, by itself. The crown phase will now no longer depend in any way on the surface phase and can run ahead on its own. Stand conditions favouring this development are, presumably, a continuous crown layer of low to moderate bulk density and an abnormally low foliar moisture content. The actual mechanism by which such an 'independent crown fire' might propagate is open to question. Perhaps the flame front is strongly deflected by wind so that an appreciable amount of convective heat is transferred in addition to the available radiation. Thomas (1967) proposes a theory to explain the increased rate of advance as a result of an inclined flame front in cases where the heat transfer is through the fuel layer. In brief, he supposes a constant rate of spread perpendicular to the flame front; horizontal spread would thus be enhanced by a factor equal to the cosecant of the angle between flame and horizontal. For an example of what this means, consider the case of the red pine plantation crown fire mentioned above. E_o is 305 kW/m^2, but the available radiative E from the crown phase is only 125 kW/m^2. The required enhancement factor is therefore 2.44, corresponding to a flame angle of only 24° to the horizontal and a spread rate of 1.0 m/s. Appreciable heat transfer by convection as well as by radiation could reduce the required amount of flame tilt somewhat. Strong deflection by wind is a necessary feature of this theory and probably of any alternate theory as well. For example, Frandsen (1971) considered the more complex case of a curving inclined front and arrived at about the same conclusion. Whatever its mechanism, an independent crown fire must be a rare and delicately balanced phenomenon, liable to collapse at any moment should one of the required conditions fail.

The Theory in Brief

All the arguments presented so far can be condensed into a few semimathematical statements.

(1) Vertical spread of fire into the crowns will occur when surface intensity, I, attains the critical value, I_o. Equation 4 gives I_o in terms of crown base height, z, and crown foliage ignition energy, h.

(2) Crown combustion will spread horizontally provided that (*a*) the required horizontal heat flux, E_o, is supplied to the crown fuel ahead ([5]); and (*b*) the mass flow of fuel (solid or gaseous) into the crown space exceeds a minimum rate, S_o ([6]).

(3) A passive crown fire will occur provided that (*a*) I substantially exceeds I_o, but (*b*) spread rate, R, remains less than the critical value, R_o, derived from d and S_o by [7]. Minimum mass flow rate, S_o, then depends in part on a contribution from surface phase, and control of R remains with the surface phase.

(4) An active crown fire will occur provided that (*a*) I exceeds I_o and (*b*) R exceeds R_o. The crown layer supplies all mass flow needed to meet S_o, but depends in part on the surface phase to meet the required E_o. R is controlled by the crown phase through d and h, but limited to the range R_o to R_s, where R_s is the maximum possible surface rate with deep vertical fire front.

(5) An independent crown fire will occur when (*a*) I exceeds I_o, (*b*) R exceeds R_o, and (*c*) E_o is supplied entirely by the crown phase, probably by enhancement (along with R) because of strong flame deflection by wind.

FIG. 1. Fire C6 in the red pine plantation at maximum intensity, moving from left to right. Note person just left of centre.

Field Experience

The experimental outdoor fire program at the Petawawa Forest Experiment Station provides support for several aspects of this theory. The pertinent data are from three kinds of conifer forest: red pine plantation, jack pine stand, and balsam fir understory in a mature red and white pine stand. Their crown layers are described in Table 1 along with data from two black spruce stands as added examples. Kiil (1975) reported an interesting fire in one of these. Fire data appear in Table 2, and the fires are interpreted below.

Red Pine Plantation

Take first the red pine plantation, from which comes the best information, even though none of the three crown fires lasted more than 2 min. Interpreted according to the classes of crown fire outlined above, fires C4 and C6 were active crown fires, while R1 was on the verge of becoming one. The two fires C4 and C6 burned under similar conditions of weather and surface fuel moisture but at quite different rates of spread. C4 was a summer fire, while C6 burned in spring when foliar moisture and bulk density were both less than in summer. By using [5] and assuming equal forward heat flux, E, in both crown phases, the ratio of their spread rates is very nearly accounted for by the inverse ratio of their dh products. By using values from Table 2, R ratio (C4:C6) is $0.28/0.46 = 0.61$ and inverse dh ratio (C6:C4) is $(0.23 \times 2930)/(0.26 \times 3970) = 0.65$. Figure 1 shows C6 at its maximum intensity. Figure 2 is a photo of C4 but taken at a stage when the spread rate

