STRUCTURE OF THE CANADIAN FOREST FIRE WEATHER INDEX

by

C.E. Van Wagner
Petawawa Forest Experiment Station
Chalk River, Ontario

Résumé en français

DEPARTMENT OF THE ENVIRONMENT
Canadian Forestry Service
Publication No. 1333
Ottawa, 1974

Issued under the authority of the
Honourable Jack Davis, P.C., M.P.,
Minister, Environment Canada

INFORMATION CANADA
Catalogue No. Fo47-1333
OTTAWA, 1974

PRINTED IN CANADA

THE PRINT SHOPPE LTD.
Contract No. 0KT4-0300

ABSTRACT

The Canadian Forest Fire Weather Index (FWI) was issued in 1970 after several years' work by a number of fire researchers in the Canadian Forestry Service. The best features of the former fire danger index were incorporated in the FWI, and a link was preserved between old and new. The FWI is based on the moisture content of three classes of forest fuel plus the effect of wind on fire behavior. It consists of six components: three primary subindexes representing fuel moisture, two intermediate subindexes representing rate of spread and fuel consumption, and a final index representing fire intensity as energy output rate per unit length of fire front. The FWI refers primarily to a standard pine fuel type but is useful as a general index of forest fire danger in Canada. It is determined every day from noon weather readings only: temperature, relative humidity, wind speed, and rain (if any).

This paper describes the development of the Fire Weather Index, the concepts behind it, and its mathematical structure.

RÉSUMÉ

L'Indice Forêt-Météo (IFM), ou Forest Fire Weather Index (FWI), est un indice des conditions météorologiques propices aux incendies de forêts. Il fut publié en 1970 après plusieurs années de travaux par des agents de recherche du Service canadien des forêts. Les meilleures caractéristiques de l'ancien Indice de danger de feu furent incorporées au nouvel indice et un lien fut conservé entre l'ancien et le nouveau. L'IFM est fondé sur la teneur en humidité de trois classes de combustibles forestiers, plus l'effet du vent sur le comportement du feu. Il consiste en six composantes: trois sous-indices primaires représentant l'humidité du combustible, deux sous-indices intermédiaires représentant le taux de propagation du feu et la consommation des combustibles, et un indice final représentant l'intensité du feu sous forme du taux de rendement d'énergie par unité de longueur. Ce nouvel Indice se réfère fondamentalement à une forêt standard de pin mais sert utilement comme indice général du danger d'incendies de forêts au Canada. C'est par des observations journalières des conditions météorologiques, à midi, qu'on le rédige: température, humidité relative, vitesse du vent et pluviosité (si elle existe).

Cet article décrit le développement de l'IFM, les concepts qui ont présidé à sa préparation, et sa structure mathématique.

PREFACE

The Fire Weather Index described in this publication is the result of four years' effort, in which a large number of fire research staff of the Canadian Forestry Service took part in varying degrees. The principal work was done by S.J. Muraro and J.A. Turner of the Pacific Forest Research Centre, A.J. Simard of the Forest Fire Research Institute, and C.E. Van Wagner of the Petawawa Forest Experiment Station. D.E. Williams, Director of the Forest Fire Research Institute, acted as coordinator of the project, which involved voluminous correspondence and several full-scale meetings. Others who contributed in various ways and gave advice and opinion as the index developed include R.C. Henderson, B.D. Lawson, and R.N. Russell of the Pacific Forest Research Centre, A.D. Kiil and J.E. Grigel of the Northern Forest Research Centre, B.J. Stocks and J.D. Walker of the Great Lakes Forest Research Centre, E.W. Howard of the Newfoundland Forest Research Centre, and D.G. Fraser, L.B. MacHattie, P.M. Paul, and Gy. Péch of the Forest Fire Research Institute. Finally, J.C. Macleod, Program Coordinator for Forest Fire Research, provided beneficial influence and support throughout.

CONTENTS

STRUCTURE OF THE CANADIAN FOREST FIRE WEATHER INDEX

INTRODUCTION

Since research on forest fire danger rating was begun in Canada by J.G. Wright in 1928, the value of keeping track of the day-to-day susceptibility of the forest to fire has gained virtually complete acceptance throughout the nation. During the ensuing several decades, Wright, his colleague H.W. Beall, and their successors developed four different fire danger systems with increasingly universal applicability across Canada. Type references for these are (1) Wright (1933), (2) Wright and Beall (1938) with supplement by Beall (1939), (3) Beall (1948), and (4) Anon. (1957). During the decade following 1957, additional versions of the fourth system were issued for the various regions of Canada, each version based on field research in the fuel types of local importance (Anon. 1959, Kiil and MacTavish 1962, Paul and MacTavish 1965, and MacTavish 1965).

Much space would be required to present the full history of research on forest fire danger rating in Canada, and this is not necessary for present purposes. Although Beall's (1947) account covers the early years very well, three concepts are nevertheless worth emphasizing. First, the development process was one of evolution in which certain features, even though modified, were retained from system to system. Second, there was a trend toward simplification in both the required weather measurements and the method of calculation, which culminated in the fourth system. Third, the approach throughout was to base the danger ratings on field experiments analyzed by empirical mathematics; physical theory, while used qualitatively to good advantage in the design of the experiments, was not used directly in the analysis leading to the final results. As a result of this philosophy, there exists a great body of field data of three kinds: weather readings, fuel moisture contents, and small test-fire ratings, all linked together. It is on this foundation that all the foregoing systems of fire danger rating rest.

The field practices used to collect field data for danger rating were described by Paul (1969), and the procedures for day-to-day operations by Williams (1964). All research data on file have been catalogued and organized for modern computer analysis by Simard (1970).

As of 1969, the fourth system (in nine different versions) was in almost universal use across Canada. Its basic features were:

1. noon weather readings of rain, relative humidity, and wind (temperature as well in several of the later versions);

2. separate fire danger indexes for different seasons;

3. fine fuel moisture content estimated from day to day with the previous day's as the starting point;

4. long-term weather effects measured by a drought index in terms of days since a rainfall of about 0.6 inch, to a limit of 25 days;

5. fine fuel moisture and drought blended to give fire danger on a scale of 0 to 16, with five classes (Nil, Low, Moderate, High, and Extreme);

6. in the later versions only, a correction for the effect of wind on fire behavior;

7. subsidiary hazard indexes for specific fuel types such as "fast-drying," slash, grass, and reindeer lichen (*Cladonia*).

In recent years, the forest fire control agencies have become more and more sophisticated and have made increasing demands on this fire danger system in ways that were not foreseen during its development in the mid-50's. In response to comments and requests from a number of provincial fire control agencies, development of a new fire danger rating index was undertaken. It was called the Canadian Forest Fire Weather Index after a suggestion by J.C. Macleod, and its basic form was proposed by Muraro (1968). The aim throughout the project was to use as much of the previous fire danger work as possible, by building on the best features and adding new components where necessary. The Fire Weather Index thus retains a solid link with previous systems and is, in effect, a further step along the line taken in 1928 by J.G. Wright when he began Canadian forest fire research.

THE BASIC STRUCTURE OF THE FIRE WEATHER INDEX

The Fire Weather Index (FWI) consists of six components: three primary, two intermediate, and, finally, one representing the intensity of a single fire in a standard fuel type (Fig. 1). The three primary components are subindexes that follow from day to day the moisture contents of three classes of forest fuel of different drying rates. The two intermediate components are subindexes representing rate of spread and amount of available fuel. The system depends solely on weather readings taken each day at solar noon: temperature, relative humidity, wind speed, and rain (if any) during the previous 24 hours. In basic form, the FWI is a set of equations that can be readily processed by computer; this is in contrast to previous systems, in which the basic form was always a set of curves that were converted directly to tables. The FWI can also be worked out from the published set of 10 tables derived directly from these equations (Anon. 1970). A brief, nontechnical description already exists (Van Wagner 1970a).

It should be stressed that although the FWI is calculated from noon weather readings, it really represents fire danger at the midafternoon

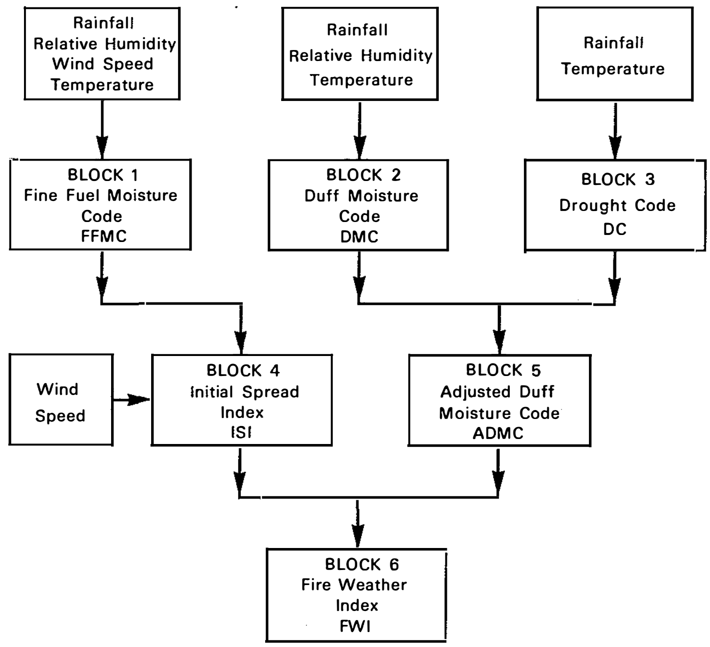

Figure 1. Block diagram of Fire Weather Index.

peak, say 1400 to 1600 hours. This comes about because in the original work the noon weather variables were correlated with fine fuel moisture data and test-fire results taken later in the afternoon. In this respect, the FWI is similar to all previous Canadian systems used since 1938.

For each of the three fuels embodied in the FWI a subsidiary index was developed with two phases, one for wetting by rain and one for drying. These subindexes, called moisture codes, are in fact bookkeeping systems that add moisture after rain and subtract some for each day's drying. They are arranged in code form with values rising with decreasing moisture content for the best psychological effect. The three moisture codes and their corresponding fuels are:

1. *Fine Fuel Moisture Code (FFMC)*, which represents the moisture content of litter and other cured fine fuels in a forest stand, in a layer of dry weight about 0.05 lb/ft^2;

2. *Duff Moisture Code (DMC)*, which represents the moisture content of loosely compacted, decomposing organic matter 2 to 4 inches deep and weighing about 1 lb/ft^2 when dry;

3. *Drought Code (DC)*, which represents a deep layer of compact organic matter weighing perhaps 10 lb/ft^2 when dry.

While these descriptions are useful for explanatory purposes, comparison of the moisture codes is best made in terms of water capacity and drying speed. Each fuel is considered to dry exponentially, so that the instantaneous drying rate is proportional to the current free moisture content. The proper measure of drying speed is then either the time constant (i.e. time to lose 1-1/*e* [about 2/3] of the free moisture above equilibrium), or the slope of the exponential curve, called here the log drying rate. Table 1 gives for each moisture code the time constant in terms of normal days with noon temperature and relative humidity at 70°F and 45%, as well as water capacity and daily weather parameters required for operation.

