Calculating and interpreting forest fire intensities

MARTIN E. ALEXANDER[1]
Department of the Environment, Canadian Forestry Service, Great Lakes Forest Research Centre, P.O. Box 490, Sault Ste. Marie, Ont., Canada P6A 5M7

Received October 10, 1980

ALEXANDER, M. E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. **60**: 349–357.

Frontal fire intensity is a valid measure of forest fire behavior that is solely a physical attribute of the fire itself. It is defined as the energy output rate per unit length of fire front and is directly related to flame size. Numerically, it is equal to the product of net heat of combustion, quantity of fuel consumed in the active combustion zone, and a spreading fire's linear rate of advance. The recommended International System (SI) units are kilowatts per metre. This concept of fire intensity provides a quantitative basis for fire description useful in evaluating the impact of fire on forest ecosystems.

ALEXANDER, M. E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. **60**: 349–357.

L'intensité du front de feu est un paramètre valable du comportement des feux de forêt, qui n'est qu'une caractéristique physique du feu en soi. Elle se définit comme la vitesse de production d'énergie par unité de longueur du front de feu et est directement reliée à la dimension des flammes. Elle est numériquement égale au produit de la chaleur nette de combustion, la quantité de combustibles consumés dans la zone de combustion active et la vitesse linéaire de progression d'un feu disséminant. L'unité SI (Système international) recommandée est le kilowatt par mètre. Ce concept d'intensité du feu fournit une base quantitative pour la description du feu, qui sert à évaluer l'impact du feu sur les écosystèmes forestiers.

[Traduit par le journal]

Introduction

The Smith and James (1978) inclusion of Byram (1959) fire intensities for four experimental burns conducted on 0.225-ha trembling aspen (*Populus tremuloides* Michx.) plots in southern Ontario represents an admirable effort. The authors had been criticized (Van Wagner and Methven 1978) for inadequate description of fire behavior in an earlier paper (James and Smith 1977) on these same four fires. The mathematical manner in which fire intensity was calculated, the units quoted by the authors and their interpretation, and the terminology used in their paper are the subjects of this paper. It is important that these points be clarified for the general readership since only recently has Byram (1959) fire intensity been mentioned in the literature by ecologists and biologists peripherally involved in forest fire research (e.g., Ohmann and Grigal 1979; Schindler *et al.* 1980). A secondary objective of this paper is to define clearly what is meant by Byram (1959) fire intensity. This basic fire-behavior characteristic has been used by forest fire researchers to evaluate fire effects for some time (e.g., Van Wagner 1962, 1963), but few investigators in other fields appear to understand its meaning and usefulness in fire-impact analyses. Finally, other fire-front characteristics and related fire-behavior parameters of direct relevance to studies of fire effects are described. Examples are given for illustration, and sample references are cited for further reading.

Forest fire description and fire effects

Muraro (1971) defined fire effects as the combined result of (*a*) the immediately evident effect of fire on the ecosystem in terms of biophysical alterations or population reduction and (*b*) postfire influences. The lack of an adequate description of the forest fire producing these responses has been evident in the fire-effects literature for several years now (McArthur and Cheney 1966; Gilmour and Cheney 1968; Methven 1978; Van Wagner and Methven 1978; Rothermel and Deeming 1980; Cheney 1981). This trend continues in spite of significant improvements in the science of fire-behavior description and quantification.

Forest fires have been described as "cool" versus "hot" or "light" versus "severe," generally on the basis of postfire observations of the remaining forest-floor layer and (or) level of stand destruction. These subjective, qualitative descriptions of fire have several shortcomings. Such descriptions will vary among individuals and from year to year, depending on the burning season.

There is also a precedent in the literature for measuring aboveground fire temperatures. Maximum temperatures in forest fire flames "... occur in a single pine needle as readily as in a crown fire" (Van Wagner and Methven 1978) and there are, of course, several practical and technical obstacles to obtaining adequate measurements of temperature (Van Wagner 1970*a*; Van

---

[1] Present address: Department of the Environment, Canadian Forestry Service, Northern Forest Research Centre, 5320—122 Street, Edmonton, Alta., Canada T6H 3S5.

0008-4026/82/040349-09$01.00/0

Wagner and Methven 1978). The temperature field in a forest fire is constantly changing in time and space. Even if time–temperature profiles could be quantified vertically and horizontally, the problems of how to interpret, present, and apply such information remain. Such profiles cannot be presented in simple physical units (Van Wagner 1970*a*). The profiles would have no practical use until they were correlated with the fire environment which produced them. Measuring temperature merely introduces a cumbersome, secondary step in the study of fire effects when direct linkage to one or more fire-behavior characteristics would be more profitable. The difficulties associated with fire description in terms of temperature can be avoided by accepting the fact that fires which behave in a similar manner (i.e., with respect to intensity, spread rate, etc.) have similar temperature patterns (Van Wagner 1970*a*).

Temperatures at varying depths in mineral soil deserve comment at this point. The degree of direct heat in mineral soil is dependent primarily on the depletion and moisture-content profile of the organic layer (Shearer 1975, 1976). For example, during prescribed fires in red pine (*Pinus resinosa* Ait.) and eastern white pine (*P. strobus* L.) stands, Van Wagner (1970*b*) found very little increase in temperature within mineral soil when 1.3 cm or more of the organic mantle remained unburned.

