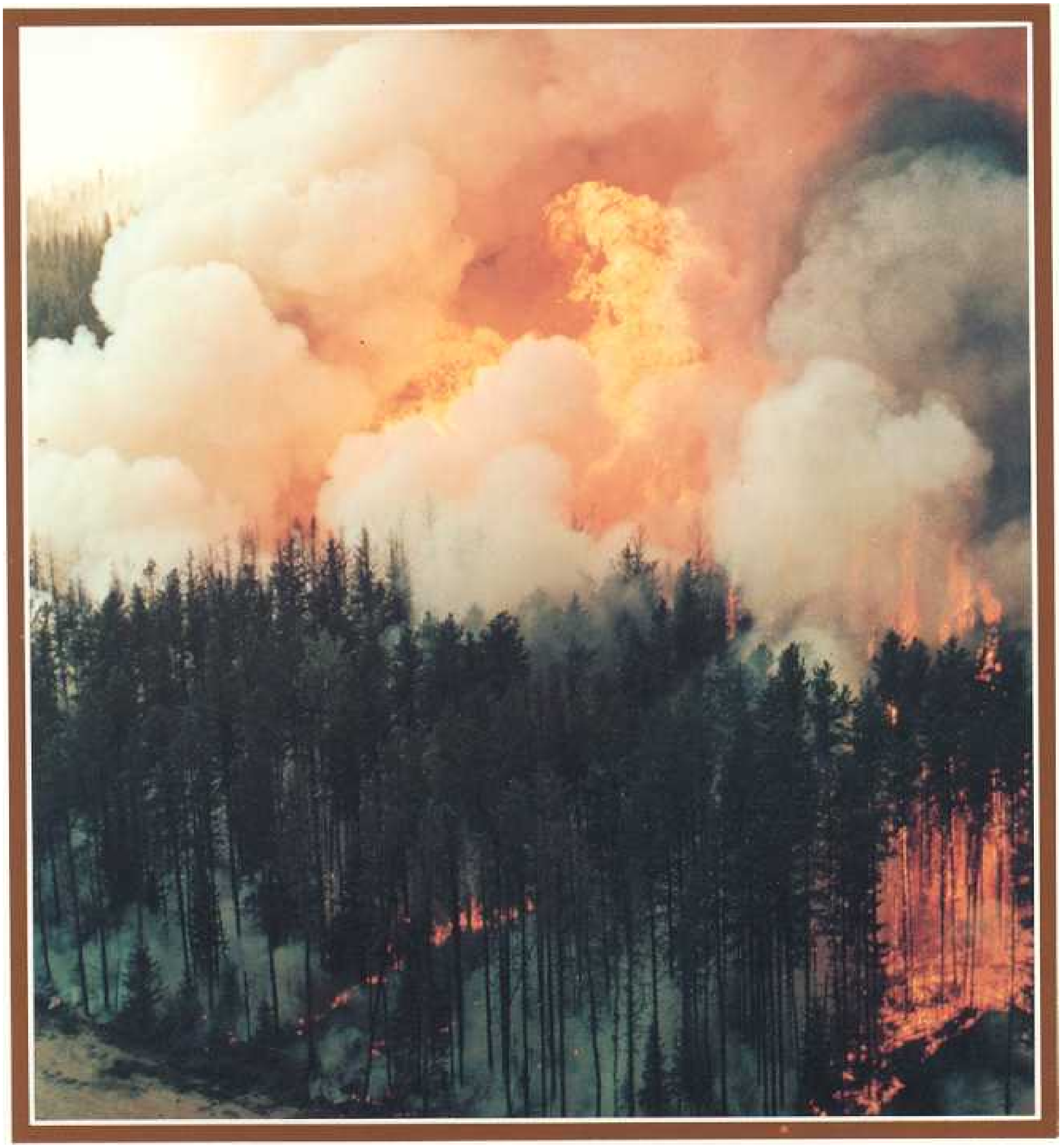
Development and Structure of the Canadian Forest Fire Weather Index System



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3. Provision and analysis of national and international statistics and information as a basis for policy formulation.

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Development and Structure of the Canadian Forest Fire Weather Index System

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Résumé en français

Canadian Forestry Service
Forestry Technical Report 35
Ottawa 1987

Catalog No. FO64-35/1987E
ISBN 0-662-15198-4

Additional copies of this publication are available at no charge from:

Canadian Forestry Service
Place Vincent Massey, 3rd Floor
Ottawa, Ontario
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A microfiche edition of this publication may be purchased from:

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Cette publication est aussi disponible en français sous le titre
Élaboration et structure de l'Indice Forêt-Météo de la méthode canadienne.