FIG. 2. Fire C4 in the red pine plantation at a stage barely meeting the criteria for active crown fire. Moving from right to left.

was estimated at 0.20 m/s rather than the maximum, 0.28; the intensity as well was correspondingly lower. Fire C4 in this stage illustrates a crown fire just barely meeting the spread rate and mass flow criteria, R_o and S_o. Fire R1 was increasing in intensity when it had to be stopped and is best interpreted as an incipient active crown fire. Note that in both Figs. 1 and 2 the flame front within the stand appears roughly vertical.

Jack Pine Stand

The jack pine forest at Petawawa provides three examples of three different stand types, each sustaining different kinds of fire. The Gwatkin Lake wildfire (Van Wagner 1965) accounted for two of these. It began in the fully stocked pure jack pine stand as fire GL-A, where the estimated surface intensity of 4800 kW/m was distinctly below the calculated I_o of 6950 kW/m, and the fire failed to crown. The addition of a red pine understory, however, changed the picture completely. Here the crown base was much lower, the corresponding I_o was only 1350 kW/m, and the fire (now called GL-B) crowned immediately. The calculated bulk density of the combined crown layers and the final spread rate are both somewhat in doubt. However, the critical R_o was probably achieved and eyewitness accounts bolster the judgement that this was an active crown fire.

During an experiment (fire SC), in an area where the jack pine was about half-stocked with crown base closer to ground, an intense surface fire developed whose flame eventually engulfed the entire trees. It quickly achieved an intensity greater than the critical I_o of 2490 kW/m, but the spread rate remained well below R_o. This fire was evidently of the passive crown type.

Balsam Fir Understory

The balsam fir understory in the red and white pine stand provides a further interesting contrast. It has a continuous crown layer with a live base no more than 1 m aboveground and a moderately low bulk density, about 0.14 kg/m^3. At first glance it seemed a dangerous place for an experimental fire. Nevertheless, on three occasions, described by Methven and Murray (1974), it proved impossible to produce continuous crowning in the fir understory, even at high fire danger. According to theory, several factors combine to explain why, and fire F3 in Table 2 is given as an example. First, by [4], I_o is only about 200 kW/m, but because wind speed at ground level is so reduced by the two canopies, pine above and fir below, an extreme fire danger is required before the surface intensity reaches this level. Second, I_o is so low that the associated rate of spread would fall far short of R_o, and the critical mass flow rate S_o could not be achieved by the crown layer alone. Third, this implies that crowning, when first initiated, would be passive and that the required conditions for active status would be very difficult to attain. In fact, some sporadic crowning was observed, but the surface intensities averaged less than 100 kW/m, and no continuous crown combustion took place. As for the overstory pine in this stand, its crown base is 20 m aboveground, calling, by [4], for a surface fire of intensity over 19 000 kW/m before the crowns could burn continuously. Such a fire is difficult to imagine within this stand; the implication is that true crown fires in such tall, mature red and white pine stands should be very rare. If ever formed, they would most likely spread as independent crown fires or not at all, in view of the formidable energy requirements for surface dependency.

Black Spruce

The two black spruce stands are included in Table 1 because of the tremendous importance of this species throughout the boreal forest, although it is a minor feature of the Petawawa forest. By the present criteria, Kiil's (1975) fire in a sparse lowland stand is evidently of the passive crown type, in which crown combustion reinforces the surface phase but plays no major part in control of fire behaviour. Nor would an active crown fire seem likely under any conditions at this low crown bulk density. The upland stand described by Weetman and Harland (1964), however, has all the characteristics needed to support full-fledged active crown fire, provided that the surface fuel can produce a fire of say 3000 kW/m in good burning conditions. Very old upland stands, with higher crown base and reduced crown bulk density because of mortality, would likely be quite resistant to crowning.