Perhaps the single most valid characteristic of a fire's general behavior and direct impact on aboveground vegetation is "fire intensity" as described by Byram (1959) and subsequently by Brown and Davis (1973). Gilmour and Cheney (1968) rightly note: "When such a fundamental variable as fire intensity has been largely neglected in the past, it is not surprising that the subject of fire effects is confusing and often contradictory."

Byram's fire intensity concept

The active front of a forest fire (Fig. 1) has three basic characteristics: (*a*) it spreads, (*b*) it consumes fuel, and (*c*) it produces heat energy in a visible flaming combustion reaction (Van Wagner 1970*a*). The energy output or production rate, termed fire intensity, is numerically equal to the product of available fuel energy and the fire's rate of advance. As Van Wagner (1977*b*) notes "... fire intensity thus conceived contains about as much information about a fire's behavior as can be crammed into one number." Byram (1959) defined *fire intensity* as the rate of energy or heat release per unit time per unit length of fire front, regardless of its depth. An updated version of Byram (1959) appears as chapter 6 in Brown and Davis (1973).

Formula

Fire intensity, I, in units of kilowatts per metre (kW/m), is determined by the simple equation (after Byram 1959, Eq. 3.3):

$$I = Hwr \tag{1}$$

where, in compatible units, H is the fuel low heat of combustion, subject principally to a slight reduction for fuel moisture conditions, in kilojoules per kilogram (kJ/kg), w is the weight of fuel consumed per unit area (in the active flaming zone) expressed in kilograms per square metre (kg/m^2), and r is the rate of spread in metres per second (m/s). A brief discussion of each variable follows.

Component variables

Heat of combustion

The caloric value used in calculating energy transfer and efficiency of energy utilization in plant communities is a quantity familiar to ecologists. Caloric values determined in a bomb calorimeter, termed total, gross, or high heats of combustion, are measured in terms of their ovendry weight, conditions seldom approached in a forest fire situation. At least two categories of heat loss (i.e., reductions) must be taken into account if one is to arrive at a net value of H suitable for use in Eq. 1. Byram (1959) called this reduced value "heat yield" and defined it as being numerically equal to the high heat of combustion minus heat losses resulting from radiation, incomplete combustion, and the presence of moisture in the fuel.

The first reduction, for the latent heat absorbed when the water of reaction is vaporized, is 1263 kJ/kg (Byram 1959). The calorimeter result reduced by this standard quantity then becomes the "low" heat of combustion. The second reduction, for fuel moisture content,[2] is 24 kJ/kg per moisture content percentage point (Van Wagner 1972*b*). Byram (1959) makes a third reduction for radiation. There are two arguments for not making this latter reduction: (1) there is no sound basis available for estimating radiant heat as a proportion of the total energy output of individual fires of different intensities, and (2) radiation is not really a loss, but contributes greatly to fire behavior (Van Wagner 1972*b*, 1973). This reduction is suggested if some special purpose requires an estimate of only convective heat output (Van Wagner 1972*b*).

Another possible reduction, one that will remain a matter of subjective judgment (Van Wagner 1972*b*), is for incomplete combustion. It is quite variable and very difficult to measure. Forest fires produce smoke which consists mainly of unburnt tars and carbon (Luke and McArthur 1978). Smoke color provides a good visible indication of the completeness of combustion. Low-vigor surface fires are typically more efficient than crown fires (i.e., emitted smoke is lighter in color).

---

[2] Items 2 and 3 in Table 3.2 of Byram (1959).

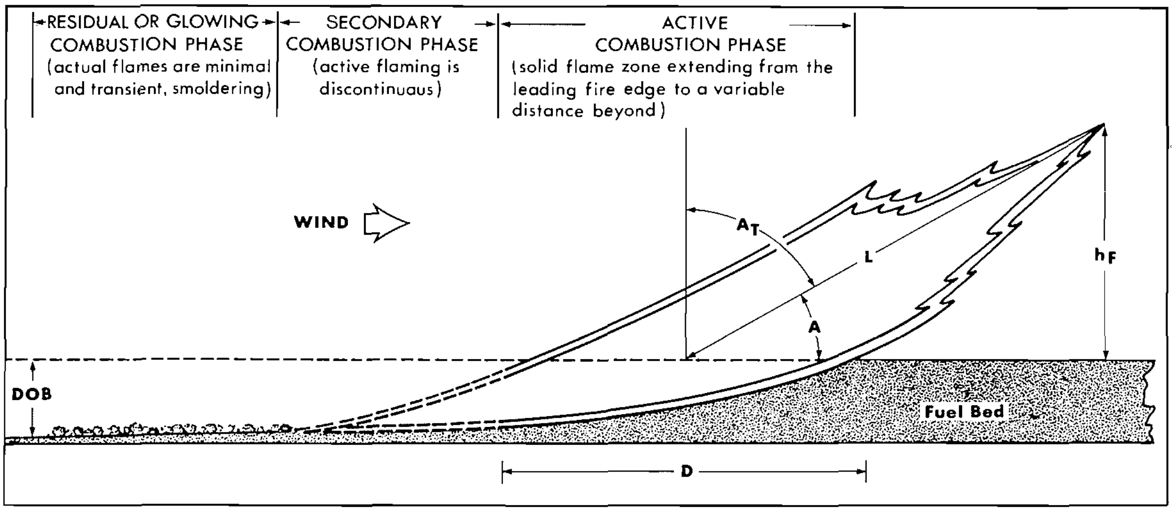

FIG. 1. Cross section of a stylized surface head fire on level terrain illustrating the energy or heat-release stages during and following passage of the flame front, flame length (L), flame height (h_F), flame angle (A), flame tilt angle (A_T), horizontal flame depth (D), and the resulting depth of burn (DOB).

