Jim Gould

Prediction of crown fire behavior in two stands of jack pine

C.E. Van Wagner

Petawawa National Forestry Institute, Forestry Canada, Chalk River, Ont., Canada K0J 1J0

Received March 16, 1992

Accepted July 15, 1992

Van Wagner, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Can. J. For. Res. **23**: 442–449.

Published data on two sets of experimental fires in jack pine (*Pinus banksiana* Lamb.) forest were subjected to two forms of analysis. The first was a classification into surface fires and two kinds of crown fire, passive and active. In the second, the data were used to develop a model to predict both the spread rate of fire and the degree of crown consumption. The model consists mainly of two limiting equations for spread rate, one for surface fires and the other for full crowning fires; the independent variable is the Canadian Initial Spread Index. A critical surface intensity is first used to distinguish surface fires from crowning fires. A further process then estimates the degree of crowning and places the calculated final spread rate somewhere in the space between the limiting equations. The model inputs include six physical stand properties plus a pre-estimate of surface fuel consumption. It is a blend of physical theory and empirical observation.

Van Wagner, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Can. J. For. Res. **23** : 442–449.

Les données publiées de deux séries de brûlages expérimentaux dans une forêt de pin gris (*Pinus banksiana* Lamb.) ont été soumises à deux sortes d'analyses. La première analyse veut dire une classification en feux de surface et deux sortes de feux de cimes, passif et actif. Dans la deuxième analyse, les données ont été utilisées pour mettre au point un modèle de prévision pour tous les deux facteurs : le taux de propagation du feu et le degré de consommation de combustible de cime. Le modèle consiste principalement de deux équations limites de taux de propagation; l'une pour les feux de surface, l'autre pour les feux de cimes complètes. La variable indépendante est l'indice canadien de taux de propagation initiale. Dans l'étude, une valeur critique de l'intensité du feu de surface est utilisée pour faire la distinction entre les feux de surface et les feux de cimes. Ensuite, à l'aide d'un autre procédé, des estimations de degré de feux de cimes sont données puis le taux final de propagation est calculé et mis à l'intérieur d'un crénau déterminé par les deux équations limites. Les valeurs d'entrée du modèle comprennent six caractéristiques physiques relatives aux peuplements ainsi qu'une estimation préliminaire en ce qui concerne la consommation de combustible de la surface. La présente étude englobe une théorie physique et des observations empiriques.

Introduction

During the years 1973–1983, two important sets of experimental fires in jack pine (*Pinus banksiana* Lamb.) forest were conducted in Ontario, both previously reported in this journal. One set, carried out 37 km north of White River at 48.9°N, 85.3°W, consisted of 12 fires in mature jack pine (Stocks 1989). The other set was located about 60 km north of Thessalon at 46.8°N, 83.3°W and consisted of 13 fires in immature jack pine (Stocks 1987). These fires lend themselves especially well to analysis for two reasons: each set represents a wide range in fire behavior from gentle surface spread to full or nearly full crowning, and all fires were documented in terms of spread rate, fuel consumption, and degree of crowning. The plots in each set were 0.4 ha in size.

For his articles, Stocks produced a good single equation for the full range of spread rate in each jack pine type based on the Initial Spread Index (ISI), the component of the Canadian Forest Fire Weather Index System (Van Wagner 1987) generally associated with fire spread rate. The present paper presents two linked analyses: (*i*) an interpretation of each fire according to the crown-fire classification theory of Van Wagner (1977) and (*ii*) a test of a two-equation method of accounting for crown-fire spread rate, after Van Wagner (1989). It is thus intended as a further contribution to the science of crown-fire behavior, but stops short of recommending any models for direct operational use.

The complete explanation of the crown-fire phenomenon by physical modelling has proved elusive. The closest approach so far is that of Albini and Stocks (1986), who described a sophisticated radiation-driven model incorporating, first, a computation of flame length and tilt angle, and then a balance between the radiative intensity of the flame sheet and the ignition energy needs of the canopy. Their model produced good estimates of spread rate for a set of nine crown fires in immature jack pine taken from Stocks (1987). But the authors note that several critical flame properties, namely height, degree of tilt by wind, and radiometric temperature must still be scaled or estimated from field observation. Nor does the model distinguish the point at which a surface fire may crown as its intensity increases. Evidently, a semi-empirical approach to crown-fire description, based partly on field data and partly on physical theory, will still be useful for practical purposes.

The two jack pine stands were described fully by Stocks (1987, 1989). In brief, the immature stand was dense and contained many dead upright stems with considerable fine dead material within its crown space. The mature stand carried a fair quantity of dead branches in its lower crown space and, in addition, a substantial but variable understory of black spruce (*Picea mariana* (Mill.) B.S.P.) growing mainly below the jack pine crowns. Actual quantities are all listed by Stocks (1987, 1989).

Symbols used in the equations are identified throughout and are also listed in the Appendix (Table A1). The symbols were chosen to match as well as possible those used in the forthcoming publication describing the new version of the Canadian Forest Fire Behavior Prediction System (Forestry Canada 1993).