Discussion

Crown Fuel

Visual experience suggests that the principal crown fuel consumed is the live foliage and that little else burns except in unusually intense fires. However, younger stands that are developing fast may contain substantial numbers of standing dead trees; also, insect attack or disease may result in considerable dead material within the live crowns. In the determination of effective bulk density, d, and ignition energy, h, such additional fuel must obviously be taken into account. Without extending the present theory, weighted average values of d and h represent the best that can be done in such cases. A word should also be said about so-called 'bridge fuels,' namely combustible matter such as loose bark, dead lower branches, lichen, small conifers, etc. in the space between ground surface and the main conifer canopy. According to the present theory, initiation of crowning depends ultimately on a surface fire of above a critical intensity. Scattered bits of flame reaching the crowns or even occasional torching trees will not start a crown fire. To affect the outcome, then, bridge fuels must presumably be present in sufficient quantity to intensify the surface fire appreciably as well as to extend the flame height.

Crowning Tendency

The difference in crowning tendency between conifers and broad-leaved trees deserves comment since in Canada only conifer forests support crown fire. On the other hand, the broad-leaved eucalypt forests of Australia and the chaparral of the southwestern United States are renowned for intense crown fire. One possible explanation lies in the amount of solvent-

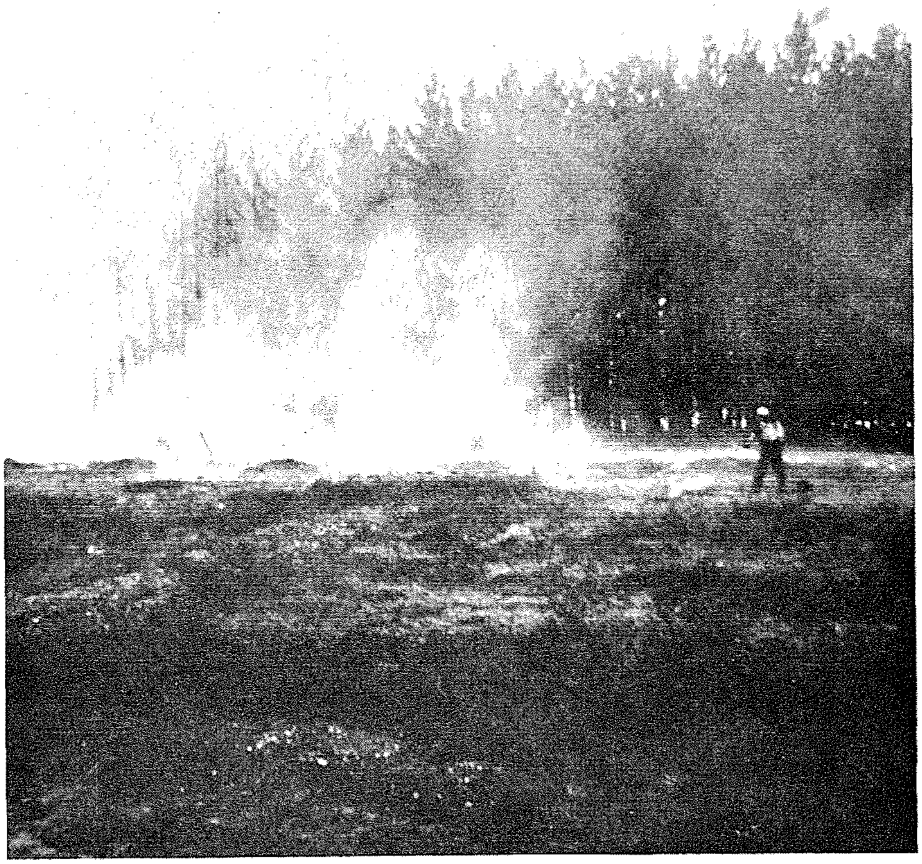

FIG. 3. Fire C6 following collapse after the wind failed. Note surface fire inside stand moving from left to right.

extractable matter such as oils, waxes, and resins. However, according to Philpot's (1969) data and to similar tests made at Petawawa, aspen leaves (for example) contain as much or more of such extract as does conifer foliage; yet aspen stands do not crown. The role of extractives in affecting ignition would presumably be to yield flammable pyrolysis products and an ignitable gas mixture at lower temperatures than could cellulosic matter alone. Their importance would also depend on differences from one species or season to another. Philpot and Mutch (1971) present some data on such differences for two western conifers. However, lowered ignition temperature alone may not greatly affect the heat of ignition. This is because the heat capacity of dry plant matter is only about one-third that of water and because most of the ignition energy is presumably absorbed as latent heat during water vaporization, an energy requirement that seems hardly avoidable. Consider equation 3, which is based on an ignition temperature of 300 °C. A reduction of even 100 °C would only lower the calculated ignition energy of fuel at 100% moisture by about 6%.