Fuel consumption

It is virtually impossible to determine precisely the amount of fuel consumed in the active combustion zone of a forest fire under field conditions. The amount of fuel consumed by secondary combustion and residual burning after passage of the main fire front (Fig. 1) will increase w and consequently result in an overestimation of fire intensity. Glowing combustion and persistent smoldering are more commonly associated with heavy woody surface fuel concentrations and (or) deep organic layers and low fuel moisture conditions (Kiil 1971). Reductions in the total w measured may be necessary if significant quantities of fuel are consumed subsequent to passage of the flaming front. In the absence of pre- and post-fire measurements, and on-site observations during the fire, appropriate reductions will have to be based on experience and judgment.

Rate of spread

The r in Eq. 1 refers to the linear rate of advance rather than perimeter increase or area growth rates, by a surface head fire, a crown fire, or a backfire. The first two fire types are spreading with the wind while the latter is burning against the wind. It can be readily observed that identical intensities can be arrived at by fires of varying rates of spread and fuel consumption. Thus, a more complete description of fire behavior could be given by quoting the rate of spread as well as the fire intensity (Van Wagner 1962, 1965*a*). Although r in Eq. 1 in metres per second is required in the calculation of intensity, metres per minute is recommended when quoting rate of spread for its own sake (Van Wagner 1978). Rate of spread provides a better mental image in metres per minute than in metres per second, especially for slow-moving fires and short lapse times.

Variation

Low heat of combustion varies so little from fuel to fuel, roughly ±10% (Van Wagner 1972*b*), that it can (generally) be thought of as a constant. Fuel consumption varies over a fairly narrow range (ca. 10-fold), whereas rate of spread may vary 100-fold (Van Wagner 1965*a*). Thus, frontal fire intensity may vary by more than 1000-fold or, according to Byram (1959), from approximately 15 to at least 100 000 kW/m, largely because of the potential variation in rate of fire spread. Such extremes have been documented in Canadian forests (e.g., Kiil and Grigel 1969; Methven and Murray 1974) and elsewhere. However, fire intensities seldom exceed 50 000 kW/m and most crown fires fall within the range of 10 000 – 30 000 kW/m.

Measurement

A basic value of ca. 18 700 kJ/kg can be used for the low heat of combustion (Van Wagner 1973; Albini 1976). Specific values are available in the literature (e.g., Hough 1969; Van Wagner 1972*b*). Techniques for measuring fuel consumption and rate of spread will vary according to the fuel complex, expected fire behavior, logistics, etc. There is a considerable body of literature available to serve as a guide to methods design, a portion of which is cited here. Although the handbook by McRae *et al.* (1979) is intended for use in boreal slash fuel complexes, it provides a detailed account of the methodology for fire intensity determinations. An extensive bibliography is included as well (Alexander 1981). Obviously fire intensity is more easily determined for controlled experimental (e.g., Lawson 1973; Van Wagner 1977*a*; Stocks and Alexander 1980) and operational (e.g., Randall 1966; Kiil 1969, 1970) prescribed fires. However, rough estimates for wildfires can be obtained (e.g., Van Wagner 1965*b*; Kiil and Grigel 1969; Walker and Stocks 1972), even if one is not on site to witness passage of the fire front.

Units

Fire intensity reported by Byram (1959) was originally and still is, to some extent, expressed in British thermal units per second per foot, (Btu/(s·ft)). The recommended International System (SI) units are kilowatts per metre (kW/m) (Van Wagner 1978). Fire intensity in kilowatts per metre is now used widely by forest fire researchers in Canada (e.g., Van Wagner 1977*a*; Stocks and Alexander 1980) and Australia (e.g., Luke and McArthur 1978; Cheney 1981), and is receiving greater use in the United States (e.g., Nelson and Ward 1980; Rothermel and Deeming 1980).

The units of fire intensity quoted by Smith and James (1978) should have been kilowatts per metre rather than kilowatts per square metre per minute. The following simple unit equation of the factors that are multiplied to obtain fire intensity in kilowatts per metre should clarify the matter (a watt (W) is a joule per second (J/s) and thus conveniently combines energy and time in one unit):

$$[2] \quad \frac{\mathrm{kJ}}{\mathrm{kg}} \times \frac{\mathrm{kg}}{\mathrm{m}^2} \times \frac{\mathrm{m}}{\mathrm{s}} = \frac{\mathrm{kJ}}{\mathrm{m} \times \mathrm{s}} = \mathrm{kW/m}$$

Fire intensity quoted in British thermal units per second per foot can be converted to kilowatts per metre by multiplying by 3.4592 (Van Wagner 1978).