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INTRODUCTION

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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);
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7. Subsidiary hazard indexes for specific fuel types such as "fast-drying," slash, grass, and reindeer lichen.

In the years leading to 1970, the forest fire control agencies became more and more sophisticated and made increasing demands on this fire danger system in ways that were not foreseen during its development in the mid–1950s. 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). No additional weather observations were to be required, but the trend toward further simplification was to be reversed to some extent. 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 original version of the Fire Weather Index and its subsidiary components was issued in 1970 (Canadian Forestry Service 1970). Subsequent editions of the index tables appeared in 1976, 1978, and 1984 (Canadian Forestry Service 1976, 1978, 1984). These incorporated some mathematical changes as well as a conversion from Imperial to metric weather units; however, the basic continuity of output has been maintained. The Fire Weather Index System thus retains a solid link with previous systems and is, in effect, a further step along the same path taken by J.G. Wright when he founded Canadian research on forest fire in 1925.

PREFACE

The original Canadian Forest Fire Weather Index System issued in 1970 was the result of four years' effort, in which many fire research staff of the Canadian Forestry Service took part. The principal work was done by S.J. Muraro and J.A. Turner of the Pacific Forest Research Centre (now the Pacific Forestry Centre), A.J. Simard of the Forest Fire Research Institute (later amalgamated with the Petawawa National Forestry Institute), and C.E. Van Wagner of the Petawawa Forest Experiment Station (now the Petawawa National Forestry Institute). 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 system developed included R.C. Henderson, B.D. Lawson, and R.N. Russell of the Pacific Forest Research Centre, A.D. Kiil, D. Quintilio, and J.E. Grigel of the Northern Forest Research Centre (now Northern Forestry Centre), B.J. Stocks and J.D. Walker of the Great Lakes Forest Research Centre (now Great Lakes Forestry Centre), E.W. Howard and D.B. Bradshaw of the Newfoundland Forest Research Centre (now Newfoundland Forestry Centre), and D.G. Fraser, L.B. MacHattie, P.M. Paul, L. Pouliot, 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.

Subsequent maintenance and further development of the Fire Weather Index System has been in the hands of the Candian Forestry Service's Fire Danger Working Group, currently comprising M.E. Alexander of the Northern Forestry Centre, B.D. Lawson of the Pacific Forestry Centre, B.J. Stocks of the Great Lakes Forestry Centre, and C.E. Van Wagner of the Petawawa National Forestry Institute.

The present publication is a revision of Departmental Publication 1333, "Structure of the Canadian Forest Fire Weather Index" issued in 1974 by the Canadian Forestry Service, Department of Environment.

ABSTRACT

The Canadian Forest Fire Weather Index (FWI) System was first 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. The system 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 System refers primarily to a standard pine fuel type but is useful as a general measure of forest fire danger in Canada. Its components are determined every day from noon weather readings: temperature, relative humidity, wind speed, and rain (if any). The development of the Fire Weather Index, the concepts behind it, and its mathematical structure are described in this paper. Revised versions of the Fire Weather Index System were issued in 1976 and 1984.

RÉSUMÉ

L'Indice Forêt-Météo (IFM) est un indice des conditions météorologiques propices aux incendies de forêts. Il a été 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 ont été retenues dans le nouvel indice et un lien a été 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 de feu sous forme de rendement énergétique par unité de longueur. L'IFM 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). Ce document décrit le développement de l'IFM, les concepts qui ont présidé à sa préparation, et sa structure mathématique. De nouvelles versions de l'IFM ont été publiées en 1976 et 1984.

Correct citation

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

INTRODUCTION

Since research on forest fire danger rating was begun in Canada by J.G. Wright in 1925, the value of keeping track of the day-to-day susceptibility of the forest to fire has gained 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 systems are (1) Wright (1933), (2) Wright and Beall (1938) with supplement by Beall (1939), (3) Beall (1948), and (4) Forestry Branch (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 (Forestry Branch 1959, Kiil and MacTavish 1962, Paul and MacTavish 1965, and MacTavish 1965).

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THE BASIC STRUCTURE OF THE FIRE WEATHER INDEX SYSTEM

The Fire Weather Index (FWI) System comprises six standard components. The first three are fuel moisture codes that follow daily changes in the moisture contents of three classes of forest fuel with different drying rates. The last three components are fire behavior indexes representing rate of spread, fuel weight consumed, and fire intensity. The system depends solely on weather readings taken each day at noon local standard time (LST): temperature, relative humidity, wind speed, and rain (if any) during the previous 24 hours. The current month must also be specified. In basic form, the FWI System is a set of equations (Van Wagner and Pickett 1985) 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 nine tables derived directly from these equations (Canadian Forestry Service 1984).