Given the importance of the latent heat requirement, many differences can be accounted for on the basis of foliar moisture content (FMC) alone. In Canada, the conifer forests most liable to crown fire have FMC's of from about 70 to 130%, lowest during the spring dip in old foliage FMC that marks the period of greatest crown fire hazard in northern conifers. Eucalypts and chaparral also spend much time

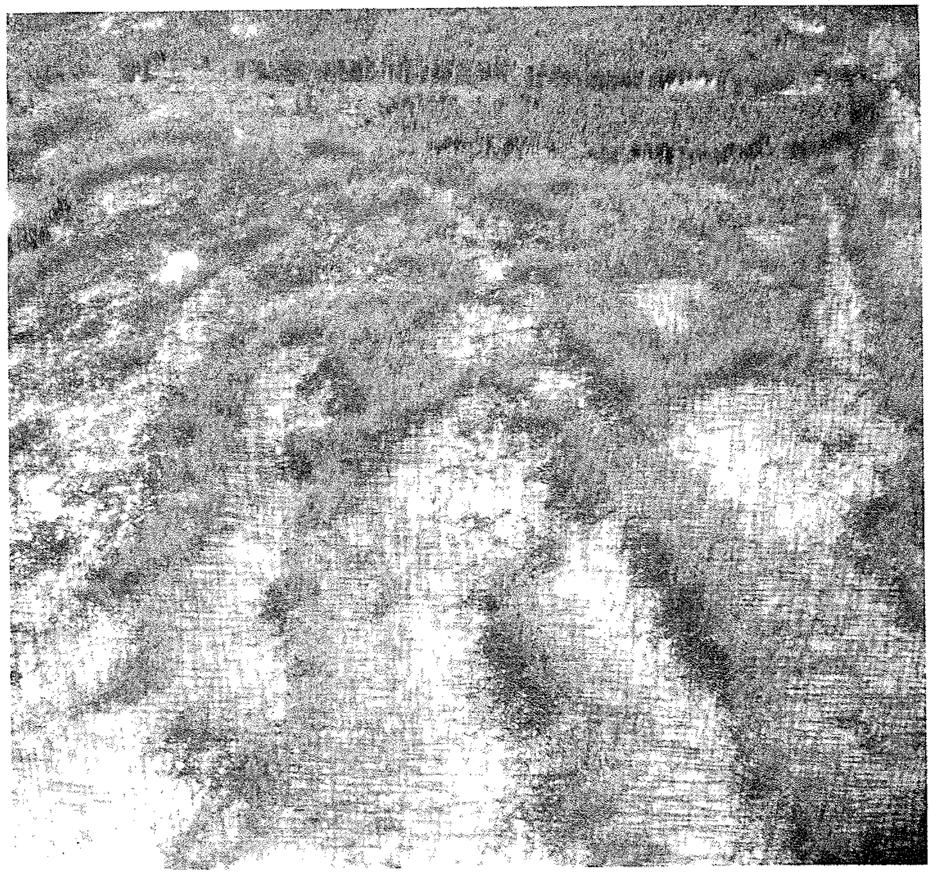

FIG. 4. Pattern of crowned-out areas 1 year after intense fire in a jack pine stand. Fire moved from bottom to top. Foliage in uncrowned strips all killed by heat. Patch of black spruce at top did not burn.

at FMC's of 100% or less. Aspen, birch, and maple on the other hand maintain FMC's of from about 140 to 200% after the flushing period is over. By [3], the heat of ignition required by foliage at 160% FMC, for example, is 4620 kJ/kg based on dry weight; at 80% it is only 2540 kJ/kg. The role of extractives in crown ignition is certainly far from settled, but the present theory points to foliar moisture as the main factor affecting the tendency to crown.