TABLE 1. PROPERTIES OF THE THREE MOISTURE CODES

Code	Time constant, days	Water capacity, inches	Required weather parameters[1]
FFMC	2/3	0.01 - 0.02	T, H, W, r
DMC	12	0.58	T, H, r
DC	52	8	T, r

[1]T - temperature, H - humidity, W - wind, r - rain.

The two slow-reacting moisture codes, the DMC and the DC, respond also to the changing day length as the season progresses. This feature is necessary because the amount of moisture lost daily by slow-drying fuels is as much dependent on the time available as on the atmospheric conditions. The midafternoon moisture content of fast-drying fuels, represented by the FFMC, is less dependent on day length.

The three moisture codes plus wind are linked in pairs to form two intermediates that are in turn combined to yield the final index, the FWI. These last three components are:

Initial Spread Index (ISI), a combination of wind and the FFMC that represents rate of spread alone without the influence of variable quantities of fuel;

Adjusted Duff Moisture Code (ADMC), a combination of the DMC and the DC that represents the total fuel available to the spreading fire;

Fire Weather Index (FWI), a combination of the ISI and the ADMC that represents the intensity of the spreading fire as energy output rate per unit length of fire front.

Each of these components involves mathematical functions described in later sections, and each component has an appropriate scale. The function of wind in the ISI is a simple exponential that doubles the FWI for every increase of 12 mph. The functions of fine fuel moisture and duff moisture are similar to those found in the previous fire danger system. Long-term drought effect was worked in by giving the DC a small but variable weight as an adjustment to the DMC.

The so-called standard fuel type can be described as a generalized pine forest, most nearly the jack pine and lodgepole pine type, which is found in an almost continuous band across Canada. This concept fits the nature of the field data that form the foundation for the FWI. Actually, fuel-moisture data and fire-behavior data from red and white pine stands and red pine plantations were used as well in the development of the FWI. It was, however, decided early in the process that the main goal was a new fire danger index based on weather only that could be used to give uniform results all across Canada. The question of how fire behavior varies with fuel type was judged to be a separate problem, to be tackled in other ways.

In the following sections of this paper, the three moisture codes and the three final components are each described in turn. Finally, there are sections on the interpretation and performance of the FWI and on its future use and development. The procedures and reasoning used in the development are recounted where needed to shed light on the various decisions. The equations are also included in order as integral parts of the story. However, a reader desiring only the mathematical structure may find all equations listed in Appendix II, together with rules for their use. The symbols and abbreviations are identified as they are introduced, and those appearing in the numbered equations are also listed in Appendix I. Natural logarithms (to base e) are indicated by "ln."

THE FINE FUEL MOISTURE CODE

Background

The ancestor of the Fine Fuel Moisture Code (FFMC or F) is the Tracer Index for litter that first appeared as the principal component of an early fire danger rating system for eastern pine forests (Wright 1937). The Tracer Index was developed from concurrent weather and fuel-moisture data obtained in pine stands at Petawawa, by multiple correlation of present moisture content with current weather and the previous day's moisture content. The fuel represented was a layer of pine needles or other surface litter, probably about 0.05 lb/ft^2. This fuel can be called relatively fast-drying, but the substantial effect of the previous day's value meant that drying time was by no means instantaneous. In subsequent years, this Tracer Index was found by various fire researchers to correlate well with litter moisture contents in many parts of Canada; it was therefore retained as an integral part of all subsequent fire danger tables issued by the federal forest research organization. The particular version of the Tracer Index chosen for this work appears in Beall's (1948) Forest Fire Danger Tables. The special needs of the new system required analysis and modification of the original Tracer Index, carried out in the following manner:

Scale

The original Tracer Index was presented in the simple code form 150 minus moisture content. Since the highest and lowest tracer values were 144 and 40, the scale length was 104. For the present system, a two-digit code was desired with a maximum value of 99; the scale length is thus five points less than the original. At the same time, the minimum value of moisture content (m) was set at 2%, and the resulting scale equation of the FFMC is

$$F = 101 - m \tag{1}$$

Drying Phase

The first step was to list a series of day-to-day drying sequences, each at constant relative humidity (H), wind (W), and temperature (T), by starting at saturation and repeatedly entering the Tracer Index tables until no further change occurred. The resulting equilibrium moisture content (E) for each drying sequence was subtracted from the day-to-day moisture contents (M) and the free moisture contents were plotted as log (M-E) against time in days. In this way, a set of six semilog curves at different wind speeds was obtained for each of eight humidity classes, all for the temperature class 60 to 80°F, i.e. 70°F. It was observed that, on the whole, these semilog lines were straight enough for exponential drying to be assumed. In other words, the rate of change from day to day could be described by the slope of the semilog drying curve, called the log drying rate (k) and expressed in units of log moisture content per day.

Second, values of k were calculated for the 48 semilog curves, then plotted against W in classes of H, and finally harmonized in the form

$$k = a + b\, W^{0.5}$$

where a and b are functions of H arranged to equal zero when H = 100. Use of the square root of wind here gives more emphasis to the lower part of the wind-speed range, where the effect on the log drying rate is relatively greatest. The complete equation for the normal temperature of 70°F is

$$k = 0.424\ [1-(H/100)^{1.7}] + 0.088\ W^{0.5}\ [1-(H/100)^{8}] \tag{2}$$

The variation of k with H is shown in Fig. 2 at two different wind speeds. For example, when H is 20 and W is 10, k is 0.672; when H is 90 and W is 0, k is only 0.073. These values of k are in terms of $\log_{10}$ and can be converted to time constant in days by dividing them into 0.4343.

Third, the process of atmospheric wetting at high humidity in the Tracer Index was examined. By starting at maximum dryness, semilog curves of day-to-day increases in moisture were obtained analogous to the drying curves. The variation in slope with humidity and wind was slight enough that a constant value of k = 0.3 was adopted.

Fourth, the curve of equilibrium moisture content E against humidity H was smoothed and modified partly in accordance with laboratory data for several kinds of forest litter (Fig. 3). In the original Tracer Index, values obtained for E by wetting were 1 to 2% lower than those obtained by drying. This hysteresis was retained in the present system. The new E curve, however, was made independent of wind speed, in contrast to the original. This was done partly for simplicity's sake and partly because in

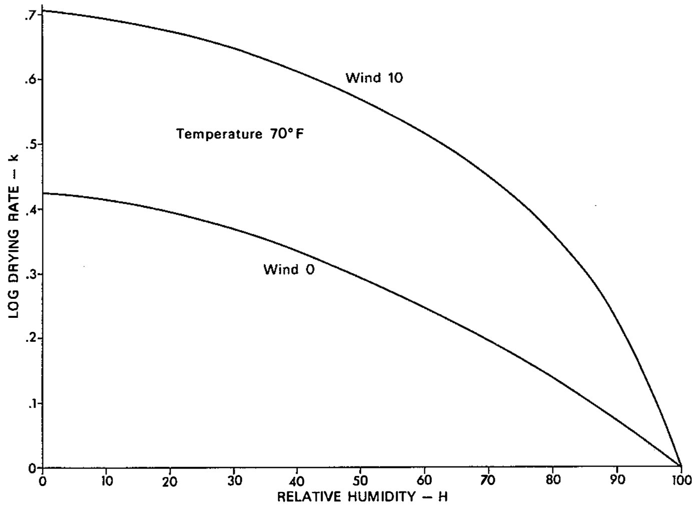

Figure 2. Relation of fine fuel log drying rate k with relative humidity H at two different wind speeds.

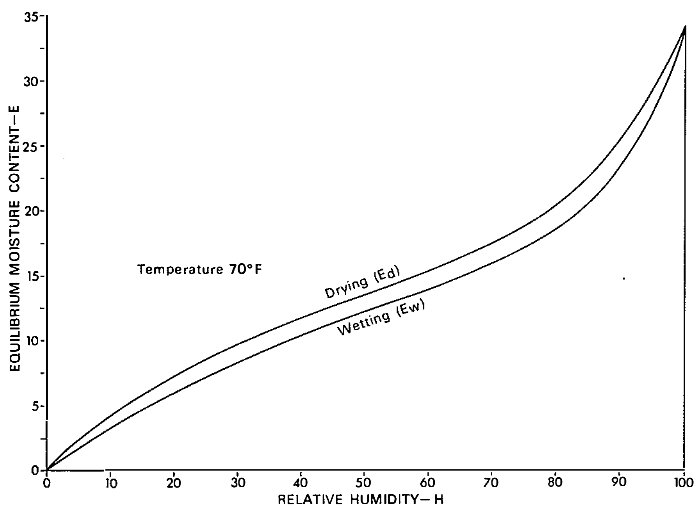

Figure 3. Relation between equilibrium moisture content E and relative humidity in FFMC.

theory E should depend only on H and T. The following equations for E were supplied by J.A. Turner, one for drying (E_d) and one for wetting (E_w). Each is in terms of H for the normal temperature 70°F.

$$E_d = 0.942\ H^{0.679} + 11\ e^{(H-100)/10} \quad (3)$$

$$E_w = 0.597\ H^{0.768} + 14\ e^{(H-100)/8} \quad (4)$$

If yesterday's moisture content (m_o) turns out to be higher than E_d, a drying regime prevails and present day's moisture content (m) is found from

$$\ln\ (m-E_d) = \ln\ (m_o - E_d) - 2.303\ k \quad (5)$$

If m_o turns out to be less than E_w,

$$\ln (E_w - m) = \ln (E_w - m_o) - 0.69 \qquad (6)$$

Fifth, a temperature effect was designed in two parts. The variation in k due to temperature in the original Tracer Index was deemed too slight, being only about 15% for a 20°F change. Some laboratory evaluations of k for pine needles showed a 50% change every 20°F, and this level of effect was accepted as more reasonable. Also, the original Tracer Index showed no variation in E with temperature, but laboratory data indicated that every 10°F change produced a shift in E of about 1% in the opposite direction. Separate effects on k and E would undoubtedly provide the most logical influence of temperature on fine fuel moisture content and are easily applied mathematically. The required functions would be

$$\text{Factor for k, } 0.242\, e^{0.0202T} \qquad \text{(A)}$$

$$\text{Additive for E, } (70-T)/10 \qquad \text{(B)}$$

Such a scheme, however, would require a separate drying table for each temperature range, an undesirable complication in the published tabular version of the FWI. A test was therefore carried out to determine how much the foregoing combined effect varied with humidity. The tested temperatures were 50, 70, and 90°F, each at 20, 42, 62, and 82% humidity. The amount of variation of the combined temperature effects with H was judged to be minor, and it was decided to present a single table for the temperature effect. An empirical equation giving the amount to be added to or subtracted from the FFMC was designed in terms of the previous day's FFMC, and based on zero effect at 70°F:

$$\Delta F = (T-70)\ (0.63 - 0.0065\ F_o) \qquad (7)$$

Finally, the FFMC is obtained by adding the temperature correction ΔF to the uncorrected value F_1:

$$F = F_1 + \Delta F \qquad (8)$$

Note: After several years testing and experience, it has become apparent that the FFMC's drying phase would be more logical and truer to physical concepts if humidity and temperature were combined in one table with wind as the separate correction. A new drying table for fine fuel has therefore been designed in which temperature T replaces wind W. For table calculation, wind is given a constant value of 8, and the temperature effect is applied on both the drying rate k and the equilibrium moisture content E, by using the functions A and B referred to above. This change renders the temperature effect more logical, and the less important wind effect can then be applied through a separate table in the manner of the present temperature correction. The second edition of the Fire Weather Index tables will incorporate these changes.