Terminology

Smith and James (1978) refer to four types of intensity: fireline, burn, burning, and fire. The latter three are used interchangeably to denote fire temperatures. The "fireline intensity" denoted in Table 1 of their paper is most commonly termed *Byram's fireline intensity* in literature from the United States (Albini 1976) The preferred term in Canadian forest fire research and management is *frontal fire intensity* (Canadian Committee on Forest Fire Control 1976; Van Wagner 1977*b*, 1978) which distinguishes between line fire intensity and area-fire or reaction intensity (I_R). I_R is the rate of heat release per unit area in the active combustion zone (kilowatts per square metre):

$$[3] \quad I_R = I/D$$

where I is frontal fire intensity (kilowatts per metre) and D is the active horizontal flame depth (metres). *Flame depth* is defined as the distance from the leading edge of the flame front to the rear edge of the solid flaming area (Fig. 1). It is worth noting that fires of varying I and D can produce identical I_R values; however, the resulting fire effects would probably be quite different.

Sample calculation

An illustration of the frontal fire intensity calculation using the data and information reported in Smith and James (1978) follows. Ash-corrected caloric values were determined for each experimental burn plot, but were not reported directly. High heat of combustion, namely 19 583 kJ/kg on average, was deduced from the "energy content and amount of dead biomass combusted" values reported for each fire. The only corrections made to these values were for energy losses due to moisture contained in the fuel. Fuel moisture contents were not reported. On the basis of the available information a minimum value of 15% was assigned to each fire in the absence of such data. Because these low-vigor surface fires were highly efficient, no reductions were made for heat losses due to energy not freed by incomplete combustion nor for radiant energy emitted. Thus, the calculated intensities represent total rates of heat output (i.e., the gross energy dissipated by the principal mechanisms of heat transfer: conduction, radiation, convection). Fuel consumption, assumed to be equivalent to the authors' "amount of dead biomass combusted" which consisted principally of surface litter and downed, dead woody fuels, was measured by pre- and post-fire weight sampling. All four plots were ignited to advance as surface head fires. The quantity "burn duration" quoted by the authors has units of seconds per metre, not seconds per square metre and, as suspected by Van Wagner and Methven (1978), is actually the reciprocal of r in Eq. 1 since the plots were essentially square in shape (45 × 50 m). The component variables and calculated frontal fire intensities in their appropriate units and terms for all four fires are documented here for completeness (Table 1). Rate of spread is quoted in metres per second for clarity in the calculation of frontal fire intensity.

Smith and James' (1978) use of the term "burn duration" with units of seconds per square metre requires clarification at this point. Because a fire moves as a band of finite depth the only valid parameter of duration is the length of time for the flame front to pass a given point, namely, *residence time* (t_R). It has the single dimension time (minutes or seconds) and can be either measured directly in the field (by instrument or observation) or calculated as follows:

$$[4] \quad t_R = D/r$$

where, D is the width of the burning strip or active horizontal flame depth (metres) and r is the fire's rate of spread (metres per minute or metres per second). For example, Kiil (1975) describes the behavior of an experimental fire in a northwestern Alberta black spruce

TABLE 1. Component variables and calculated frontal fire intensities ($I = Hwr$) for the four experimental fires in trembling aspen stands reported by Smith and James (1978)

Burn plot	Net heat of combustion (H) (kJ/kg)	Fuel consumed (w) (kg/m^2)	Rate of spread (r) (m/s)	Frontal fire intensity (I) (kW/m)
1	18 037	0.675	0.038	463
2	17 841	0.750	0.026	348
3	18 002	0.756	0.038	517
4	17 961	0.651	0.026	304

(*Picea mariana* [Mill.] B.S.P.) stand in which the head fire rate of advance was 6.6 m/min and flame depth averaged 3 m. The backfire spread at a rate of 0.5 m/min with a coresponding fire-front depth of 0.8 m. Thus, the computed residence times from Eq. 4 are 0.45 min or 27 s and 1.6 min or 96 s, respectively.

Interpretation

Frontal fire intensity is the energy output (kilowatts) being generated from a strip of the active combustion area, 1 m wide, extending from the leading edge of the fire front to the rear of the flaming zone. Note that expected temperatures at any height above a surface fire can be estimated or calculated if ambient temperature and frontal fire intensity are known (after Van Wagner 1973, 1975):

$$[5] \quad \Delta T{:}3.9(I)^{2/3}/h$$

where, ΔT is the temperature rise above ambient (degrees Celsius), 3.9 (in present units) is a proportionality constant derived empirically from field measurements, I is frontal fire intensity (kilowatts per metre), and h is the height above ground (metres). For example, with the ambient temperatures in Table 1 of Smith and James (1978) and the computed frontal fire intensities, temperatures at 5 m above the surface probably approached 61, 54, 63, and 50°C, respectively.

Characterization

The frontal fire intensities in Table 1 are comparable to those reported by Sando[3] for experimental prescribed fires in six aspen–hardwood stands in northern Minnesota and southern Wisconsin ($\bar{x}$ 240 kW/m; range 93–550 kW/m). The intensities in Table 1 are indicative of the low-intensity surface fire category (McArthur and Cheney 1966) suggested for most prescribed fires. Characterizing fires as low-, moderate-, or high-intensity according to various levels of frontal fire intensity (e.g., Cheney 1981) is a valid and useful form of communication among investigators. A frontal fire intensity of greater than 4000 kW/m is considered a high-intensity fire (McArthur and Cheney 1966; Sando 1978) but such characterization will vary according to the heat tolerance of individual tree species, growth stage, etc.