Wind

The empirical experience at Petawawa, both from experiment and casual observation, is that wind is first needed to intensify the surface fire, which in the absence of wind might burn gently all day without crowning. Once crowned, the fire requires wind to maintain it, even though the fire front within the stand may be roughly vertical. If the wind fails, the crown fire collapses (e.g. crown fire C6 as shown in Fig. 3). Certainly wind may tilt the overhead flame above the crowns forward but must counteract very strong upward convection to affect the flame angle appreciably. Considerable flame deflection by very strong wind is presumably a requirement for independent crown fires, whose mechanism must depend somehow on the enhanced forward heat transfer rate possible with tilted flame. Aerial photos of large burned areas often suggest how short-term variations in wind speed interact with stand structure and topography to produce intermittent active crowning (Fig. 4).

Previous Work on Crown Fire

As a proportion of the total literature on forest fires, the amount devoted to the behaviour and theory of crown fires is small. An early published attempt to calculate heat balances in crown fires was by Molchanov (1957). He computed the amount of surface heat output needed to ignite the crown base a given height aboveground but did not take into account the rate aspect of fire intensity and heat transfer. However, his conclusions, based both on calculation and on visual experience, seem quite reasonable: (1) crown fires are increasingly difficult to start as the crown base increases in height aboveground; (2) crown fires generally require a surface fire to supply part of the heat needed for lateral spread; (3) only in a very strong wind and when crown conditions are ideal can the crown phase spread by itself, and such behaviour is very erratic.

Sando and Wick (1972) developed a method of describing the fuel in conifer crowns by two quantitative parameters potentially useful in crown fire theory. One is the mean crown height, the height aboveground to where the crown bulk density reaches a specified minimum value. The other is the crown volume ratio, the inverse of the fraction of the whole space from ground to treetop height that is actually occupied by tree crowns. The mean crown height corresponds to z, the crown base height used in [4]. Crown volume ratio is a complex measure of stand density, depending on the size and spacing of individual trees, although not a direct measure of fuel quality. By using the above concepts, Kilgore and Sando (1975) measured the effect of a prescribed fire on the crowning potential in the understory conifers beneath a giant sequoia stand and obtained substantial increases in both mean crown height and crown volume ratio. There is no doubt that the sequoia overstory is now substantially safer from damage by intense fire in the understory, but the interpretation of crown fire behaviour remains qualitative.

The simple concept of crown fire as spreading by direct thermal radiation through the crown layer has been used (Van Wagner 1974) as the basis of a relative crown spread index that depends on variation in foliar moisture content and crown bulk density as the seasons progress. This index was designed particularly to take account of the period of reduced foliar moisture content in spring just before the new needles flush, when crowning potential in most Canadian conifer forests is at its maximum.

Beyond the above items there are many references reporting rates of spread of particular crown fires and commenting on various aspects of fuel arrangement. For example, the Australians have collected a great deal of practical knowledge of the conditions promoting crown fire and its behaviour in eucalypt stands (McArthur 1967) as well as in pine plantations (Douglas 1964). As far as can be determined, however, there are no other references dealing with the physical theory of crown fire spread.

Conclusion

Crowning forest fires are very exciting phenomena and dangerous as well. It is therefore not surprising that they have not been more objectively studied. A few small experimental crown fires have been burned at the Petawawa Forest Experiment Station, but they are not easy to arrange. Nevertheless, experimental crown fires of short duration are feasible and, given the difficulty of observing crowning wildfires, are well worth the effort.

The theory proposed here depends on three simple crown properties: height above ground, foliar bulk density, and foliar moisture content. It defines three classes of crown fire: passive, active, and independent. The limiting criteria are critical levels of three properties of the fire itself: initial surface intensity, spread rate after crowning begins, and rate of forward heat transfer to the unburned crown fuel. Such a picture is no doubt simple and incomplete but will perhaps stimulate further measurement of crown fires and eventually lead to a satisfactory way of integrating crown fire into schemes for predicting forest fire behaviour in general.