It is well recognized, of course, that fine fuel moisture content undergoes a strong wavelike variation over the 24-hour daily cycle. After the fuel is wet by rain, this diurnal wave is superimposed on the general drying trend until day-to-day equilibrium has been achieved. The drying phase of the FFMC thus clearly describes the afternoon state only, and another means is required to estimate fine fuel moisture content at other times of day. Muraro *et al.* (1969) have designed such a scheme, further developed into a Diurnal FFMC Table for general use by Van Wagner (1972b). Following still earlier work by Péch,[1] this table shows that the effect of low overnight humidity on fine fuel moisture, while very apparent during the morning, is no longer important by midafternoon.

Rainfall Phase

Next, the effect of rain in the Tracer Index was examined. It was apparent from the original rainfall table that, as the size of the rainfall increased, a smaller and smaller proportion of the total rain was held by the litter. J.A. Turner supplied the following set of empirical equations to match this table. Duration of rainfall, a refinement in the original Tracer Index, has been omitted from the present work. The first 0.02 inch of rain is assumed to have no effect.

$$F_r = (F_o/100)\, f(r_o) + 1 - C \qquad (9)$$

where $f(r_o)$ is given by three equations for different ranges of r_o:

$$f(r_o) = -56 - 55.6 \ln (r_o + 0.04),\ 0.02 < r_o < 0.055 \qquad (10a)$$

$$f(r_o) = -1 - 18.2 \ln (r_o - 0.04),\ 0.055 < r_o < 0.225 \qquad (10b)$$

$$f(r_o) = 14 - 8.25 \ln (r_o - 0.075),\ r_o > 0.225 \qquad (10c)$$

and

$$C = 8.73\, e^{-0.1117\, F_o} \qquad (11)$$

The moisture increase due to rain is assumed to occur always before the day's drying commences. The equations making up the FFMC are listed again in Appendix II with rules for their use.

THE DUFF MOISTURE CODE

Background

In Beall's (1939) supplement to the second generation of Canadian forest fire danger indexes, there appeared a subsidiary index called the

[1]Péch, Gy. 1968. Comments on revising the night humidity correction table. Unpublished report, Forest Fire Res. Inst., Ottawa.

Drought Index. While the Tracer Index represented usually only several days of past weather and its effect on fine fuel moisture content, the Drought Index took account of up to 25 days of weather history. Its purpose was to stratify the day-to-day fire weather according to the number of days since appreciable rain; in physical concept it could be likened to a simple reservoir in which rain accumulated additively, and which lost a constant amount for each day without rain. Although the Drought Index, unlike a real fuel, was linear in both its drying and its wetting phases, it performed a useful function in the next two systems of danger rating.

When work began several years ago on the present modification and improvement of the Canadian fire danger rating system, it was generally agreed that a subsidiary index was required that represented the moisture content of some real slow-drying forest fuel. The fuel chosen, on account of its universal and continuous presence in Canadian forests, was the duff layer, roughly equivalent to the F-layer of soil science. An index filling this need appears in the new system as the Duff Moisture Code (DMC). It was developed after 4 years of field work, mainly in red pine and jack pine stands. The basic method was to transfer rectangles of organic matter to trays 24 x 16 inches in area set in the forest floor and to weigh them daily. The DMC represents duff layers about 3 inches deep and 1 lb/ft^2 in dry weight. Since a published description already exists (Van Wagner 1970b), only an outline of its structure is presented here.

Scale

A scale for the DMC was designed after the manner of the U.S. Build-up Index (Anon. 1966) on a logarithmic function of the actual moisture content that rises with dryness. The type expression is

$$P = c\,[\log\,(M_{max} - E) - \log\,(M - E)]$$

where c is a scale constant,

and the actual scale equation in natural logarithms for the chosen moisture limits of 300 and 20% was

$$P = 244.72 - 43.43\ \ln\,(M - 20) \qquad (12)$$

This scale is illustrated in Fig. 4. The main advantage of such a scale is that it permits the addition of daily drying increments that are independent of the current value of the code.

Rainfall Phase

In the wetting phase of the DMC, two principles form the basis of the equations:

1) The increase in moisture content per inch of rain is inversely proportional to the amount of the rainfall.

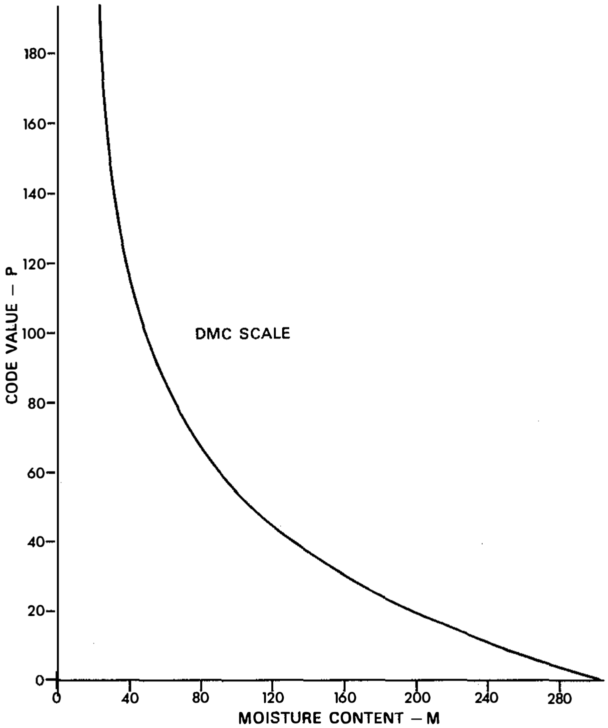

Figure 4. Graph of scale linking DMC to actual duff moisture content.

2) The wetting effect of a rainfall decreases with increasing initial moisture content.

In other words, the duff layer retains a greater fraction of a light rainfall than of a heavy one, and the wetter the duff the less rain it can absorb. Although the effect of rainfall duration was demonstrated in the original work, it was decided to omit this complication in the practical moisture code. In the DMC, the effective rain r_e is given as a function of the total rain r_o by

$$r_e = 0.92\ r_o - 0.05 \qquad (13)$$

and the moisture content after rain (M_r) by

$$M_r = M_o + 1000\ r_e/(1.92 + br_e) \qquad (14)$$

The coefficient b was first expressed as a plotted curve, which was then rendered in terms of the initial code P_o by a set of three empirical equations for different ranges of P_o.

$$b = 100/(0.5 + 0.3\ P_o) \quad , P_o \leq 33 \qquad (15a)$$

$$b = 14 - 1.3\ \ln P_o \quad , 33 < P_o \leq 65 \qquad (15b)$$

$$b = 6.2\ \ln P_o - 17.2 \quad , P_o > 65 \qquad (15c)$$

Drying Phase

The drying phase of the DMC consists of two equations and a short table based on the following points:

1) Day-to-day drying in constant weather is exponential.

2) The duff layer has, for practical purposes, a constant equilibrium moisture content E of 20%.

3) The log drying rate K is proportional to temperature, becoming negligible at about 30°F.

4) The log drying rate K is proportional to the deficit in relative humidity.

5) The day length, varying with season, has an effect roughly proportional to three less than the number of hours between sunrise and sunset.

The log drying rate K is given by

$$K = 0.1052\ (T-30)\ (100-H)\ L_e \times 10^{-5} \quad (16)$$

where L_e is an empirical day-length factor listed by month in Table 2. The present day's DMC is then found from

$$P = P_o\ (\text{or } P_r) + 100K \quad (17)$$

where K is multiplied by 100 to yield values matching the chosen scale.

The equations making up the DMC are listed again in Appendix II with rules for their use.

TABLE 2. DAY-LENGTH FACTOR L_e IN DUFF MOISTURE CODE

Month	L_e
April	12.8
May	13.9
June	13.9
July	12.4
August	10.9
September	9.4
October	8.0

THE DROUGHT CODE

Background

The Fine Fuel Moisture Code covers only the thin surface layer of fast-drying material, while the Duff Moisture Code applies to organic layers of about 3 inches depth and 1 lb/ft^2 in dry weight. Real fire danger, however, is also affected by the state of the deeper organic layers common in many parts of Canada, by concentrations of large downed wood, and even by the availability of water in small streams and swamps. It was decided, therefore, to include a third, very slow drying moisture index in the FWI and to call it the Drought Code.

The Drought Code (DC) was first developed by Turner (1966) to serve as an index of the water stored in the soil rather than follow the moisture state of a particular slow-drying forest fuel. Since it loses moisture exponentially, it is quite suited to represent certain heavy fuels. Muraro and Lawson (1970) identified one such material: they established that the DC follows reasonably well the moisture variations in deep, compact duff layers on Vancouver Island. These layers are, on the average, about 10 inches deep and 9 lb/ft^2 in dry weight. One function of a slow-acting moisture code such as the DC is to warn of occasions when the lower layers of deep duff may be drier than the upper. Both Muraro and Lawson (1970) and Kiil[2] report field studies of this phenomenon, which results in persistent deep smoldering even though surface fire behavior may not be severe.

In its initial form, the DC was called the Stored Moisture Index (SMI) and was expressed directly in 100ths of an inch of water up to a maximum of 800 (i.e. 8 inches of water). To match the style of the DMC, the SMI was converted to a logarithmic scale rising with dryness. A brief mathematical description of the DC follows, and Turner (1972) gives a complete description.

Scale

The scale of the SMI (the original form of the DC) was 800 units in length, 800 representing saturation and zero representing the driest condition normally encountered. The required equation for the new logarithmic scale was analogous to the one forming the basis of the DMC. As an exponential expression for the moisture equivalent Q, the chosen scale equation is

$$Q = 800\, e^{-D/400} \qquad (18)$$

where D is the current DC.

---

[2]Kiil, A.D. 1970. Distribution of moisture in spruce-fir duff and its relevance to fire danger rating. Can. Forest. Serv., Northern Forest Res. Centre Intern. Rep. A-34.

As in the DMC, this type of scale permits the addition of daily drying increments that are independent of the current value of the DC (Fig. 5).