Methods

Crown-fire classification

The classification system used was derived and described by Van Wagner (1977), who developed three criteria based on the following three critical values:

Printed in Canada / Imprimé au Canada

1. Critical surface intensity for start of crowning, ISO (kW/m). If the intensity of surface fire (SFI) exceeds ISO, then the fire will rise into the crowns.

   [1] $\mathrm{ISO} = (0.01h)^{3/2}\ (\mathrm{CBH})^{3/2}$

   where CBH is height of crown above ground (m), h is crown ignition energy (kJ/kg), and 0.01 is an empirical constant.

2. Critical spread rate for solid crown flame, RAC (m/min). If the actual spread rate (ROS) is greater than RAC, then a full continuous flame will develop in the crown layer.

   [2] $\mathrm{RAC} = \dfrac{S_o}{d} = \dfrac{0.05}{d}$

   where S_o is the critical minimum mass flow rate through the crown layer for continuous flame (kg/(s·m^2)) and d is crown-layer bulk density (kg/m^3). Based on empirical experience (Van Wagner 1977), S_o was assigned a value of 0.05.

3. Critical energy flux, E_o (kW/m^2). This is the critical minimum value of the forward horizontal energy flux (E) through the crown layer that would be required to maintain crown fire spread without help from a surface fire below.

These critical values were then incorporated into three criteria to be used for distinguishing three classes of crown fire:

1. Passive crown fire: SFI > ISO, but ROS < RAC.
2. Active crown fire: SFI > ISO, ROS > RAC, but $E < E_o$.
3. Independent crown fire: SFI > ISO, ROS > RAC, $E > E_o$.

In a passive crown fire, the crowns may burn sporadically and partially or be too sparse to permit continuous flame in the crown space. The burning crowns may reinforce forward heat transfer, but the main control resides in the surface phase. The crown phase may appear to lag somewhat behind the surface phase but remains connected with it.

In an active crown fire, the crowns burn more or less completely with continuous deep flame. Although the crown flame is steady and continuous, the crown phase still depends on the surface phase for part of the crown layer's requirements for ignition energy. The crown phase assumes the main control, leaning ahead of the surface fire but remaining linked with it.

The concept of independent crown fire remains dubious. Both Van Wagner (1977), by a simple analysis, and Albini and Stocks (1986), by a more sophisticated process, determined that true independent crown-fire spread ahead of the surface phase could only proceed if the flame front from crown base to flame tip were tilted well forward, perhaps so much as to approach the horizontal. In other words, the spread of crown fire independent of any surface fire is essentially ruled out as a stable phenomenon on level terrain. The concept may still have value in rough or steep terrain and as a short-term fluctuation under the most extreme conditions, but is not pursued further here.

Classification computations

The classification process required the estimation of the ISO, and the RAC, as well as the SFI. Some of the background data were listed by individual plots, others were available as average stand values only.

The computations were straightforward for the immature stand with its essentially uniform crown layer. The mature stand, however, with its distinct black spruce understory, presented a problem. Because the spruce occupied the space below the mature pine crowns, it was, in all cases, the layer in which crowning began. It contributed 42% of the prefire foliage weight and, because very few fires in the mature stand penetrated into the pine canopy, most of the foliage that was actually consumed. However, the theory of Van Wagner (1977) assumes a single uniform crown layer, constant throughout its depth in all properties. For mature pine, a compromise was therefore arranged. First, because the pine canopy played no part in the onset of crowning, ISO (the criterion for it) was based on the spruce understory layer alone. Second, it was assumed that fully active crown fire must depend mainly on the pine canopy above; the spruce understory would be consumed but would lose its direct control over the fire's behavior. RAC (the criterion for full crowning) was, therefore, based on the weighted properties of the pine crown layer alone.

Foliar moisture contents were required for both analyses in this paper. Crown weights are listed by Stocks (1987, 1989) for both stands, but no crown moisture data is available. Foliar moisture contents (FMC) were therefore estimated according to fire dates from a Petawawa trend for jack pine (Van Wagner 1967) and from a Kapuskasing trend for black spruce (Springer and Van Wagner 1984). However, all four locations differ somewhat in latitude; also, according to Springer and Van Wagner (1984), the 2.5 deg. difference between Kapuskasing (49.5°N) and Petawawa (46.0°N) sets the more northerly spring FMC trend back by 2 weeks. The actual fire dates were therefore adjusted in proportion by this schedule: (*i*) immature pine (46.8°N), 4 days later than Petawawa; (*ii*) mature pine (48.9°N), 12 days later than Petawawa; and (*iii*) black spruce (48.9°N), 3 days earlier than Kapuskasing.

The estimation of FMC was based on old-foliage FMC trends, on grounds that any attempt to include newly flushed foliage would have been too difficult. In fact, the average FMCs found were 111.5% for immature pine, 104.5% for mature pine, and 82.0% for the latter's black spruce understory. Each stand, however, included a substantial weight of fine dead twigs (<1.0 cm) in the pine crown layer (Stocks 1987, 1989). These were simply assigned a moisture content of 9%, a reasonable value in dry weather.