Flame size relationships

Frontal fire intensity is directly related to many aspects of the flame geometry of the fire front (Luke and McArthur 1978; Nelson 1980). Readers, given frontal fire intensity, may find it useful to calculate the predicted flame length, to conjure up a mental image of the fire's average flame front dimensions. *Flame length* is defined as the distance between the tip of the flame and the ground midway in the zone of active combustion (Fig. 1). An approximate relation between flame length, L (metres), and frontal fire intensity, I (kilowatts per metre), is given by either of the following equations (after Byram 1959, Eq. 3.4):

$$[6] \quad L = 0.0775\ (I)^{0.46}$$

$$[7] \quad L = (I/259.833)^{0.46}$$

For illustration, the average predicted flame lengths for the four fires reported on by Smith and James (1978) would range from 1.1 to 1.4 m.

Equations 6 and 7 can be used by investigators to compare predicted versus observed flame lengths. For example, Sando (see footnote 3) found that predicted flame lengths using Byram's (1959) Eqs. 3.3 and 3.4 agreed well with flame lengths observed on the six fires referred to earlier. They will, however, underpredict flame lengths for crown fires. This can be corrected by adding one-half of the mean canopy height (Byram 1959).

Several fire researchers have used and (or) suggested that frontal fire intensity could be determined from direct observation of flame length (e.g., Sneeuwjagt and Frandsen 1977; Rothermel and Deeming 1980). Solving Eqs. 6 and 7 for I we have:

$$[8] \quad I = L^{2.174}/0.003\,848\,63$$

$$[9] \quad I = 259.833(L)^{2.174}$$

---

[3] Sando, R. W. 1972. Prescribed burning of aspen–hardwood stands for wildlife habitat improvement. Paper presented at the 34th Midwest Fish and Wildlife Conference (December 10–13, Des Moines, IA).

where, I is frontal fire intensity (kilowatts per metre) and L is flame length (metres). Equations 8 and 9 will underestimate intensity in slash fires because the flame length-to-depth ratio is lower than would be the case in fine-fuel fires. In other words, the flame is spread out more and squatter. Other flame length–intensity formulae have been developed empirically but the above equations tend to give more realistic results over a range of frontal fire intensities (Albini 1976). A review and analysis of this subject has been completed recently (Nelson 1980).

Flame length can be indirectly deduced from the height and orientation of the flame front:

$$[10] \quad L = h_F/\sin A$$

$$[11] \quad L = h_F/\cos A_T$$

where, h_F is flame height (metres), A is the flame angle (degrees), and A_T is the flame tilt angle (degrees). *Flame height* represents the maximum vertical extension of the flame front and does not consider the occasional flashes which rise above the general level of the front (Fig. 1). *Flame angle* is defined as the angle formed between the flame front and the unburned fuel bed (Fig. 1). *Flame tilt angle* is defined as the angle formed between the fire front and the vertical (Fig. 1). At very low wind speeds on level terrain, flame length is equatable to the vertical flame height (i.e., $A = 90°$ and $A_T = 0°$). Ryan (1982) has developed an inexpensive and reliable passive sensor for measuring flame height which, along with an estimate of A, can be used to estimate flame length and frontal fire intensity, at least for low- to moderate-intensity prescribed and experimental surface fires.

Correlating with fire effects

Frontal fire intensity alone may not be the appropriate "thermometer" to gauge certain fire effects. In addition to indicating the general nature of a forest fire, frontal fire intensity is best related to direct impact of fire on tree damage and mortality. For instance, Van Wagner (1973) found that the maximum height of lethal scorch of conifer needles to show a very strong relationship ($r^2 = 0.98$) with frontal fire intensity in eastern Ontario pine stands:

$$[12] \quad h_s = 0.1483(I)^{2/3}$$

where h_s is the height of lethal crown scorch (metres) and I is frontal fire intensity (kilowatts per metre). Equation 12 is based on 13 experimental fires and a frontal fire intensity range of 67–1255 kW/m. Similar results are reported in the literature (e.g., McArthur and Cheney 1966; Van Loon 1973; Luke and McArthur 1978).

Discussion

The value of determining fire intensity lies not so much in the exact description of energy, but rather in the provision of numerical data for comparing fires. An average value or estimate is still useful because of the possible range in intensity from fire to fire. In such cases, the estimate of spread rate, which has the greatest bearing on variation in frontal fire intensity, should be based on a length of run sufficient to eliminate short-term fluctuations. The scale of the effect being studied and the size of the study area will dictate the appropriate precision of measurement and specific value(s) of I.

Except for very uniform fuel, weather, and terrain conditions, frontal fire intensity varies in time and space. Smith and James (1978) attempted to account for this variability by estimating the standard deviation of I by differences in measured fuel consumption in an existing heterogeneous surface fuel bed. In discussing the variance in frontal fire intensity, rate of spread would have to be considered as well. It is possible to describe frontal fire intensity in simple statistical terms by plotting its distribution in relation to percentage of burned area. For example, Van Loon (1973) mapped the frontal fire intensity pattern of an experimental prescribed fire in a 1.2-ha slash pine (*Pinus elliottii* Engelm.) plantation plot. Five intensity classes were delineated at 86 kW/m (25 Btu/(s·ft.)) intervals. A tabulation of that information appears in Table 2. Van Loon (1973) calculated the mean frontal fire intensity for the plot to be 125 kW/m.