Rainfall Phase

Rainfall in the DC is first reduced to an effective rainfall r_d and then simply added to the existing moisture equivalent Q_o to give Q_r, the moisture equivalent after rain. The two equations are

$$r_d = 0.83\ r_o - 0.05 \tag{19}$$

and

$$Q_r = Q_o + 100\ r_d \tag{20}$$

Drying Phase

The daily dry-weather additives to the DC actually represent potential evapotranspiration (V), which is given by an empirical equation dependent on noon temperature and season

$$V = 0.2(T-27) + L_f \tag{21}$$

the seasonal adjustment L_f being listed by month in Table 3. These V values are halved for convenience and added to the initial code D_o (or, in case of rain, to D_r). The present day's DC is thus found from

$$D = D_o\ (\text{or } D_r) + 0.5\ V \tag{22}$$

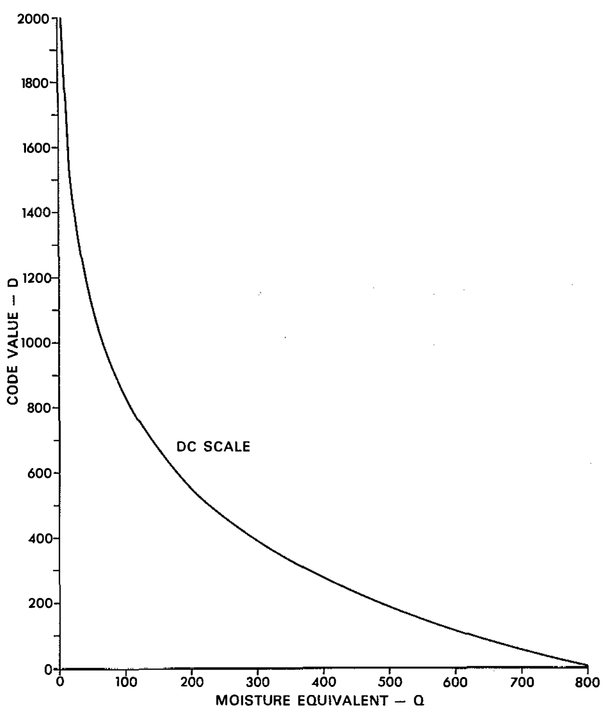

Figure 5. Graph of scale linking DC to its moisture equivalent.

TABLE 3. DAY-LENGTH ADJUSTMENT L_f IN DROUGHT CODE

Month	L_f
November to March	-1.6
April	+0.9
May	3.8
June	5.8
July	6.4
August	5.0
September	2.4
October	0.4

The equations making up the DC are listed again in Appendix II with rules for their use.

SCALE FOR THE FIRE WEATHER INDEX

The previous Canadian fire danger index was on a scale of 0-16, called here the D-scale. This scale, however, was not uniform across Canada, since the same weather data yielded different index values among the nine regional versions. Aside from the goal of a uniform national index, there were three other reasons for developing a new scale:

1) In some regions, the D-scale was not long enough to cover the whole possible range of fire weather.

2) A more open scale with higher values at high fire danger was desired.

3) No interpretation existed of the D-scale in terms of physical units of fire intensity.

At the same time it was decided to preserve a link between the old scale and the new, both in concept and through an actual equation.

The first step was to interpret the D-scale as some function of fire intensity, stated as rate of energy output per unit length of fire front. From the experimental fire program at Petawawa there were available some 22 fires in pine stands for which the old Danger Index was known and an intensity in Btu/sec-ft (after Byram 1959) could be calculated. Some fires burned in a jack pine stand, some in a red and white pine stand, and some in a red pine plantation. These fires were plotted on semilog paper as log intensity versus Danger Index (Fig. 6), in which the D-scale is shown extended beyond

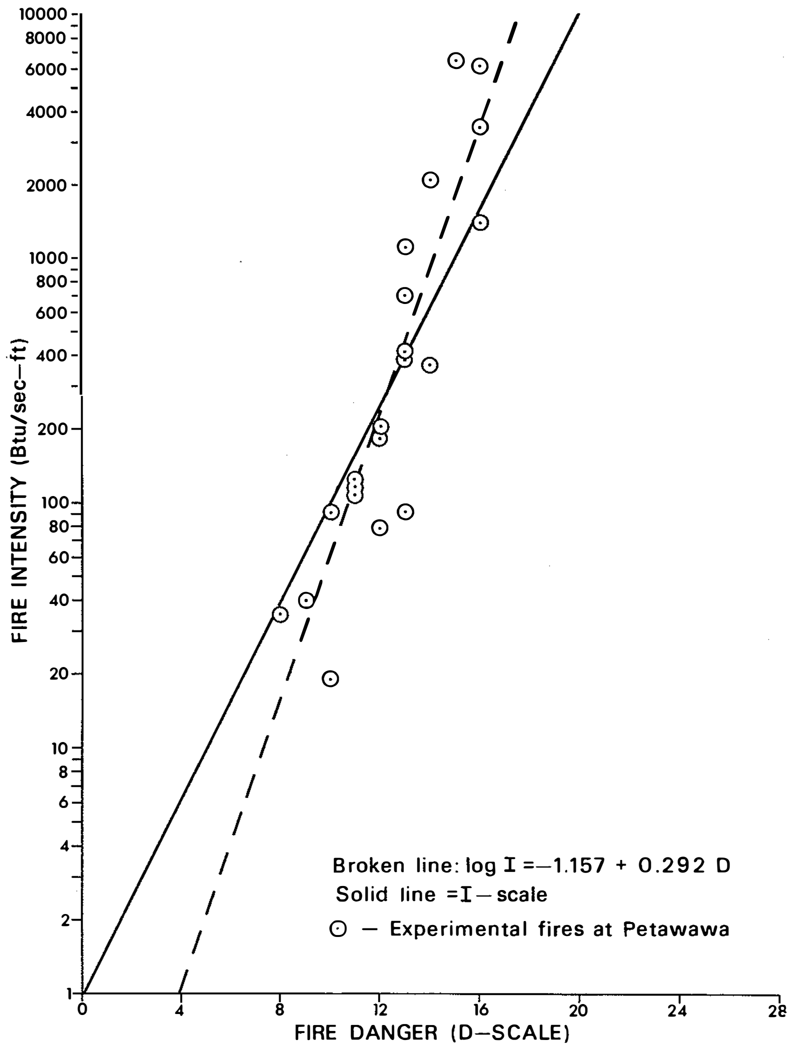

Figure 6. Graph of I-scale and relation between intensity of experimental fires and D-scale.

its normal limit of 16. The resultant grouping gave reasonable cause for assuming the D-scale to be a plain logarithmic function of fire intensity. The straight line representing the intensity scale was placed after three arguments had been considered. First, the red pine plantation was judged to be more inflammable than the so-called standard fuel type. Second, the Ontario version of the D-scale gives somewhat higher values for the same weather than the average of the nine regional versions. Third, the line of best fit would strike the D-scale axis too far above zero for practical purposes. The intensity scale line was accordingly passed through the center of the main group of moderate intensities, falling to the right of the highest red pine intensities and reaching 1 at D-scale 0. This line was named the I-scale and forms the link between the old and the new systems of danger rating.

At this point it was decided to leave the new scale open at the top. This was in keeping with its concept as a function of fire intensity, and not as a percentage or fraction of some imagined worst possible state. As a result, no matter how high the FWI should rise, it can rise still higher if the fire weather worsens. There is no artificial upper limit such as existed in the old system.

Since the I-scale values were judged too large and inconvenient for direct use, a reduced function of this scale was required. The first function chosen was the simple square root of the I-scale, called the B-scale, and the remaining equations required to calculate the FWI were worked out on this B-scale. Later it was observed that the B-scale had two drawbacks. It had to extend beyond the limit of 16 on the D-scale, into a region for which no reliable fire intensity estimates were available. In this upper region, the B-scale gave values of several hundred, somehow out of proportion to the lower part of the range. Also, below 10 the B-scale actually has lower values than the D-scale, and this was hardly in keeping with the concept of a more open scale. Another scale was therefore developed called the S-scale, which yields values higher than the D-scale throughout its whole range; a level of 100 will occasionally be reached, but 200 will almost certainly never be exceeded. The FWI was recast on this S-scale, whose relation to the I-scale and the D-scale can be seen in Fig. 7.

Equations for these various scales are

$$I = 10^{0.2D} = e^{0.416D}$$

$$B = 10^{0.1D} = I^{0.5}$$

$$\ln S = 0.614\ D^{0.647} = 2.72\ (0.434\ \ln B)^{0.647}$$

It should be noted that these equations form somewhat artificial links between the old and the new danger systems. They cannot be used to convert day-to-day index values from one system to another, since the two systems react differently to variations in fire weather.

THE INITIAL SPREAD INDEX

Background

It would, of course, be easy to take the three moisture codes together with wind (for its direct effect on the fire) and process them by computer in one long equation yielding the day's FWI. This operation has been divided into three steps for two reasons: first, it would be impractical to design a single table for manual determination of the FWI from these four quantities and, second, the intermediate components might themselves be valuable for presenting a full picture of the daily fire weather.

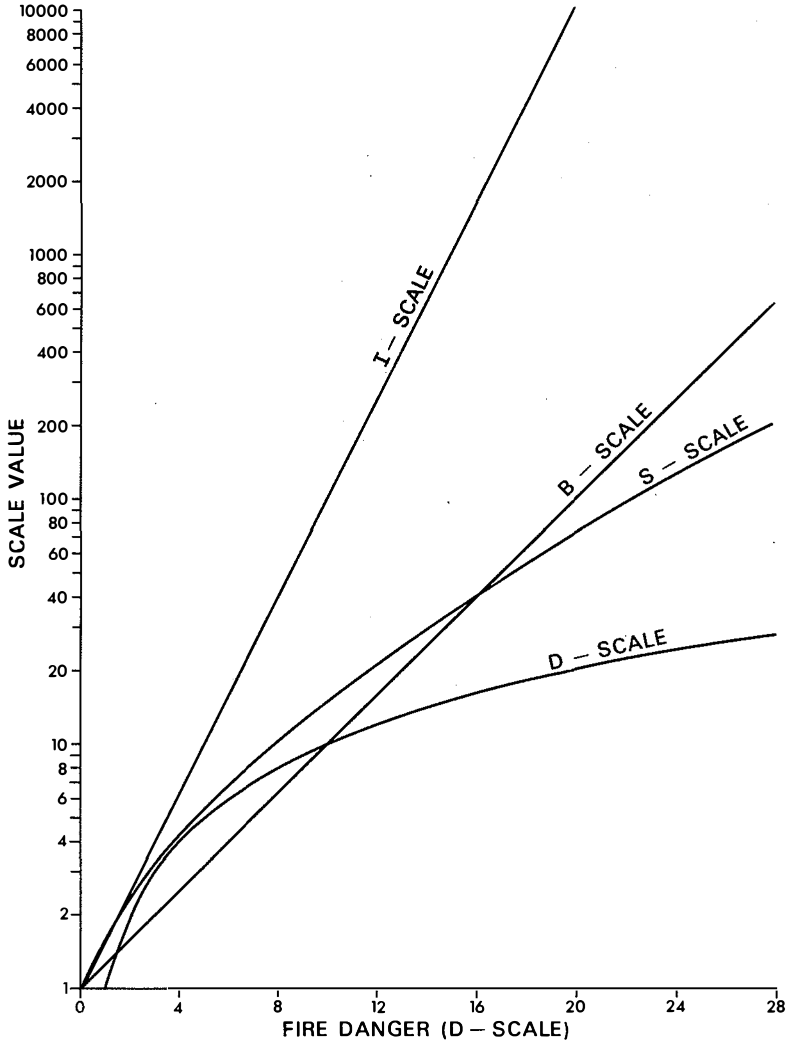

Figure 7. Four danger scales (I, B, S, and D) all graphed against D-scale on semi-log paper.