As an intermediate step leading to ISO, weighted average crown moisture content (M) was then computed for each plot based on the pine canopy with its dead twig component for the immature stand, but using the black spruce FMCs directly for the mature stand. Crown ignition energy then followed according to Van Wagner (1977) from

[3] $h = 460 + 25.9M$

Also needed for ISO were values for CBH. The estimated value of CBH in the immature stand was 4 m and for the mature pines themselves, 12 m. But the black spruce understory, on which the onset of crowning depended in the latter, extended irregularly from near the ground to the overhead pine canopy. Based on advice from B.J. Stocks (personal communication), an effective CBH of 2 m was therefore assigned to it. ISO then followed from eq. 1.

The first step in computing RAC was the determination of average stand values for vertical crown length (L), from the difference between total stand height (H) and CBH. Based on

TABLE 1. Crowning criteria for the immature jack pine fires

	Surface-intensity criterion*			Spread-rate criterion†				
Fire No.	SFI	ISO	SFI/ISO	ROS	RAC	ROS/RAC	Fire class‡	CFB
2	2 149	836	2.57	10.7	11.3	0.95	P	0.56
3	4 638	669	6.39	16.9	13.6	1.24	A	0.87
4	3 906	720	5.43	14.3	12.5	1.14	A	0.69
5	5 846	867	6.74	14.6	12.6	1.16	A	0.88
6	5 068	889	5.70	14.6	12.9	1.13	A	0.76
7	601	747	0.80	2.1	14.6	0.14	S	—
11*a*	13 380	888	15.07	29.3	12.4	2.36	A	0.96
11*b*	22 543	888	25.39	49.4	12.4	3.99	A	0.96
12	11 866	787	15.08	20.2	14.9	1.36	A	0.86
13	11 689	833	14.03	16.2	10.4	1.56	A	0.59
14	18 386	819	22.45	27.3	14.6	1.87	A	0.90
17	4 020	824	4.88	7.9	11.6	0.68	P	0.30
18	293	939	0.31	0.7	13.8	0.05	S	—

*kW/m.
†m/min.

TABLE 2. Crowning criteria for the mature jack pine fires

	Surface-intensity criterion*			Spread-rate criterion†				
Fire No.	SFI	ISO	SFI/ISO	ROS	RAC	ROS/RAC	Fire class‡	CFB
1	185	372	0.49	0.90	22.9	0.04	S	—
2	687	372	1.85	1.92	27.9	0.07	P	0.07
3	628	372	1.69	1.80	18.4	0.10	P	0.13
4	152	366	0.42	0.72	23.6	0.03	S	—
5	4059	383	10.60	15.36	23.1	0.66	P	0.67
6	132	383	0.34	0.54	24.1	0.02	S	—
7	190	372	0.51	1.50	27.1	0.06	S	—
8	291	372	0.78	1.56	24.5	0.06	S	—
9	1972	465	4.24	4.26	30.3	0.14	P	0.77
10	339	389	0.87	1.68	25.1	0.07	S	0.12
11	858	389	2.21	3.60	27.3	0.13	P	0.30
12	3284	389	8.44	10.20	27.4	0.37	P	0.38

*kW/m.
†m/min.
‡S, surface fire; P, passive crown fire; A, active crown fire.

the stand data, L for the immature stand was 10 m – 4 m = 6 m, and for the mature stand (pine layer alone) 20 m – 12 m = 8 m. The second step was the calculation of d, obtained by dividing the plot values of crown fuel load (CFL) by L. Again, by the terms of the compromise, the basis of CFL in both stands was the pine layer alone with its foliage and dead twigs. Equation 2 then gave RAC.

For estimation of the effective SFI, all elements of surface fuel listed by Stocks (1987, 1989) as consumed, both his woody "surface" fuel and his forest-floor fuel, were included. Byram's familiar formula was then used to calculate SFI for each plot, using the listed spread rates and a value of 18 000 kJ/kg for heat of combustion throughout. This value is based on data and formulae given by Van Wagner (1972). It is a rounded blend of the values for live conifer foliage at 100% FMC and forest litter at 20% moisture content.

The two critical comparisons, SFI vs. ISO and ROS vs. RAC, were made at this point, and the fire criteria given earlier were applied. Because the intermediate steps described above were straightforward calculations based on stand and fuel data listed by Stocks (1987, 1989), only the parameters needed for classification are listed here. See Table 1 for the immature pine set and Table 2 for the mature set.

Classification results

The surface-intensity criterion is shown in the form SFI/ISO; if it is greater than 1, then crown consumption is expected. The spread-rate criterion is shown in the form ROS/RAC; if it is greater than 1, then the crown fire should be active rather than passive. The actual crown fraction burned (CFB), listed in the tables, is the main yardstick against which the results can be judged.

By strict application of the criteria, the immature set (Table 1) comprises two surface fires (7, 18), two passive crown fires (2, 17), and nine active crown fires (the rest). The three classes are readily distinguished, crown consumption becoming more and more complete with rising SFI/ISO. The two passive crown fires consumed only moderate amounts of crown fuel, as is appropriate for such behavior.