Despite a critical review of Byram's (1959) concept of fire intensity by Tangren (1976), it remains the best single objective description of the fire front (Van Wagner 1977*b*). It does have its limitations. Frontal fire intensity does not necessarily describe the total energy or heat released in a forest fire. After passage of the flaming front, considerable burning may take place (Fig. 1). Thus, the length of time that fire persists over an area is not entirely synonymous with residence time, t_R, except for fine, loosely compacted, homogeneous fuels. The duration of combustion is referred to as the *burn-out time* which is defined simply as the "... time taken for all fractions of the fuel bed to burn out" (Cheney 1981). Burn-out time t_B (seconds or minutes) is difficult to ascertain but can be measured with thermocouples or estimated from the product of H (kilojoules per kilogram) and total fuel consumed or w_T (kilograms per square metre), and combustion rate C (kilowatts per square metre) as follows (from McArthur and Cheney 1966):

$$[13] \quad t_B = Hw_T/C$$

Combustion rate is defined as the heat release per unit burning area per unit of time (Byram 1959) and is related primarily to fuel size, arrangement, and moisture content. The principal distinction between C and I_R is in the computation (from Cheney 1981):

[14] $C = Hw/t_R$

Combustion rates have been derived, from experimental fire-behavior field studies, for several Australian fuel beds by McArthur and Cheney (1966) but are noticeably lacking for North American complexes. The total energy or heat release per unit area E (kilojoules per square metre) in a forest fire is simply a reflection of total fuel consumed (i.e., Hw_T). When $t_B \simeq t_R$ then the product of Hw will approximate E.

There is little doubt that fire effects are greatly dependent upon fire behavior. Because there are many aspects of fire behavior, there are also many quantitative descriptors. The fire-behavior characteristic(s) selected as a correlation parameter must have a logical relationship to the effect being studied. For example, nutrient effects are probably best gauged by the degree of fuel consumption, a measure directly related to the quantity of organic matter ashed by the fire process (Van Wagner and Methven 1978).

Responses by minor vegetation following fire, and seedbed conditions for tree regeneration, are directly influenced by depth of burn (Van Wagner 1963; Chrosciewicz 1974; Shearer 1975, 1976; Miller 1977). *Depth of burn* represents the degree of reduction in organic-layer thickness due to consumption by the fire process (Fig. 1) which in turn determines postfire organic-layer depth and percentage of mineral soil exposure. It is generally stated as the thickness (centimetres) removed (McRae *et al.* 1979). Other expressions of depth of burn include weight removed and percent reduction of the initial layer. Since it is a function of the degree of dryness throughout the organic layer (Van Wagner 1972*a*; Sandberg 1980), which correspondingly is associated with relatively long-term weather, depth of burn is somewhat independent of the spread rate and therefore of frontal fire intensity. Depth of burn is also an adequate substitute for total energy release and burn-out time where the principal surface fuel is "duff."

To be of any use, observational data on forest fire behavior must be related to the prefire and present burning conditions (e.g., Stocks and Walker 1972; Quintilio *et al.* 1977). The Canadian Forest Fire Weather Index and its component codes and indexes (Van Wagner 1974; Van Wagner and Pickett 1975; Anonymous 1978; Turner and Lawson 1978) are effective integrators of past and current weather influences on burning conditions. By quoting these values (preferably calculated from on-site or nearby weather observations) for experimental fires (e.g., Methven and Murray 1974; Kiil 1975), operational prescribed fires (e.g., Chrosciewicz 1976) or wildfires (e.g., Walker and Stocks 1972) one can understand and (or) duplicate the burning conditions that have occurred. It is possible to calculate values for past fires if suitable historical data are available (e.g., Methven *et al.* 1975).

TABLE 2. Distribution of frontal fire intensities experienced in a 1.2-ha slash pine plantation plot (adapted from Van Loon 1973)

Class	Frontal fire intensity (kW/m)	Proportion of area (%)
I	<86	8
II	86–173	56
III	173–259	26
IV	259–346	7
V	346–432	3

Concluding remarks

Many biologists and ecologists view fire as a binary event: an area burned or it did not. Fire scientists might list a multitude of quantitative fire descriptors, some of which could be useful in understanding and predicting fire effects. On the other hand, environmental scientists should be looking at some variables connected with fire occurrence other than presence or absence. Prediction of the biological and ecological effects of fire must ultimately be linked to quantitative characteristics of fire behavior.

Acknowledgments

I wish to thank K. C. Ryan and C. E. Van Wagner for their comments on an earlier draft of this article and subsequent discussions.

ALBINI, F. A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Res. Note INT-30.

ALEXANDER, M. E. 1981. Bibliography supplement to CFS prescribed burn handbook. Ont. Minis. Nat. Resour., Aviat. Fire Manage. Cent., Fire Manage. Bull. 88.

ANONYMOUS. 1978. Canadian Forest Fire Weather Index tables. 3rd ed. Can. For. Serv. For. Tech. Rep. 25.

BROWN, A. A., and K. P. DAVIS. 1973. Forest fire: control and use. 2nd ed. McGraw-Hill, New York.

BYRAM, G. M. 1959. Combustion of forest fuels. *In* Forest fire: control and use. *Edited by* K. P. Davis. McGraw-Hill, New York. pp. 61–89.