The first of the two intermediate components is the Initial Spread Index (ISI), a combination of the effects of wind speed and fine fuel moisture content. Its main function is simply to intermediate in the determination of the FWI, and it had to be designed with this principal end in mind. At the same time it was called a "spread index" in the belief that a fire's rate of spread is mainly dependent on wind speed and fine fuel moisture content. In addition, because it is undoubtedly true that the rate of spread of an established fire can be influenced by the amount of available heavy fuel, the name was modified by prefixing "initial." To develop the ISI, functions for the effects of wind and fine fuel moisture on fire spread were designed separately, then multiplied together, and finally adjusted to the chosen scale.

The Wind Function

After work began on the problem of the wind function, it soon became apparent that there exists as yet no general theory to account for the effect of wind on forest fires throughout the whole range of intensity. The choice of a wind function thus became a matter of judgment in which various kinds of evidence were examined, including the wind effects in the Australian, American, and former Canadian danger systems, several laboratory studies, and the set of experimental jack pine fires at Petawawa. Some of these were graphed and described by Simard,[3] and a few are shown in Fig. 8, plotted as spread rate (or index) versus wind speed on semilog paper. These include a curve for Australian eucalypt fires (McArthur 1967), a curve from the U.S. Spread Index based on Nelson's (1964) tables, a curve for fires in the northeastern United States (Anon. 1958), and a curve from Beall's (1948) Canadian tables. Index values in the former Canadian system were converted to B-scale before plotting. It was apparent in both Simard's treatment and Fig. 8 that most of the curves were roughly exponential.

Before a choice of wind function could be made, it was necessary to define the type of exposure on which to base the wind scale. The wind-measurement methods used in the systems shown in Fig. 8 were examined, as well as data compiled by Simard (1971) comparing airport winds with winds at fire weather stations. The weight of evidence pointed to the international standard 10-meter open wind, and this was adopted. The winds measured 4 feet above ground in the forest during the Petawawa jack pine fires were multiplied by 5 for purposes of Fig. 8. (This factor was obtained from a study of local wind data.)

The chosen wind effect, f(W), is a simple exponential

$$f(W) = e^{0.0811W} \tag{23}$$

where W is 10-meter open-wind speed. This function (see Fig. 8) doubles the B-scale index for every 8 mph increase in wind speed. It is fairly close to several published effects of wind on forest fire and matches fairly well the available experimental field evidence. Nevertheless, it is essentially empirical, and at very high wind speeds its validity is uncertain.

The Fine Fuel Moisture Function

The function for fine fuel moisture (FFM) in the FWI is based on an analysis of FFM effect in the former fire danger system. As with wind, it was decided after due examination of the literature that no acceptable general theory on FFM effects yet exists. In contrast to the case of wind, however, many empirical data have been collected over several decades on the effect of FFM on test fire behavior, all of which are embodied in the former system.

---

[3]Simard, A.J. 1968. Relative spread index. Progr. Rep. 2. Can. Dep. Forest. Rural Develop., Forest Fire Res. Inst., Ottawa.

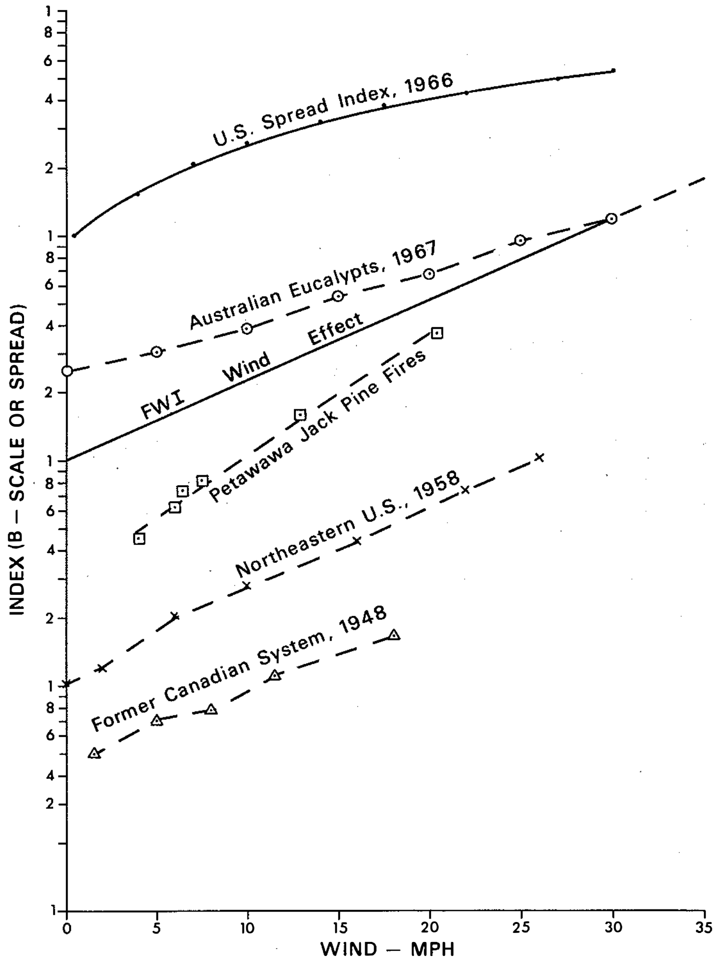

Figure 8. Effect of wind speed on B-scale FWI along with wind effects from five other sources. (Observe shape and slope of curves - their relative position is unimportant in this graph.)

To derive an FFM function, f(F), for the FWI, summer danger indexes in all nine versions of the old system were plotted against FFM content at several levels of the old Drought Index. The average curve at a moderate drought level (15) was then plotted as B-scale index against FFM content and modified slightly after consultation. The final function is a fairly straight descending line on semilog paper, 4 times as strong at 6% as at 16% FFM content, and flattening out gradually above 16%. It is shown graphed in Fig. 9, with an Australian curve from McArthur (1967), an American curve from Anon. (1966), and a curve from the previous Canadian system (Anon. 1957). The empirical equation chosen as a reasonable fit is

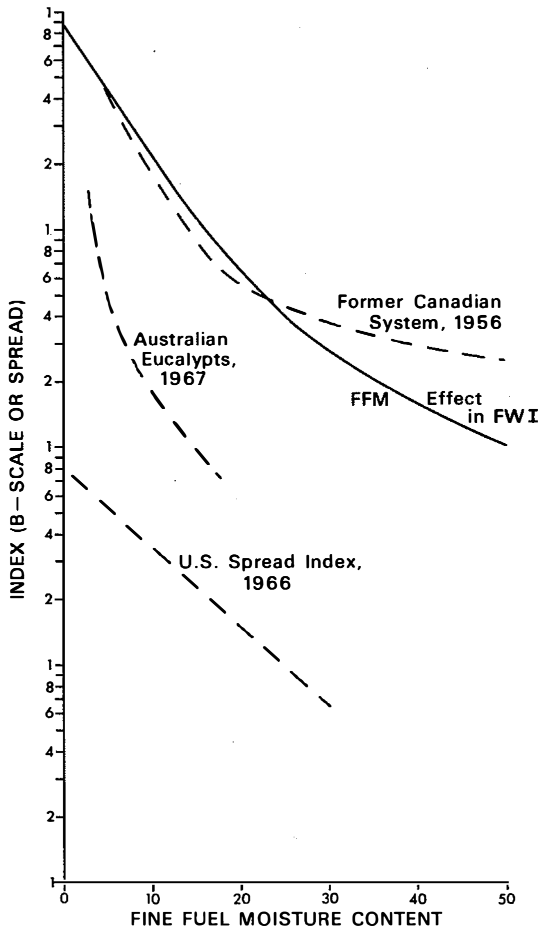

Figure 9. Effect of fine fuel moisture (FFM) on B-scale FWI along with FFM effects from three other sources. (Observe shape and slope of curves - their relative position is unimportant in this graph.)

$$f(F) = (91.9\, e^{-0.1386m}) \quad (1 + m^{4.65}/7{,}950{,}000) \qquad (24)$$

where m is fine fuel moisture content in percent, determined by subtracting the FFMC from 101 according to Equation 1.

The ISI Equation

The ISI is merely the product of the functions of wind and fine fuel moisture, together with a reference constant 0.0208. This constant was determined at a later stage, and was designed to make the B-scale FWI equal to 40 for an arbitrary set of conditions at which the British Columbia Coast Index in the former system equalled 16. These conditions were:

Wind speed - 8 mph

Fine fuel moisture content - 6%

Old Drought Index - 25

The constant itself was multiplied by 10 to provide a convenient range of values for the ISI. The equation is, then,

$$R = 0.208\, f(W)\, f(F) \qquad (25)$$

where R is Initial Spread Index.

THE ADJUSTED DUFF MOISTURE CODE

The second of the two intermediates that lead directly to the FWI is the Adjusted Duff Moisture Code (ADMC), a combination of the Duff Moisture Code (DMC) and the Drought Code (DC). Once it was decided to introduce the slow-reacting DC into the new system, a method was sought that would give a limited, variable weight to the DC, reserving the main effect for the DMC. In particular, when the DMC is near zero, the DC should not affect the daily fire danger no matter how high its level. The function best meeting these requirements is the harmonic mean.

Before the DMC and DC could be combined, their scales had to be made equivalent in terms of average rate of rise in dry weather. Since the daily additives in each code respond to noon weather in different ways, this could only be done empirically. Accordingly, three seasons' daily additives of each code were averaged, nonrainy days in June, July, and August being used. For Petawawa weather, the average daily increase in the DC turned out to be 2.5 times that in the DMC, and this ratio was adopted. Before the harmonic mean (i.e. the ADMC) can be calculated, the DC must therefore be multiplied by 0.4.

The relative behavior of DMC and the reduced DC is generally as follows. In spring, when calculation begins, the two codes rise together until the first rain. Because the DMC is reduced more by rain, the DC will remain comparatively higher after each rainfall. The DMC may fluctuate between high and low levels several times during a fire season, but the DC tends to rise gradually throughout the warm part of the season and to fall when cool weather starts. The reduced DC is therefore almost always higher than the DMC. By the nature of the harmonic mean, the smaller DMC accordingly receives the greater weight.

The harmonic mean of two variables a and b is 2 ab/(a+b). When the DMC and the reduced DC are combined in this way, the ADMC is given by

$$U = 0.8PD/(P + 0.4D) \qquad (26)$$

where U is ADMC, P is DMC, and D is DC. This ADMC has the following properties:

1) When the DMC is zero, the ADMC is also zero no matter what the value of the DC.

2) The proportional weighting given to the DC is variable, increasing as the ratio of DMC to DC rises toward 1.

3) Except when the DMC is zero, the ADMC is always greater than, but never more than double, the DMC alone.

4) After each rain the ADMC rises at a faster rate than the DMC. The higher the DC with respect to the DMC, the faster does the ADMC regain a given previous value.

5) Because the DC tends to increase over a whole summer, a slight seasonal effect is imparted to the ADMC. That is, a given run of daily weather generally results in a higher ADMC in autumn than in spring.

THE FIRE WEATHER INDEX

The Duff Moisture Function

To give the Fire Weather Index meaning as a measure of fire intensity, factors are required for both rate of spread and fuel consumption. The ISI clearly represents rate of spread, but ADMC is simply a blend of two fuel moisture codes and retains their basic form, a logarithmic function of moisture content. A function was therefore needed to transform the ADMC into terms of fuel weight consumed. It was derived in the following manner.