The mature pine fire set (Table 2) presents a quite different pattern. The criteria indicate six fires that fail both criteria. Five of these (1, 4, 6, 7, 8) consumed no crown fuel and thus meet the strict definition of surface fire. The other one (10) consumed a small amount of understory crown, but remains for practical purposes in the surface-fire class. The other six fires (2, 3, 5, 9, 11, 12) qualify as passive crown fires with moderate to high values of CFB to match. No mature pine fires met the additional criterion for active crowning.

Judging by the data in Tables 1 and 2, the classification works well for the immature set and fairly well for the mature set. Fire 9 in the mature set is obviously anomalous, with a spread rate much too low to match its CFB in comparison with fires 5, 11, and 12. Blending the two fire sets together in this sense would not be successful because an analysis of CFB in terms of SFI/ISO cannot by itself identify active crowning; when two stands differ considerably in structure, the spread-rate criterion ROS/RAC would be required as well. Such a further joint analysis was judged not worth pursuing. This classification was in fact carried out for two reasons: not only to test the concepts of Van Wagner (1977), but because its parameters were all required at various stages in the second part of the whole analysis.

Prediction of spread rate

The classification of fires in the above manner may shed light on their structure and behavior, but provides no direct means of estimating rate of spread. In the absence of a closed, predictive model based solely on physical principles, what can be done with some empirical help? The analysis leading to the above classification (Van Wagner 1977) offers some ideas on how to proceed. (It is understood that the compromise to account for the double crown layer in the mature stand, described earlier, holds in all that follows as well.) Suppose that, as burning conditions intensify and a surface fire rises into the crowns, control of its propagation rate passes gradually from the surface phase to the crown phase; even though in a fully developed active crown fire, the two phases must remain linked. Suppose further that the degree of control assumed by the crown phase is in proportion to the degree of CFB, the surface phase retaining the rest. This concept implies a transition zone between surface and complete crown fire, consisting of a range of conditions that produce partial or intermittent crowning (intermittent, that is, on a scale small in time and space). It also implies that what has been called a passive crown fire is merely the physical state of a fire in this transition zone. In other words, once a fire begins to crown, there are no sharp class boundaries, but merely a gradual shift through a range of degree of passivity to the fully active state. At the same time, as crown consumption rises, the process of forward heat transfer is enhanced. The fire spreads faster and faster, but with decreasing rate of increase after CFB reaches 1. Presumably an equilibrium may be reached at any point on this scale, depending on burning conditions.

An empirical way of expressing the above concept is to design two equations: (*i*) a lower one to define the spread rate of all possible surface fires, as if the crown layer were present but not flammable, and (*ii*) an upper one to define the spread rate of all possible fully active crown fires, as if there were no minimum physical limit on the mass flow rate through the crown layer. These two equations overlap in the horizontal sense; each is in terms of a common independent variable, in this case the ISI. Any crowning fire can then be placed according to its degree of CFB in the vertical space between the two bounding curves. The ROS is thus given by

$$[4] \quad \mathrm{ROS} = \mathrm{RSS} + \mathrm{CFB}\,(\mathrm{RSC} - \mathrm{RSS})$$

where RSS and RSC are the spread rates given by the surface and crown fire equations, respectively.

The left part of the surface-spread curve must represent the set of true surface fires, while the right part of the crown-spread curve must represent the set of true fully active crown fires. Otherwise their imaginary extrapolations (to right and left as needed) can only be set by trial. Furthermore, it is understood that these extrapolations will, in tune with the empirical concept, be designed to give the best possible outcome in terms of the data on which the model is based. By such a process, two pairs of equations were produced, the first pair to describe the immature pine set, namely

$$[5] \quad \mathrm{RSS} = 20\,(1 - e^{-0.20\,\mathrm{ISI}})^{5.0}$$

$$[6] \quad \mathrm{RSC} = 110\,(1 - e^{-0.037\,\mathrm{ISI}})^{1.2}$$

and the second pair to describe the mature pine set, namely

$$[7] \quad \mathrm{RSS} = 15\,(1 - e^{-0.05\,\mathrm{ISI}})^{2.0}$$

$$[8] \quad \mathrm{RSC} = 110\,(1 - e^{-0.037\,\mathrm{ISI}})^{1.2}$$

Because no fully active crown fires occurred in the mature pine stand, the RSC equation derived for the immature pine fires was used for mature pine as well. However, eqs. 6 and 8 are not quite complete. FMC, used earlier as a factor in the onset of crowning, should also affect the crown fire's spread rate (Van Wagner 1977). A factor designed to account for this foliar moisture effect (FME) was developed by Van Wagner (1974, 1989). It combines the supposed effect of moisture on the flame's radiation intensity and on h of the crown fuel in the equation

$$[9] \quad \mathrm{FME} = \frac{1000\ (1.5 - 0.00275\ \mathrm{FMC})^4}{h}$$

In the present case, M was used in place of FMC. Values of M were computed for all plots, based for both the immature and mature stands on the pine crown layer alone with its dead twig component.