CANADIAN COMMITTEE ON FOREST FIRE CONTROL. 1976. Glossary of forest fire control terms. 3rd ed. Natl. Res. Counc. Can., Publ. No. 15520.

CHENEY, N. P. 1981. Fire behaviour. *In* Fire and the Australian Biota. Austalian Academy of Science, Canberra. A.C.T. pp. 151–175.

CHROSCIEWICZ, Z. 1974. Evaluation of fire-produced seedbeds for jack pine regeneration in central Ontario. Can. J. For. Res. **4**: 455–457.

——— 1976. Burning for black spruce regeneration on a lowland cutover site in southeastern Manitoba. Can. J. For. Res. **6**: 179–186.

GILMOUR, D. A., and N. P. CHENEY. 1968. Experimental prescribed burn in radiata pine. Aust. For. **32**: 171–178.

HOUGH, W. A. 1969. Caloric value of some forest fuels of the southern United States. U.S. For. Serv. Southeast. For. Exp. Stn. Res. Notes SE-110.

JAMES, T. D. W., and D. W. SMITH. 1977. Short-term effects of surface fire on the biomass and nutrient standing crop of *Populus tremuloides* in southern Ontario. Can. J. For. Res. **7**: 666–679.

KIIL. A. D. 1969. Fuel consumption by a prescribed burn in spruce-fir logging slash in Alberta. For. Chron. **45**: 100–102.

——— 1970. Effects of spring burning on vegetation in old partially cut spruce–aspen stands in east-central Alberta. Can. For. Serv. Rep. A-X-23.

——— 1971. Prescribed fire effects in subalpine spruce-fir slash. Inf. Rep. NOR-X-3. Can. North. For. Res. Cent.

——— 1975. Fire spread in a black spruce stand. Bi-Mon. Res. Notes, Can. For. Serv. **31**: 2–3.

KIIL, A. D., and J. E. GRIGEL. 1969. The May 1968 forest conflagrations in central Alberta—a review of fire weather, fuels and fire behavior. Can. For. Serv. Rep. A-X-24.

LAWSON, B. D. 1973. Fire behavior in lodgepole pine stands related to the Canadian Fire Weather Index. Can. For. Serv. Pac. For. Res. Cent. Rep. BC-X-76.

LUKE, R. H., and A. G. MCARTHUR. 1978. Bushfires in Australia. Aust. Gov. Publ. Serv. Canberra. A.C.T.

MCARTHUR, A. G., and N. P. CHENEY. 1966. The characterization of fires in relation to ecological studies. Aust. For. Res. **2**(3): 36–45.

MCRAE, D. J., M. E. ALEXANDER, and B. J. STOCKS. 1979. Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Can. For. Serv. Rep. O-X-287.

METHVEN, I. R. 1978. Fire research at the Petawawa Forest Experiment Station: the integration of fire behaviour and forest ecology for management purposes. *In* Proceedings of the Fire Ecology in Resource Management Workshop. Inf. Rep. NOR-X-210. Can. North. For. Res. Centr. pp. 23–27.

METHVEN, I. R., and W. G. MURRAY. 1974. Use of fire to eliminate understory balsam fir in pine management. For. Chron. **50**: 77–79.

METHVEN, I. R., C. E. VAN WAGNER, and B. J. STOCKS. 1975. The vegetation on four burned areas in northwestern Ontario. Can. For. Serv. Inf. Rep. PS-X-60.

MILLER, M. 1977. Response of blue huckleberry to prescribed fires in a western Montana larch-fir forest. U.S. For. Serv. Res. Pap. INT-188.

MURARO, S. J. 1971. Prescribed-fire impact in cedar–hemlock logging slash. Can. For. Serv. Publ. No. 1295.

NELSON, R. M., JR. 1980. Flame characteristics for fires in southern fuels. U.S. For. Serv. Res. Pap. SE-205.

NELSON, R. M., JR., and D. E. WARD. 1980. Backfire particulate emissions and Byram's fire intensity. U.S. For. Serv. Southeast. For. Exp. Stn. Res. Notes SE-290.

OHMANN, L. F., and D. F. GRIGAL. 1979. Early revegetation and nutrient dynamics following the 1971 Little Sioux forest fire in northeastern Minnesota. For. Sci. Monogr. **21**: 1–80.

QUINTILIO, D., G. R. FAHNESTOCK, and D. E. DUBÉ. 1977. Fire behavior in upland jack pine: the Darwin Lake Project. Inf. Rep. NOR-X-174. Can. North. For. Res. Centr.

RANDALL, A. G. 1966. A prescribed burn following a clearcut in the spruce type. Univ. Maine, Agric. Exp. Stn., Misc. Publ. 675.

ROTHERMEL, R. C., and J. E. DEEMING. 1980. Measuring and interpreting fire behavior for correlation with fire effects. U.S. For. Serv. Gen. Tech. Rep. INT-93.

RYAN, K. C. 1982. Evaluation of a passive flame-height sensor to estimate forest fire intensity. U.S. For. Serv. Res. Note PNW-390. In press.

SANDBERG, D. V. 1980. Duff reduction by prescribed underburning in Douglas-fir. U.S. For. Serv. Res. Pap. PNW-272.

SANDO, R. W. 1978. Natural fire regimes and fire management—foundations for direction. West. Wildlands, **4**(4): 34–44.