Once again, this time for lack of a general theory on how the proportion of fuel available for combustion increases with dryness, the function was drawn mainly from an analysis of the analogous effect in the former danger system. Summer danger indexes in all nine versions of the former system were graphed against the old Drought Index at several levels of fine fuel moisture content, all values being first transformed to units of the new system. The old D-scale index was converted to B-scale by the appropriate scale equation, and the old Drought Index (DRI) to DMC according to the relation

$$DMC = 13.0 + 2.92\ DRI$$

(This conversion was developed from a graph of DMC against DRI by using 3 years' local data for June, July, and August. Although the range of DMC values for each value of DRI was wide owing to the differences in structure, the average DMC's fell on a reasonably straight line.)

The transformed graphs of old danger index against old drought index turned out to be fairly straight lines tending to converge near zero. For each line the ratio of B-scale indexes at DRI 25 and 5 (DMC 86 and 28) was calculated, the average being 2.5. The value of the desired duff moisture function was arbitrarily set equal to 10 at DMC 28, and consequently to 25 at DMC 86. The function was also given a small value at zero DMC, on grounds of the following reasoning.

The DMC and DC themselves refer only to two classes of slow-drying fuel. However, the function representing them in the FWI equation, being really a fuel-consumption factor, must account for all fuel burned, fast-drying as well as slow-drying. The small function value at zero DMC therefore represents the small constant weight of fine fuel assumed to burn in any fire that spreads at all. After some trial, this small value was set at 2.

The three points now available (at DMC 0, 28, and 86) formed a gentle curve flattening as it rose, and were matched with the function $0.626P^{0.0809} + 2$.

The result had one important limitation. It was based on the effect of the old Drought Index, which had a scale length of only 25 days without appreciable rain - say 75 on the DMC scale. Since the new danger system must handle rainless periods much longer than this, some justification for extrapolation was needed. This was provided by a theory to account for the increased amount of duff available as fuel as the moisture content decreases. A brief description is given here and a detailed account appears elsewhere (Van Wagner 1972a).

Suppose that fire spreads by preheating and igniting the fine fuel layer only - say 0.05 to 0.10 lb/ft^2. Any duff that is consumed must therefore be ignited and burned during passage of the fire front. To accomplish this, the fire must transfer heat downward to drive off moisture and raise the duff to ignition temperature. If the amount of energy transferred downward within the fire front can be estimated, as well as the amount of energy required to raise unit weight of moist duff to ignition temperature, a

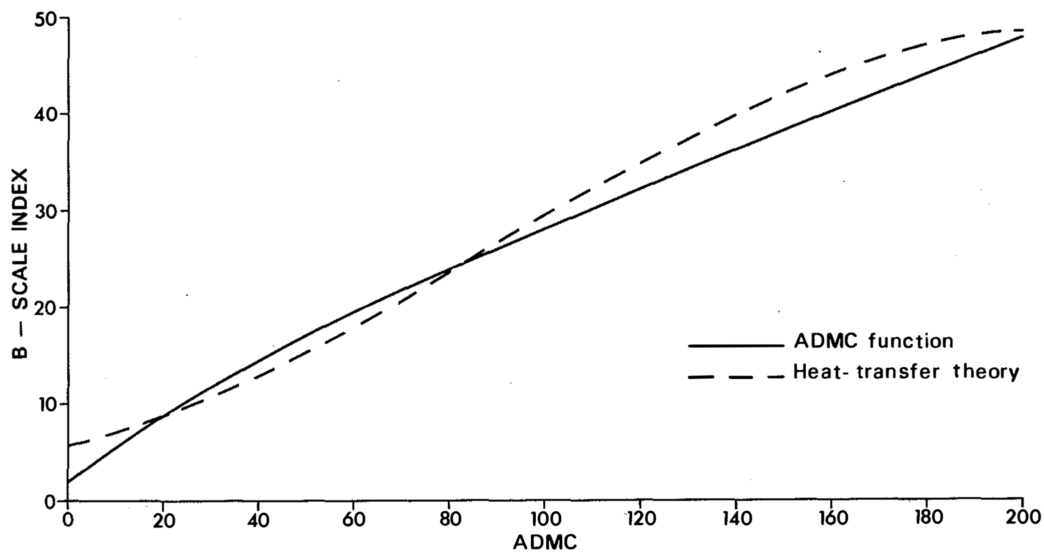

Figure 10. Effect of ADMC on B-scale FWI along with curve based on heat transfer theory.

balance can be struck that will yield the weight of duff available as fuel. Several assumptions were made, reducing the theory to the simplest possible terms. A curve was then drawn that, as it turned out, matched the function already derived very well in a relative sense over the DMC range at least up to 200 (Fig. 10). This theory, while far from secure, does afford a rational basis for the desired extrapolation of the duff moisture function, called f(D). Finally, although the function was derived in terms of the DMC, it is the ADMC that is used in the final equation. The equation for f(D) is then

$$f(D) = 0.626U^{0.809} + 2 \qquad (27)$$

The FWI Equation

The functions required to calculate the FWI are now all at hand. The duff moisture function is given by Equation 27. The reference constant, whose derivation was covered in the section describing the ISI, is already an integral part of the ISI. The constant was multiplied by 10 for convenience, and the ISI's value must be readjusted by the factor 0.1. The B-scale FWI is then given by

$$B = 0.1\ R\ f(D) \qquad (28)$$

The final S-scale FWI is then found from

$$\ln S = 2.72\ (0.434 \ln B)^{0.647} \qquad (29)$$

This last equation has one restriction. When B is less than 1, its logarithm is negative and cannot be taken to a fractional power. In such cases, S is simply set equal to B. Finally, it should be noted that this equation yields smaller and smaller values as the moisture codes decrease, but never a true zero. For reporting, the FWI and its various components are rounded to the nearest whole number.

THE FIRE WEATHER INDEX IN USE

Calculation

The FWI and its components may be determined either from the published set of tables (Anon. 1970, in English; Anon. 1972, in French) or by computer. There are two possible types of computer programs: equation-based or table-based. The equations constitute the standard form of the FWI, and a mathematical program is desirable for development or statistical work on the FWI. However, it is obviously not possible to design a set of tables that will give the same result every time as a set of equations. For this reason, where the FWI is being computed daily for many stations at a central location, and must bear comparison with values found locally from the tables, a table-based program is more suitable. Several mathematical programs have been developed for statistical work. The first was by Nikleva and Parent (1971). The second, by Simard,[4] handles many stations and seasons, contains routines for unrealistic and missing data, and requires a computer with at least 30K of storage capacity. Another, by Engisch and Walker,[5] is simpler, handles one station for one season at a time, and was designed for a small computer of only 8K storage capacity, the DEC PDP8-L. Operational programs based on the tables are in use at the Forest Fire Research Institute in Ottawa and elsewhere in Canada.

Since the FWI depends on weather readings only, it can just as easily be calculated from forecast weather to yield forecast fire danger. Paul (1970) and Pouliot (1970) describe centralized operations for issuing daily current and forecast fire danger in the Maritimes and Quebec respectively. These descriptions refer to the former fire danger system, but the same techniques apply for the FWI.

Interpretation

The FWI was originally conceived to represent line-fire intensity as defined by Byram (1959) in the equation

$$I = HWR$$

where, in compatible units,

H is heat of combustion,

W is fuel consumed (weight per unit area),

R is rate of advance,

I is energy output rate per unit length of fire front.

Accordingly, the FWI scale was derived from a graph of the intensities of some experimental fires over old fire danger (Fig. 6). Also, the ISI and ADMC were designed to represent the factors R and W respectively in the foregoing equation. The heat of combustion H is known to vary somewhat with fuel species and moisture content but for practical purposes was considered constant. It can consequently be thought of as embedded in the reference constant.

[4]Simard, A.J. 1970. Computer program to calculate the Canadian Forest Fire Weather Index. Can. Forest. Serv., Forest Fire Res. Inst. Intern. Rep. FF-12.

[5]Engisch, R.L., and J.D. Walker. 1971. PDP-8L version of Simard's Fire Weather Index Program. Can. Forest. Serv., Petawawa Forest Exp. Sta. Intern. Rep. PS-23.

Fire intensity calculated in this simple manner has its deficiencies as a measure of fire behavior. For example, the proportion of the total fuel consumed that actually contributes to the flaming front varies from fuel type to fuel type. Of course, the FWI is not a direct arithmetical representation of fire intensity, owing to the distortion involved in the design of the S-scale. In fact, another interpretation is possible. Suppose that, as W (the combustible fuel per unit area) increases, so does R in proportion, other burning conditions remaining unchanged. That is, $W = kR$ where k is some constant. Then, substituting,

$$I = HkR^2$$

If H is taken to be constant, R is seen to be proportional to the square root of I, in other words, to the B-scale. The B-scale thus turns out to be simply a spread scale, and the same interpretation could apply with a little stretching to the S-scale FWI itself. The basis for this interpretation is, of course, the assumption of proportionality between W and R. It certainly seems reasonable to expect R to increase with W, if only on account of the greater flame size. Otherwise it would be necessary to assume that, once fine fuel was at moisture equilibrium, no further increase in spread rate would be possible no matter how long a dry spell persisted. It is difficult, however, to find good evidence of a 1:1 proportionality; so this interpretation is best left somewhat vague.

Because the FWI combines so many effects, the same index value can be reached by many different weather combinations and histories. For example, any one of the three moisture codes may be high or low in opposition to the other two. First, 2 or 3 good days' drying after heavy rain will produce a high FFMC while the DMC and DC remain low. Second, a light rain after a long dry period will result in a low FFMC while the DMC remains high. Third, the DC may rise or fall gradually while the other two fluctuate many times.

As another example, a moderately high FWI may be due to a high ADMC that has built up in average day-to-day weather. A sudden dry, windy day will then produce a very high FWI. The FWI will, in fact, be found to vary more from day to day than the former danger index on account of its stronger wind effect. All these considerations point up the well-known impossibility of communicating a complete picture of daily fire danger in a single number. The subsidiary components of the FWI are needed as well for proper interpretation of the fire weather. Lawson (1972) has written an excellent interpretative guide to the FWI; it is aimed particularly at British Columbia, but its basic principles apply everywhere.

Calibration

No sooner was the FWI's development completed than the question of how well it could predict certain aspects of fire business became of great interest. Two studies using provincial fire data have so far been conducted, by Turner[6] in British Columbia and by Stocks[7] in Ontario, in which the FWI and several of its components were compared with fire occurrence, area burned, and individual fire size. The results have been very favorable, especially in the matter of fire occurrence, but the picture is not yet complete. Such relations are partly confounded by the variable frequency of fire-starting agents abroad in different kinds of weather, and by the tendency of fire control agencies to adjust their control effort to the level of fire danger. The results of these statistical studies will always need some interpretation, and absolute experimental calibration in terms of rates of spread and energy output is a desirable complementary procedure.

The question may arise: How does the FWI perform at high latitudes? It is probable that the three moisture codes will give reasonable results at latitudes from 45 to 55 degrees; at 60 or more degrees, however, the day length, sun angle, and diurnal trend of temperature and humidity are quite different. In the District of Mackenzie and Yukon Territory especially, the FFMC and DMC probably need special calibration by local fuel-moisture studies. An unsettled question concerning the DC at all latitudes is how much carry-over to allow from one fire season to the next in the event of a high autumn value and dry winter.