The FME is used in a relative sense and must be normalized for use against some standard value. In the present use, the RSC equation was based on crown-fire spread rates in the immature pine stand. A normal value ($\mathrm{FME_0}$) was therefore computed based on the mean M for the immature plots (67.0%), yielding $\mathrm{FME_0} = 1.365$. For each plot in both stands, the outcome of eqs. 6 and 8 was multiplied by the factor $\mathrm{FME/FME_0}$, yielding the required values of RSC.

The two pairs of spread equations are graphed in Figs. 1 and 2, along with the actual observed spread rates for each fire set (the RSC curve for mature pine was reduced in proportion to its lower mean FME). Before these equations can be used, however, the model must first decide whether or not the fire is crowning. The criterion is again the ISO, as previously calculated by eq. 1. For the model's purpose, this criterion must be expressed in terms of spread rate rather than energy output rate; this is easily done by working backwards through Byram's intensity equation.

$$[10] \quad \mathrm{RSO} = \frac{\mathrm{ISO}}{300\ \mathrm{SFC}}$$

TABLE 3. Comparison of calculated values, CFB$_\mathrm{c}$ and ROS$_\mathrm{c}$, with the observed values, CFB$_\mathrm{o}$ and ROS$_\mathrm{o}$, for the immature jack pine fires; also the intermediate quantities RSO, RSS, RSC

Fire No.	ISI	RSO	RSS	RSC	CFB$_\mathrm{c}$	CFB$_\mathrm{o}$	ROS$_\mathrm{c}$	ROS$_\mathrm{o}$
2	6.8	4.2	4.5	17.8	0.07	0.56	5.6	10.7
3	8.9	2.4	7.9	30.0	0.73	0.87	23.8	16.9
4	8.0	2.6	6.5	24.9	0.60	0.69	17.4	14.3
5	9.8	2.2	9.4	24.9	0.82	0.88	22.0	14.6
6	8.7	2.6	7.6	21.4	0.70	0.76	17.1	14.6
7	7.8	2.6	6.2	22.4	0.58	—	6.2	2.1
11*a*	13.2	2.0	13.8	32.2	0.94	0.96	30.9	29.3
11*b*	19.7	2.0	18.1	45.7	0.98	0.96	45.1	49.4
12	8.3	1.3	7.0	23.5	0.74	0.86	19.0	20.2
13	8.7	1.2	7.6	23.1	0.78	0.59	19.5	16.2
14	9.4	1.2	8.7	25.5	0.83	0.90	23.5	27.3
17	6.8	1.6	4.5	18.1	0.50	0.30	11.1	7.9
18	5.8	2.1	3.0	13.1	0.19	—	3.0	0.7

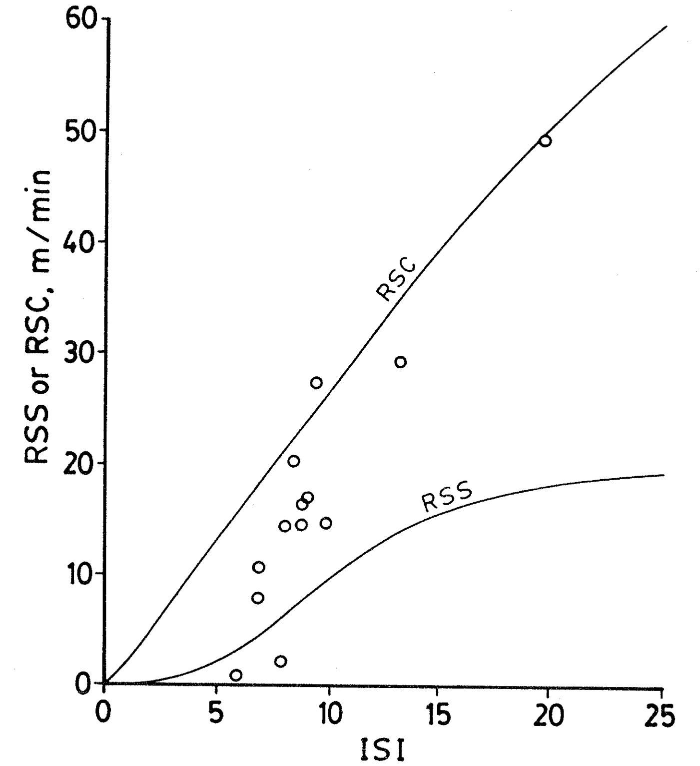

FIG. 1. Curves of eqs. 5 and 6, showing RSS and RSC in terms of ISI for the immature jack pine fires. Actual fire spread rates shown as plotted circles.

where RSO is the required critical spread rate for the start of crowning (m/min), SFC is total surface fuel consumption (kg/m^2), and 300 is a compound constant found by dividing the chosen heat of combustion (18 000 kJ/kg) by 60, to reconcile the different time units in RSO and ISO. Then, if RSS (eq. 5 or 7) is less than RSO, the fire is called a surface fire, RSO equals RSS, and the procedure is complete.