Symbols

C, criterion for initial crown combustion, 0.010 in unit system used below

d, bulk density, kg/m^3

E, forward heat flux through crown layer, kW/m^2

E_0, critical E for independent crown fire, kW/m^2

h, heat of ignition, kJ/kg

H, net heat of combustion, kJ/kg

I, fire intensity as energy output rate per unit of fire front, kW/m

I_o, critical surface intensity for crown combustion, kW/m

I_s, fire intensity, surface phase, kW/m

m, moisture content of crown foliage, percentage of dry weight

R, rate of spread, m/s

R_o, critical minimum spread rate for active crown fire, m/s

R_s, critical maximum spread rate for active crown fire, m/s

S, mass flow rate through crown layer, kg/$m^2 \cdot s$

S_o, critical mass flow rate for solid crown flame, 0.05 kg/$m^2 \cdot s$

ΔT, critical temperature rise at crown base, °C

z, height of crown base above ground, m

Acknowledgments

The author is grateful to Dr. R. H. Silversides of the Pacific Forest Research Centre, Canadian Forestry Service, Victoria, B.C., and to Dr. F. A. Albini, Northern Forest Fire Laboratory, United States Forest Service, Missoula, Montana, for helpful advice and encouragement. J. W. Bell was responsible for most of the field observations.

BROWN, A. A., and K. P. DAVIS. 1973. Forest fire: control and use. Chap. 1. 2nd ed. McGraw-Hill, N.Y.

BYRAM, G. M. 1959. Combustion of forest fuels. *In* Forest fire: control and use. Chap. 2. *Edited by* K. P. Davis. McGraw-Hill, N.Y.

DOUGLAS, D. R. 1964. Some characteristics of major fires in coniferous plantations. Aust. For. **28**(2): 119–124.

FRANDSEN, W. H. 1971. Fire spread through porous fuels from the conservation of energy. Combust. Flame, **16**(1): 9–16.

KIIL, A. D. 1975. Fire spread in a black spruce stand. Can. For. Serv., Bi-Mon. Res. Notes, **31**(1): 2–3.

KILGORE, B. M., and R. W. SANDO. 1975. Crown-fire potential in a sequoia forest after prescribed burning. For. Sci. **21**(1): 83–87.

MCARTHUR, A. G. 1967. Fire behaviour in eucalypt forests. For. Timber Bur. Leafl. 107. Canberra, Australia.

METHVEN, I. R., and W. G. MURRAY. 1974. Using fire to eliminate balsam fir in pine management. For. Chron. **50**(2): 77–79.

MOLCHANOV, V. P. 1957. Conditions for the spread of crown fires in pine forests. Lesn. Khoz. **10**(8): 50–53. (Also, Translation ODF TR213, Can. Dep. For. Rural Develop.)

PHILPOT, C. W. 1969. The effect of reduced extractive content on the burning rate of aspen leaves. U.S. For. Serv. Res. Note INT-92.

PHILPOT, C. W., and R. W. MUTCH. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. U.S. For. Serv. Res. Pap. INT-102.

SANDO, R. W., and C. H. WICK. 1972. A method of evaluating crown fuels in forest stands. U.S. For. Serv. Res. Pap. NC-84.

THOMAS, P. H. 1963. Size of flames from natural fires. Ninth Symp. (Int.) on Combustion, 1962. Proc. 844–859. Academic Press, N.Y.

——— 1967. Some aspects of the growth and spread of fire in the open. Forestry, **40**(2): 139–164.

THOMAS, P. H., D. L. SIMMS, and H. G. H. WRAIGHT. 1964. Fire spread in wooden cribs. Joint Fire Res. Org., Fire Res. Note 537. Boreham Wood, U.K.

VAN WAGNER, C. E. 1964. History of a small crown fire. For. Chron. **40**(2): 202–205, 209.

——— 1965. Story of an intense crown fire at Petawawa. Pulp Pap. Mag. of Can., Woodlands Rev. June, 1965.

——— 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Can. Dep. For. Rural Develop. Publ. 1229.

——— 1974. A spread index for crown fires in spring. Can. For. Serv. Inform. Rep. PS-X-55.

WEETMAN, G. F., and R. HARLAND. 1964. Foliage and wood production in unthinned black spruce in northern Quebec. For. Sci. **10**(1): 80–88.