Because of the fairly strong wind effect embodied in the FWI, the standardized consistent measurement of wind speed becomes more critical than formerly if individual stations are to be comparable. Simard (1969) discusses this problem and has proposed one scheme (Simard 1971) for obtaining the desired uniformity. At the time of writing all the foregoing calibration problems are receiving attention.

The FWI record can be used to compare the severity of fire weather from season to season or from station to station. Williams (1959) devised a severity rating scheme for the former fire danger system, and this has been modified for use with the FWI (Van Wagner 1970c). Stocks (1971) determined the normal severity pattern as it varies from month to month throughout Ontario.

Ultimately, the most desirable calibration of any fire danger index is in terms of the control effect needed per unit of fire perimeter. There is as yet no sound theory to link control effort with some pertinent parameter of fire behavior, and the many varied attack methods make this a very difficult question indeed. This problem could profitably be tackled empirically as well as theoretically.

---

[6]Turner, J.A. 1970. Calibration of the Fire Weather Index in British Columbia. Progr. Rep. 1. Can. Forest. Serv., Pacific Forest Res. Centre, Victoria.

[7]Stocks, B.J. 1971. An analysis of the Fire Weather Index in Ontario (1963 to 1968). Can. Forest. Serv., Great Lakes Forest Res. Centre Intern. Rep. 0-25.

Danger Classes

It is customary in fire danger rating to quote a danger class as well as an index number, especially in publicity for the public-at-large. While the FWI scale is uniform all across Canada, the range of fire weather certainly is not. It was suggested, therefore, that the various regions should choose their own limits for the following danger classes: Very Low, Low, Moderate, High, Very High, Extreme. (Some regions have used only four or five of these six classes.)

To develop a rational class breakdown, the following procedure was recommended. First, compile a historical sample of several seasons' FWI's, decide how many Extreme days should be allowed each season on the average, and set the lower limit for Extreme. Second, decide in a similar way on limits for the lowest class. Third, arrange the intermediate classes on a geometric progression in terms of the I-scale. For example, when this scheme was applied to several seasons' data at Petawawa, the Extreme class being set to yield about 4 days a year, the following class breakdown resulted:

Danger class	FWI limits
Extreme	25+
High	13-24
Moderate	6-12
Low	2-5
Very Low	0-1

From recent experience, the FWI at Petawawa is unlikely to exceed 50 more than about once every 10 years, which is a fair indication of the size of the Extreme class at this location. Simard and Valenzuela (1972) have compiled distributions of the FWI and its components for 364 stations across Canada for the period 1957-66. This information forms an excellent basis for the design of danger classes in any region; it also shows clearly the immense range in fire weather throughout Canada. The highest FWI discovered during this work was 153, from a location in southern British Columbia. It is unlikely that a level of 200 will ever be reached in Canada.

Future Development

Since it was built up to represent fire behavior in a particular standard fuel type, the FWI will obviously have different meanings in other fuel types. It is the problem of variation in fire behavior among fuel types that offers the greatest scope for further development in fire danger rating. With respect to a given fuel type there are three possibilities. First, satisfactory correlation may exist between fire behavior and the FWI itself, the curve form varying from fuel type to fuel type. Second, if this fails, it may be possible to predict fire behavior by combining two or three of the moisture codes with wind in some other way. Third, the critical fuel in a particular fuel type may not fit any of the FWI's moisture codes; in this case a special index would have to be developed from basic data. The Canadian Forestry Service is now carrying out experimental fires in important fuel types throughout Canada, and the resulting predictive index developed for a particular fuel type is called a "burning index."

At this point a problem in terminology deserves mention. All through this paper, the term Fire Weather Index (or FWI) has been used for either the single index number arising out of the final equation or the whole system of codes and indexes leading to it. In future, however, the term Fire Weather Index will refer only to Table 6 in the set of tables (Anon. 1970) and the index value derived from it. All the moisture codes and indexes described in this paper, taken together with the burning indexes as they are issued, will from now on be referred to as the Canadian Forest Fire Behavior System (CFBS).

So far, three burning indexes have been added to the CFBS - one for spruce-fir logging slash in British Columbia (Muraro 1971), one for lodgepole pine slash (Quintilio 1972), and one for jack pine slash (Stocks 1972).

Finally, all who took part in developing the Fire Weather Index well realize that changes may become desirable from time to time. The first requirement of a fire danger rating system is that it represent nature. The second is that the information produced be in a form useful to the fire-control agencies. It would be presumptuous to assume that the system described here is the last word in either of these ways. As research progresses, some of the concepts used here may become obsolete; and, as fire control practices change, so may the information on fire weather and behavior desired by the agencies. It is therefore fully expected that, in keeping with the philosophy established by Wright and Beall in the early years, this fire danger rating system will in the future continue to evolve in response to the needs of forest fire control throughout Canada.

REFERENCES

Anon. 1957. Forest fire danger tables, 1956. Can. Dep. Northern Aff. Nat. Resources, Forest. Br. Issued separately for following regions: Newfoundland, New Brunswick, Ontario, Manitoba, Alberta East Slope. 14 p.

Anon. 1958. Manual for forest fire control. U.S. Forest Serv., Northeastern Forest Fire Protect. Comm., Chatham, N.Y.

Anon. 1959. Forest fire danger tables. Can. Dep. Northern Aff. Nat. Resources, Forest Br. Issued separately for Saskatchewan and Alberta. 14 p.

Anon. 1966. Derivation of spread phase tables, National Fire-Danger Rating System. U.S. Forest Serv., Div. Fire Contr. 54 p.

Anon. 1970. Canadian Forest Fire Weather Index. Can. Dep. Fish. Forest., Can. Forest. Serv. 25 p.

Anon. 1972. Indice Forêt-Météo: méthode canadienne (provisoire). Serv. Can. Forêts, Inst. Rech. Feux Forêts.

Beall, H.W. 1939. Tables for estimating the tracer index from early afternoon readings and table for diurnal hazard variation. Can. Dep. Mines Resources, Dominion Forest Serv. Suppl. to Forest-fire Res. Note 5. 20 p.

Beall, H.W. 1947. Research in the measurement of forest fire danger. Paper presented to Fifth Brit. Empire Forest. Conf. Reprinted in 1967 as Inform. Rep. FF-X-8, Can. Dep. Forest. Rural Develop., Forest Fire Res. Inst. 9 p.

Beall, H.W. 1948. Forest fire danger tables (provisional), 2nd edition revised. Can. Dep. Mines Resources, Dominion Forest Serv. Forest Fire Res. Note 12. 73 p.

Byram, G.M. 1959. Combustion of forest fuels. Chapter 3 *in* K.P. Davis, ed. Forest fire: control and use. McGraw-Hill, New York. 585 p.

Kiil, A.D., and J.S. MacTavish. 1962. Forest fire danger tables: District of Mackenzie, Northwest Territories. Can. Dep. Forest., Forest Res. Br. 12 p.

Lawson, B.D. 1972. An interpretive guide to the Canadian Forest Fire Behavior System. Can. Forest. Serv., Pacific Forest Res. Centre Rep. BCP-3-72.

MacTavish, J.S. 1965. Forest fire danger tables: British Columbia Coast. Can. Dep. Forest. Publication 1099. 20 p.

McArthur, A.G. 1967. Fire behaviour in eucalypt forests. Australia Forest. Timber Bur., Forest Res. Inst. Leafl. 107. 36 p.

Muraro, S.J. 1968. A modular approach to a revised national fire danger rating system. *In* Contributions on the development of a national fire danger rating system. Can. Forest. Serv., Pacific Forest Res. Centre Inform. Rep. BC-X-37. 9 p.

Muraro, S.J. 1971. A burning index for spruce-fir logging slash. Can. Forest. Serv., Pacific Forest Res. Centre. Suppl. BC-3 to Canadian Forest Fire Behavior System. 16 p.

Muraro, S.J., R.N. Russell, and B.D. Lawson. 1969. Development of diurnal adjustments table for the Fine Fuel Moisture Code. Can. Forest. Serv., Pacific Forest Res. Centre Inform. Rep. BC-X-35. 24 p.

Muraro, S.J., and B.D. Lawson. 1970. Prediction of duff moisture distribution for prescribed burning. Can. Forest. Serv., Pacific Forest Res. Centre Inform. Rep. BC-X-46. 23 p.

Nelson, R.M. 1964. The National Fire Danger Rating System: Derivation of Spread Index for eastern and southern states. U.S. Forest Serv., Southeastern Forest Exp. Sta. Res. Pap. SE-13. 44 p.

Nikleva, S., and L.E. Parent. 1971. Calculation of fire danger indices by computer. Can. Dep. Environ., Atmos. Environ. Serv. Tech. Mem. TEC757. 7 p.

Paul, P.M. 1969. Field practices in forest fire danger rating. Can. Forest. Serv., Forest Fire Res. Inst. Inform. Rep. FF-X-20. 27 p.

Paul, P.M. 1970. Fire weather forecasting for the Maritime Provinces (1964-70). Can. Forest. Serv., Maritimes Forest Res. Centre Inform. Rep. M-X-22. 79 p.

Paul, P.M., and J.S. MacTavish. 1965. Forest fire danger tables: British Columbia - Cariboo. Can. Dep. Forest. Publication 1101. 18 p.

Pouliot, L. 1970. Prévision de météorologie forestière au Québec. Serv. Can. Forêts, Inst. Rech. Feux Forêts. Rap. d'Inform. FF-X-24. 55 p.

Quintilio, D. 1972. A burning index for lodgepole pine logging slash. Can. Forest. Serv., Northern Forest Res. Centre. Suppl. NFRC-1 to Canadian Forest Fire Behavior System.

Simard, A.J. 1969. Variability in wind speed measurement and its effect on fire danger rating. Can. Forest. Serv., Forest Fire Res. Inst. Inform. Rep. FF-X-19. 39 p.

Simard, A.J. 1970. Reference manual and summary of test fire, fuel moisture, and weather observations made by forest fire researchers between 1931 and 1961. Can. Forest. Serv., Forest Fire Res. Inst. Inform. Rep. FF-X-25. 113 p.

Simard, A.J. 1971. Calibration of surface wind speed observations in Canada. Can. Forest. Serv., Forest Fire Res. Inst. Inform. Rep. FF-X-30. 19 p.

Simard, A.J., and J. Valenzuela. 1972. A climatological summary of the Canadian Forest Fire Weather Index. Can. Forest. Serv., Forest Fire Res. Inst. Inform. Rep. FF-X-34. 425 p.

Stocks, B.J. 1971. Fire severity index distribution in Ontario 1963 to 1968. Can. Forest. Serv., Great Lakes Forest Res. Centre Inform. Rep. O-X-151. 18 p.

Stocks, B.J. 1972. A burning index for jack pine logging slash. Can. Forest. Serv., Great Lakes Forest Res. Centre. Suppl. ONT-1 to Canadian Forest Fire Behavior System.

Turner, J.A. 1966. The stored moisture index: a guide to slash burning. Brit. Columbia Forest Serv., Protect. Div. 7 p.