If, however, RSS exceeds RSO, the fire is classed as a crown fire, and value for the CFB is needed to complete eq. 4. An empirical estimate of CFB to fit the model's concept is based on the excess of RSS over RSO. The CFB is assumed to begin rising the moment RSS exceeds RSO but with decreasing slope, so as to fit the form $y = 1 - \exp(-ax)$. The value of "*a*" was based on the difference between RSO and RAC, that is, on the difference in spread rate between the point where crown consumption begins and the point at which it becomes complete. For the immature stand, the mean values of RSO and RAC were 2.15 and 12.89, respectively, and, for the mature stand, 1.45 and 25.14, respectively. Taking CFB to be 0.9 at 90% of the difference RAC − RSO, analysis of the exponential formula yielded for the immature stand

$$[11] \quad \mathrm{CFB} = 1 - e^{-0.238(\mathrm{RSS-RSO})}$$

and for the mature stand

$$[12] \quad \mathrm{CFB} = 1 - e^{-0.108(\mathrm{RSS-RSO})}$$

The predictive process is then as follows:

1. Compute ISO by eq. 1.
2. Compute RSO by eq. 10.
3. Compute RSS by eq. 5 or 7.
4. If RSS < RSO, then ROS = RSS and the fire is a surface fire.
5. If RSS > RSO, then the fire is, to some degree, a crown fire.
6. Compute FME by eq. 9.
7. Compute RSC by eq. 6 or 8, multiplying by FME/FME$_\mathrm{o}$.
8. Compute CFB by eq. 11 or 12.
9. Compute ROS by eq. 4.

The model's results for the immature pine fires appear in Table 3, and for mature pine in Table 4. The tables list ISI, the three calculated intermediate spread rates, and then both the calculated and observed values of CFB and ROS, in adjacent columns for comparison. In addition, calculated values of ROS are graphed over the observed values for both fire sets in Figs. 3 and 4.

Discussion

The sequence of calculation steps leading to ROS does not lend itself easily to statistical analysis, especially in view of the empirical nature of eqs. 5 to 8. At least, however, the calculated values can be tested against the observations. A regression of ROS$_\mathrm{c}$ vs. ROS$_\mathrm{o}$ for the immature pine fires yields $y = 4.2 + 0.85x$ with $r^2 = 0.90$. The same regression for mature pine yields $y = 0.14 + 0.81x$ with $r^2 = 0.95$. In the sense of internal consistency within the data sets, these are fairly favourable results, although the r^2 value for the mature

TABLE 4. Comparison of calculated values, CFB$_c$ and ROS$_c$, with observed values, CFB$_o$ and ROS$_o$, for the mature jack pine fires; also the intermediate quantities RSO, RSS, RSC

Fire No.	ISI	RSO	RSS	RSC	CFB$_c$	CFB$_o$	ROS$_c$	ROS$_o$
1	5.9	1.8	1.0	11.9	—	—	1.0	0.9
2	6.9	1.0	1.3	14.7	0.03	0.07	1.7	1.9
3	6.9	1.1	1.3	14.6	0.03	0.13	1.6	1.8
4	6.4	1.8	1.1	12.6	—	—	1.1	0.7
5	17.3	1.5	5.0	32.0	0.32	0.67	13.6	15.4
6	3.3	1.6	0.3	6.4	—	—	0.3	0.5
7	5.2	2.9	0.8	9.7	—	—	0.8	1.5
8	7.7	2.0	1.5	13.7	—	—	1.5	1.6
9	10.5	1.0	2.5	18.4	0.15	0.77	4.9	4.3
10	7.1	1.9	1.4	12.6	—	0.12	1.4	1.7
11	9.6	1.6	2.2	18.0	0.06	0.30	3.1	3.6
12	12.1	1.2	3.1	21.4	0.18	0.38	6.4	10.2

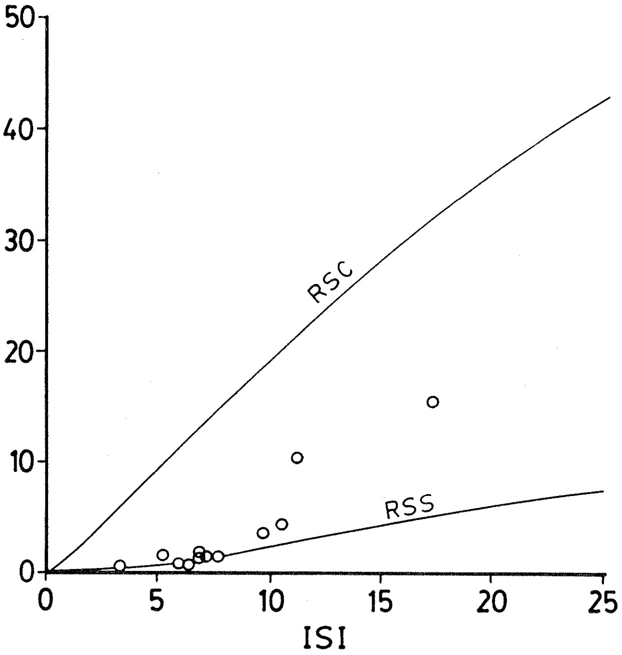

FIG. 2. Curves of eqs. 7 and 8, showing RSS and RSC in terms of ISI for the mature jack pine fires. Actual fire spread rates shown as plotted circles.