It should be understood that although the FWI is calculated from noon weather readings, it really represents fire danger at its midafternoon peak, generally specified as 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 System is similar to all previous Canadian systems used since 1938.

For each of the three fuels embodied in the FWI System a subsidiary index was developed with two phases, one for wetting by rain and one for drying. These subindexes, called fuel 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 as moisture content decreases 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 0.25 kg/m^2;

2. *Duff Moisture Code (DMC)*, which represents the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg/m^2 when dry;

3. *Drought Code (DC)*, which represents a deep layer of compact organic matter weighing perhaps 25 kg/m^2 when dry.

Although 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 its instantaneous drying rate is proportional to its current free moisture content. The proper measure of drying speed is either the timelag (i.e. time to lose 1–1/*e* [about 2/3] of the free moisture above equilibrium), or the slope of the exponential curve of free moisture content over time, here called the log drying rate. Table 1 gives for each moisture code the timelag in terms of normal days (with noon temperature 21.1°C (70°F) and relative humidity 45 percent in July), as well as its water capacity, fuel properties, and the daily weather parameters required for calculation.

The two slow-reacting moisture codes, the DMC and DC, respond to changing daylength 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 noon atmospheric conditions. The midafternoon moisture content of fast-drying fuels, represented by the FFMC, is less dependent on day length.

Table 1. Properties of the three fuel moisture codes

Code	Timelag days	Water capacity mm	Required parameters[1]	Nominal fuel depth cm	Nominal fuel load kg/m^2
FFMC	2/3	0.6	T, H, W, r	1.2	0.25
DMC	12	15	T, H, r, mo	7	5
DC	52	100	T, r, mo	18	25

[1]T — temperature, H — humidity; W — wind, r — rain, mo — month.

The three moisture codes plus wind are linked in pairs to form two intermediate indexes that are in turn combined to yield the final index, the FWI (Figure 1). 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;

Buildup Index (BUI), 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 BUI 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 19 km/h. 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 also used in the development of the FWI. It was decided early on, however, that the main goal was a new fire danger index based solely on weather that could be used to give uniform results throughout 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. Equations are also included in order, as integral parts of the story. The symbols and abbreviations are identified as they are introduced, and all symbols are listed as well in Appendix I. Natural logarithms (to base *e*) are indicated by "ln", common logarithms (to base 10) by "log."

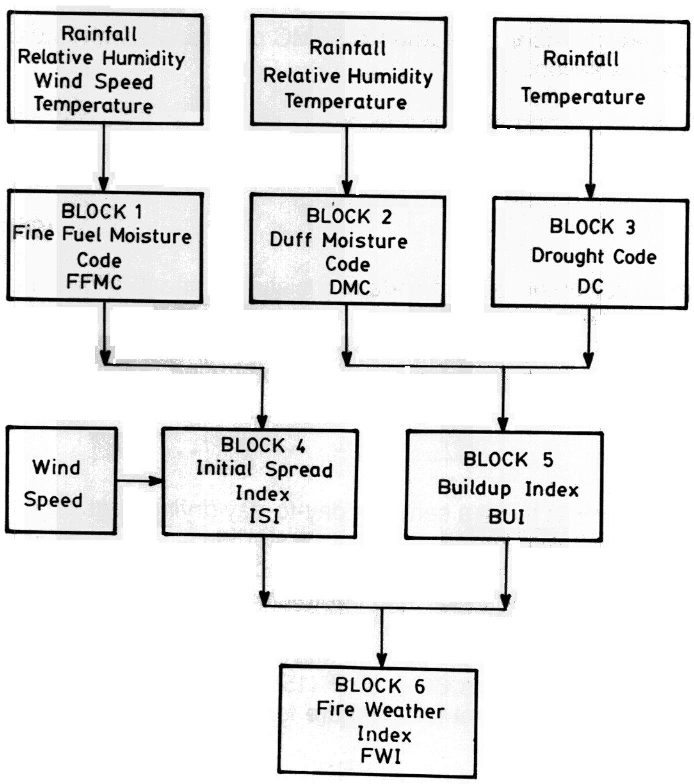

Figure 1. Block diagram of the Fire Weather Index System.