Turner, J.A. 1972. The Drought Code component of the Canadian Forest Fire Behavior System. Can. Dep. Environ., Can. Forest. Serv. Publication 1316.

Van Wagner, C.E. 1970a. New developments in forest fire danger rating. Can. Forest. Serv., Petawawa Forest Exp. Sta. Inform. Rep. PS-X-19. 4 p.

Van Wagner, C.E. 1970b. An index to estimate the current moisture content of the forest floor. Can. Dep. Fish. Forest. Can. Forest Serv. Publication 1288. 23 p.

Van Wagner, C.E. 1970c. Conversion of Williams' severity rating for use with the Fire Weather Index. Can. Forest. Serv., Petawawa Forest Exp. Sta. Inform. Rep. PS-X-21. 5 p.

Van Wagner, C.E. 1972a. Duff consumption in eastern pine stands. Can. J. Forest Res. 2(1):34-39.

Van Wagner, C.E. 1972b. A diurnal table for the Fine Fuel Moisture Code. Can. Forest. Serv., Petawawa Forest Exp. Sta. Inform. Rep. PS-X-38. 8 p.

Williams, D.E. 1959. Fire season severity rating. Can. Dep. Northern Aff. Nat. Resources, Forest Res. Div. Tech. Note 73. 13 p.

Williams, D.E. 1964. Forest fire danger manual. Can. Dep. Forest. Publication 1027. 28 p.

Wright, J.G. 1933. Forest-fire hazard tables for mixed red and white pine forests. Can. Dep. Interior, Forest Serv. Forest-Fire Hazard Pap. 3. 20 p.

Wright, J.G. 1937. Preliminary improved fire hazard index tables for pine forests at Petawawa Forest Experiment Station. Can. Dep. Mines Resources, Dominion Forest Serv.

Wright, J.G., and H.W. Beall. 1938. Preliminary improved forest-fire hazard tables for eastern Canada. Can. Dep. Mines Resources, Dominion Forest Serv. Forest-Fire Res. Note 5. 42 p.

APPENDIX I

Symbols and Abbreviations

SYMBOLS AND ABBREVIATIONS

All quantities used in the numbered equations are represented in the following list by single letters, sometimes with subscript. The symbols are arranged in groups according to their place in the whole. All moisture contents are in percent.

Weather

T - noon temperature, degrees F

H - noon relative humidity, percent

W - noon wind speed, mph

r_o - rainfall in open, measured at noon, inches

r_e - effective rainfall, DMC

r_d - effective rainfall, DC

Fine Fuel Moisture Code (FFMC)

m_o - fine fuel moisture content from previous day

m - fine fuel moisture content after drying

E_d - fine fuel EMC for drying

E_w - fine fuel EMC for wetting

k - log drying rate, FFMC, $\log_{10}$ m/day

$f(r_o)$ - rainfall function in FFMC

C - correction term in FFMC rain effect

F_o - previous day's FFMC

F_r - FFMC after rain

F_1 - FFMC before temperature adjustment

ΔF - temperature adjustment for FFMC

F - present day's final FFMC

Duff Moisture Code (DMC)

M_o - duff moisture content from previous day

M_r - duff moisture content after rain

M - duff moisture content

K - log drying rate in DMC, $\log_{10}$ M/day

L_e - effective day length in DMC, hours

b - slope variable in DMC rain effect

P_o - previous day's DMC

P_r - DMC after rain

P - DMC

Drought Code (DC)

Q - moisture equivalent of DC, 0.01 inch water

Q_o - moisture equivalent of previous day's DC

Q_r - moisture equivalent after rain

V - potential evapotranspiration, units of 0.01 inch water per day

L_f - day length adjustment in DC

D_o - previous day's DC

D_r - DC after rain

D - DC

Fire Weather Index (FWI)

$f(W)$ - wind function

$f(F)$ - fine fuel moisture function

$f(D)$ - duff moisture function

R - Initial Spread Index (ISI)

U - Adjusted Duff Moisture Code (ADMC)

B - FWI (intermediate form)

S - FWI (final form)

APPENDIX II

Equations and Procedures

EQUATIONS AND PROCEDURES

Fine Fuel Moisture Code (FFMC)

$$F = 101 - m \quad (1)$$

$$k = 0.424\ [1-(H/100)^{1.7}] + 0.088\ W^{0.5}\ [1-(H/100)^{8}] \quad (2)$$

$$E_d = 0.942\ H^{0.679} + 11e^{(H-100)/10} \quad (3)$$

$$E_w = 0.597\ H^{0.768} + 14e^{(H-100)/8} \quad (4)$$

$$\ln\ (m - E_d) = \ln\ (m_o - E_d) - 2.303k \quad (5)$$

$$\ln\ (E_w - m) = \ln\ (E_w - m_o) - 0.69 \quad (6)$$

$$\Delta F = (T - 70)\ (0.63 - 0.0065\ F_o) \quad (7)$$

$$F = F_1 + \Delta F \quad (8)$$

$$F_r = (F_o/100)\ f(r_o) + 1 - C \quad (9)$$

$$f(r_o) = -56 - 55.6\ \ln\ (r_o + 0.04),\ 0.02 < r_o < 0.055 \quad (10a)$$

$$f(r_o) = -1 - 18.2\ \ln\ (r_o - 0.04),\ 0.055 < r_o < 0.225 \quad (10b)$$

$$f(r_o) = 14 - 8.25\ \ln\ (r_o - 0.075),\ r_o > 0.225 \quad (10c)$$

$$C = 8.73\ e^{-0.1117\ F_o} \quad (11)$$

The FFMC is calculated as follows:

1) The previous day's F becomes F_o.

2a) If $r_o > 0.02$ calculate $f(r_o)$ by one of Equations 10a, 10b, 10c.

b) Calculate C by Equation 11.

c) Calculate F_r by Equation 9.

3) Calculate E_d by Equation 3.

4) Calculate m_o from F_o (or F_r if rain) by Equation 1.

5a) If $m_o > E_d$, calculate k by Equation 2.

b) Calculate m by Equation 5.

6a) If $m_o < E_d$, calculate E_w by Equation 4.

b) If $m_o < E_w$, calculate m by Equation 6.

7) If $E_d > m_o > E_w$, let $m = m_o$.

8) Calculate F_1 from m by Equation 1.

9) Calculate ΔF by Equation 7.

10) Add ΔF to F_1 to get F (Equation 8).

There are three restrictions on the use of these equations:

1) Equation 9 must not be used when $r_o < 0.02$; that is, in dry weather the rainfall procedure must be skipped.

2) F_r cannot theoretically be less than zero. If a negative answer results from Equation 9, it should be raised to zero.

3) The right-hand bracketed quantity in Equation 7 must always be positive, which it no longer is when F_o exceeds 97. Therefore, when $F_o > 97$, set ΔF equal to zero. Within these restrictions, the FFMC equations will handle any values of rain, temperature, humidity, or wind, and give a sensible answer.

Note: The following changes in the FFMC drying routine have been made in a revised version of the FWI:

1) Set wind W constant at 8.

2) Replace Equation 7 by two separate effects on k and E as follows:

a) Multiply k (Equation 2) by the factor $0.242e^{0.0202T}$.

b) Add to E (Equation 3 or 4) the term (70-T)/10.

3) An equation for the wind correction has yet to be designed.

4) Calculate F from m (Equation 5 or 6) by Equation 1.

5) Restriction 3 then disappears.

Duff Moisture Code (DMC)

$$P = 244.72 - 43.43 \ln (M - 20) \quad (12)$$

$$r_e = 0.92\, r_o - 0.05 \quad (13)$$

$$M_r = M_o + 1{,}000\, r_e/(1.92 + b r_e) \quad (14)$$

$$b = 100/(0.5 + 0.3\, P_o) \quad , P_o \leq 33 \quad (15a)$$

$$b = 14 - 1.3 \ln P_o \quad , 33 < P_o \leq 65 \quad (15b)$$

$$b = 6.2 \ln P_o - 17.2 \quad , P_o > 65 \quad (15c)$$

$$K = 0.1052\, (T\text{-}30)\, (100 - H)\, L_e \times 10^{-5} \quad (16)$$

$$P = P_o \text{ (or } P_r) + 100K \quad (17)$$

The instructions for working out the DMC are:

1) The previous day's P becomes P_o.

2a) If $r_o > 0.05$, calculate r_e by Equation 13.

b) Calculate M_o from P_o by Equation 12.

c) Calculate b by one of Equations 15a, 15b, 15c.

d) Calculate M_r by Equation 14.

e) Convert M_r to P_r by Equation 12.

3) Take L_e from Table 2.

4) Calculate K by Equation 16.

5) Add 100K to P_o (or P_r if rain) to get the present day's DMC (Equation 17).

There are three restrictions on the use of the DMC equations, resulting from their empirical nature:

1) The rainfall effect must be skipped when $r_o < 0.06$. Otherwise r_e would be negative.

2) P_r must not be allowed to become negative. This means that M_r must be limited to a maximum of 300 after the use of Equation 14.

3) Values of T less than 30 must not be used in Equation 16. Otherwise K would be negative.

Drought Code (DC)

$$Q = 800\ e^{-D/400} \tag{18}$$

$$r_d = 0.83\ r_o - 0.05 \tag{19}$$

$$Q_r = Q_o + 100\ r_d \tag{20}$$

$$V = 0.2\ (T - 27) + L_f \tag{21}$$

$$D = D_o\ (\text{or } D_r) + 0.5\ V \tag{22}$$

The DC is determined daily in the following way:

1) The previous day's DC becomes D_o.

2a) If $r_o > 0.05$, calculate r_d by Equation 19.

b) Calculate Q_o from D_o by Equation 18.

c) Calculate Q_r by Equation 20.

d) Convert Q_r to D_r by Equation 18.

3) Take L_f from Table 3.

4) Calculate V by Equation 21.

5) Add one-half of V to D_o (or D_r) to get present day's DC.

These equations have three restrictions, similar to those necessary in the calculation of the DMC:

1) The rainfall effect must not be applied when $r_o < 0.06$.

2) Q must not be allowed to exceed 800.

3) T has a lower limit of 27 in Equation 21.

Initial Spread Index (ISI)

$$f(W) = e^{0.0811W} \quad (23)$$

$$f(F) = (91.9\, e^{-0.1386m})\ (1 + m^{4.65}/7{,}950{,}000) \quad (24)$$

$$R = 0.208\ f(W)f(F) \quad (25)$$

Adjusted Duff Moisture Code (ADMC)

$$U = 0.8PD/(P + 0.4D) \quad (26)$$

Fire Weather Index (FWI)

$$f(D) = 0.626U^{0.809} + 2 \quad (27)$$

$$B = 0.1R\ f(D) \quad (28)$$

$$\ln S = 2.72(0.434\ \ln B)^{0.647} \quad (29)$$

The final steps in the calculation are straightforward:

1) Calculate f(W) and f(F) by Equations 23 and 24.

2) Calculate ISI by Equation 25.

3) Calculate ADMC by Equation 26.

4) Calculate f(D) by Equation 27.

5) Calculate B by Equation 28 and S by Equation 29.

Equation 29 has one restriction. When B is less than 1, its logarithm cannot be taken to a fractional power. In such cases, set S equal to B.

1333-4-74-2M