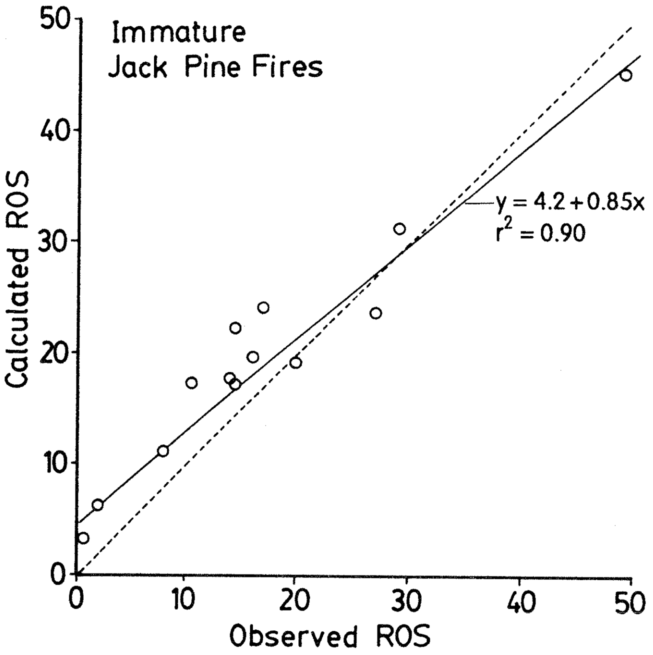

FIG. 3. Regression of calculated vs. observed ROS for the immature jack pine fire set. Line of perfect agreement shown broken.

set has limited meaning in view of the cluster of points near the origin. The mean value of ROS$_c$/ROS$_o$ was 1.09 for the immature set and 0.85 for the mature set.

Estimation of CFB is an intermediate step in the prediction of ROS; it has a strong bearing as well on the calculation of fire intensity by specifying the proportion of the crown fuel that will be included in the total fuel consumption. When the calculated values (CFB$_c$) are regressed against the observed values (CFB$_o$), the immature pine sets yields $y = 0.29 + 0.56x$, using 0.01 for zero x when necessary. Omitting the five mature pine fires for which zero CFB was correctly predicted, the regression for the remaining seven is $y = 0.33x$. Values of r^2 are 0.50 and 0.66, respectively. These results appear less favourable than for ROS; however, in the immature set, mean CFB$_c$/CFB$_o$ = 1.01, and the errors are at least concentrated in two individual fires. In particular, immature fire 2 was almost rated as active by the classification scheme (Table 1), but both its CFB and ROS were severely underpredicted by the model (Table 3). Fire 7 in the same set was correctly rated as surface (Table 1), but was assigned a substantial CFB (and ROS) by the model (Table 3). Among the mature pine fires, fire 9 seems especially anomalous. According to the model, its observed CFB of 0.77 is considerably too high to match its relatively low ROS of 4.3 m/min (Table 4). But CFB was on the whole badly underpredicted in the mature stand, so that mean CFB$_c$/CFB$_o$ was only 0.32. This implies that the favourable ROS prediction in this stand could only have resulted from a pair of compensating errors.

Although analysis by classification into surface fires and passive or active crown fires may provide some clues to the energy transfer processes involved, a model for directly predicting spread rate is of more interest. In the present example, the specific need for distinguishing classes of crown fire disappears into the concept of gradually increasing crown consumption as burning conditions become more severe.

Several obvious weaknesses in the spread-rate model are worth mentioning. First, CBH is seldom possible to measure

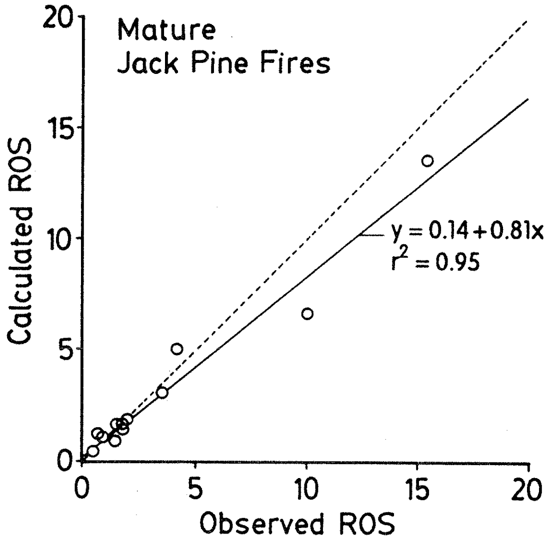

FIG. 4. Regression of calculated vs. observed ROS for the mature jack pine fire set. Line of perfect agreement shown broken.

accurately. Furthermore, average stand values only were available here; variation within and among individual plots may be at the root of some of the error. Second, the proper value of SFI for crown-fire modelling should perhaps be based on something less than complete SFC. Nevertheless, for want of a sound basis for judging a reduced value, the full SFC was used. Third, the subjective design of the extrapolated sections of the limiting spread-rate equations to yield favourable results is hard to avoid because there is no objective way to accomplish this step. Fourth, the model produced fairly consistent results in the immature pine stand with its relatively uniform crown layer, but the compromise procedure in the two-layered mature stand did not work quite as well.