SCHINDLER, D. W., R. W. NEWBURY, K. G. BEATY, J. PROKOPOWICH, T. RUSZCZYNSKI, and J. A. DALTON. 1980. Effects of a windstorm and forest fire on chemical losses from forested watersheds and on the quality of receiving streams. Can. J. Fish. Aquat. Sci. **37**: 328–334.

SHEARER, R. C. 1975. Seedbed characteristics in western larch forests after prescribed burning. U.S. For. Serv. Res. Pap. INT-167.

——— 1976. Early establishment of conifers following prescribed broadcast burning in western larch – Douglas-fir forests. Proceedings of the Annual Tall Timbers Fire Ecology Conference. Vol. 14. pp. 481–500.

SMITH, D. W., and T. D. JAMES. 1978. Characteristics of prescribed burns and resultant short-term environmental changes in *Populus tremuloides* woodland in southern Ontario. Can. J. Bot. **56**: 1782–1791.

SNEEUWJAGT, R. J., and W. H. FRANDSEN. 1977. Behavior of experimental grass fires vs. predictions based on Rothermel's fire model. Can. J. For. Res. **7**: 357–367.

STOCKS, B. J., and M. E. ALEXANDER. 1980. Forest fire behaviour and effects research in northern Ontario: a field oriented program. *In* Proceedings of the Sixth Conference on Fire and Forest Meteorology. April 22–24, Seattle, WA. Society of American Foresters, Washington, D.C. pp. 18–24.

STOCKS, B. J., and J. D. WALKER. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Can. For. Serv. Inf. Rep. O-X-169.

TANGREN, C. D. 1976. The trouble with fire intensity. Fire Technol. **12**: 261–265.

TURNER, J. A., and B. D. LAWSON. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Can. For. Serv. Pac. For. Res. Cent. Rep. BC-X-177.

VAN LOON, A. P. 1973. A prescribed burning experiment in young slash pine. I. Site description and establishment. N.S.W. For. Comm. Res. Note. No. 25. pp. 1–30.

VAN WAGNER, C. E. 1962. On the value of a numerical concept of fire intensity. Pulp Pap. Mag. Can. **63**: 458–459.

——— 1963. Prescribed burning experiments: red and white pine. Can. For. Branch Dep. Publ. No. 1020.

——— 1965*a*. Describing forest fires—old ways and new. For. Chron. **41**: 301–305.

——— 1965*b*. Story of an intense crown fire at Petawawa. Pulp Pap. Mag. Can. **66**: 358–361.

——— 1970*a*. On the value of temperature data in forest fire research. Can. For. Serv. Intern. Rep. PS-20.

——— 1970*b*. Temperature gradients in duff and soil during prescribed fires. Can. Dep. Fish. For. Bi-Mon. Res. Notes, **26**: 42.

——— 1972*a*. Duff consumption by fire in eastern pine stands. Can. J. For. Res. **2**: 34–39.

——— 1972*b*. Heat of combustion, heat yield and fire behaviour. Can. For. Serv. Inf. Rep. PS-X-35.

——— 1973. Height of crown scorch in forest fires. Can. J. For. Res. **3**: 373–378.

——— 1974. Structure of the Canadian Forest Fire Weather Index. Can. For. Serv. Publ. No. 1333.

——— 1975. Convection temperatures above low-intensity forest fires. Bi-Mon. Res. Notes Can. For. Serv. **31**: 21. (Erratum, **31**: 36.)

——— 1977*a*. Conditions for the start and spread of crown fire. Can. J. For. Res. **7**: 23–34.

——— 1977*b*. *In* Readers' forum. Fire Technol. **13**: 349–350.

——— 1978. Metric units and conversion factors for forest fire quantities. Can. For. Serv. Inf. Rep. PS-X-71.

VAN WAGNER, C. E., and I. R. METHVEN. 1978. Discussion: two recent articles on fire ecology. Can. J. For. Res. **8**: 491–492.

VAN WAGNER, C. E., and T. L. PICKETT. 1975. Equations and Fortran IV program for the 1976 metric version of the Forest Fire Weather Index. Can. For. Serv. Inf. Rep. PS-X-58.

WALKER, J. D., and B. J. STOCKS. 1972. Analysis of two 1971 wildfires in Ontario: Thackeray and Whistle Lake. Can. For. Serv. Inf. Rep. O-X-166.

Appendix

List of symbols, quantities and units

The symbols used in this paper are a blend of simplicity and the most commonly accepted nomenclature and terminology reviewed in numerous sources. Original abbreviations and definitions have been retained in most instances. SI units are generally used for forest fire quantities for which approved standards exist

Symbol	Quantity	Units
A	Flame angle	degrees
A_T	Flame tilt angle	degrees
C	Combustion rate	kW/m^2
D	Flame depth	m
DOB	Depth of burn	cm
E	Total energy release per unit area	kJ/m^2
h	Height at temperature rise ΔT	m
h_F	Flame height	m
h_s	Lethal scorch height	m
H	Low heat of combustion	kJ/kg
I	Frontal fire intensity	kW/m
I_R	Area-fire or reaction intensity	kW/m^2
L	Flame length	m
r	Rate of spread	m/s or m/min
t_B	Burn-out time	s or min
t_R	Residence time	s or min
ΔT	Temperature rise above ambient	°C
w	Weight of fuel consumed per unit area during the active combustion phase	kg/m^2
w_T	Weight of total fuel consumed per unit area	kg/m^2