By Tables 3 and 4 the general run of ISI values was much the same for both stands, whereas average fire behavior was quite different. The obvious practical reason was the contrast between the immature stand with its uniform crown layer and the mature stand with its highly variable spruce understory. In the physical sense, the reason is best expressed in terms of *d*, which directly controls the ease with which full crowning can be achieved. Thus, mean values of *d* were 0.238 kg/m^3 for the immature crown, but only 0.121 and 0.049 for the mature pine crown and its spruce understory, respectively. Much higher surface spread rates were therefore needed to promote active crowning action in the mature stand than in the immature stand.

As it stands, the model is a blend of physical principle and empirical trial. As such, its success depends, first, on the internal consistency of the initial data set. The second requirement is that the model account for the main variable processes and factors that determine crown spread rate. Barring the possibility of compensating errors, the generally favourable results imply that both these conditions were met in the present case. The third requirement for full validity is that the model be tested against independent data, another distinct step that is not easily accomplished. It is difficult enough, for instance, to obtain good information on the basic behavior of wild crown fires, to say nothing of the pertinent details of stand structure on the burned areas. Furthermore, the great variation among natural forest stands, even within a relatively well-defined class, such as mature jack pine, places a practical limit on the degree of accuracy ultimately possible in the use of such a model on a landscape scale.

Some elements of the present model appear in the forthcoming new version of the Canadian Forest Fire Behavior Prediction System (Forestry Canada 1993), including a version of the two-equation crown-fire model for one fuel type, Conifer Plantation. Preview descriptions have been written by Lawson *et al.* (1985) and by Stocks *et al.* (1989).

The present model needs firm values for at least six basic stand properties; some are readily measured, others depend on interpretation and judgement. Some trial in the construction of the working equations is also inevitable. Within this framework, the present results indicate what can be done by combining physical concepts with a good set of empirical data to produce a credible model of crown-fire behavior.

Albini, F.A., and Stocks, B.J. 1986. Predicted and observed rates of spread of crown fires in immature jack pine. Combust. Sci.Technol. **48**: 65–74.

Forestry Canada. 1993. Development and structure of the Canadian Forest Fire Behaviour Prediction System. For. Can. Inf. Rep. ST-X-3.

Lawson, B.D., Stocks, B.J., Alexander, M.E., and Van Wagner, C.E. 1985. A system for predicting fire behavior in Canadian forests. *In* Proceedings of the 8th Conference on Fire and Forestry Meteorology, 29 April - 2 May 1985, Detroit, Mich. *Edited by* L.R. Donoghue and R.E. Martin. Society of American Foresters, Bethesda, Md. Publ. 85-04. pp. 6–16.

Springer, E.A., and Van Wagner, C.E. 1984. The seasonal foliar moisture trend of black spruce at Kapuskasing, Ontario. Can. For. Serv. Res. Notes **4**: 39–42.

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

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

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

Van Wagner, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fire. Can. For. Branch Dep. Publ. 1204.

Van Wagner, C.E. 1972. Heat of combustion, heat yield, and fire behaviour. Can. For. Serv. Inf. Rep. PS-X-35.

Van Wagner, C.E. 1974. A spread index for crown fires in spring. Can. For. Serv. Petawawa Nat. For. Inst. Inf. Rep. PI-X-55.

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

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35.

Van Wagner, C.E. 1989. Prediction of crown fire in conifer stands. *In* Proceedings of the 10th Conference on Fire and Forest Meteorology, April 1989, Ottawa, Ont. *Edited by* D.C. MacIver, H. Auld, and R. Whitewood. Environment Canada and Forestry Canada, Ottawa, Ont. pp. 207–212.

Appendix

TABLE A1. Symbols used in equations

Symbol	Definitions and units
d	Crown fuel bulk density (kg/m^3)
E	Forward horizonal energy flux (kW/m^2)
E_o	Critical energy flux (kW/m^2)
h	Crown fuel ignition energy (kJ/kg)
H	Total stand height (m)
L	Crown length (vertical) (m)
M	Weighted crown fuel moisture content (%)
CBH	Crown base height (m)
CFB	Crown fraction burned
CFL	Crown fuel load (kg/m^2)
FMC	Foliar moisture content (%)
FME	Foliar moisture effect
ISI	Initial Spread Index
ISO	Critical intensity for start of crowning (kW/m)
RAC	Critical spread rate for solid crown flame (m/min)
ROS	Final spread rate (m/min)
RSC	Crown-fire spread rate (m/min)
RSO	Critical spread rate for start of crowning (m/min)
RSS	Surface-fire spread rate (m/min)
S_o	Critical minimum mass flow through the crown layer for continuous flame (kg/(s$\cdot$m^2))
SFC	Total surface fuel consumption (kg/m^2)
SFI	Surface-fire intensity (kW/m)
subscript c	Calculated
subscript o	Observed