THE FINE FUEL MOISTURE CODE

BACKGROUND

The ancestor of the Fine Fuel Moisture Code (FFMC) 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 0.25 kg/m^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 retained, therefore, 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.

The following description of the Fine Fuel Moisture Code is fairly complete because there is no other substantial reference to it.

SCALE

The original Tracer Index was presented in the simple code form of 150 minus moisture content. Because the highest and lowest tracer values were 144 and 40, the scale length was 104. For the tabular version of the new system, a two-digit code was desired with maximum value of 99, a scale length 5 points less than the original. The minimum moisture content (m) was set at 2 percent, resulting in a scale equation

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

where F is FFMC. This scale was the basis of the FFMC in the first three editions of the FWI System, but was changed in the 1984 version on the following grounds:

1) The real moisture content of pine litter ranges up to about 250 percent.

2) A realistic moisture scale was desired to render the standard FFMC compatible with future developments in fine fuel moisture prediction.

A new scale, the FF scale, was devised, described by the following equations

$$= 59.5\,(250-m)/(147.2 + m) \tag{2a}$$

$$m = 147.2\,(101-F)/(59.5 + F) \tag{2b}$$

This scale (see Figure 2) permits realistic conversions from code to moisture content, allows the internal operations of the FFMC to be carried out on moisture content value, and retains the traditional code scale for quoting the FFMC itself. Furthermore, the former artificial 2 percent minimum limit on moisture content is no longer deemed necessary in computing practice. The potential code scale length is now 101.

DRYING PHASE

The first step in analyzing the Tracer Index 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 original temperature class 60 – 80°F (15.6 – 26.7°C). The class midpoint 70°F (21.1°C) was then taken to be the normal temperature for the whole analysis.

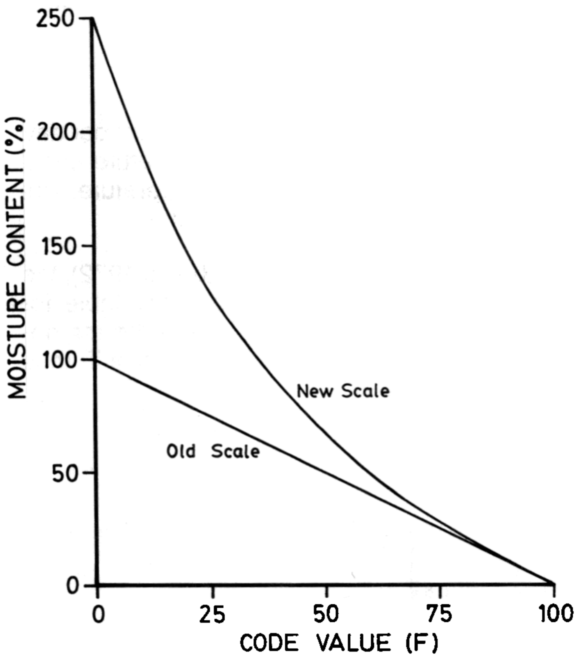

Figure 2. Graph of scales linking FFMC to fine fuel moisture content.

It was observed that, on the whole, these semilog lines were straight enough that exponential drying could be assumed. In other words, regardless of actual moisture content, 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

$$k = a + bW^{0.5} \tag{3}$$

where a and b are functions of H arranged to equal zero when H = 100. The complete equation in terms of H and W is

$$k_o = 0.424[1-(H/100)^{1.7}] + 0.0694W^{0.5}[1-(H/100)^8] \tag{4}$$

using k_o to indicate the log drying rate at the normal temperature of 21.1°C. The variation of k_o with H and W is illustrated in Figure 3. The use of the square root of wind emphasizes the proportionally greater effect of wind on drying rate at lower wind speeds, evident in both the Tracer Index and in the theory and laboratory evidence of Van Wagner (1979).

Third, the process of atmospheric wetting at high humidity was examined. By starting at maximum dryness, 24 semilog curves of day-to-day increases were obtained analogous to the drying curves. The variation in slope turned out to be very slight, around an average k value of 0.3. This constant value was incorporated into the first three editions of tables for the FWI system (Canadian Forestry Service 1970, 1976, 1978). But physical logic argues that the atmospheric wetting rate must be controlled by temperature and relative humidity, and evidence from both laboratory and field support this judgment. Accordingly, variation in wetting rate has been incorporated into the latest version of the FWI system tables (Canadian Forestry Service 1984) by recasting the drying rate equations in terms of 100–H instead of H, as follows:

$$k_o = 0.424\left[1-\left(\frac{100-H}{100}\right)^{1.7}\right] + 0.0694W^{0.5}\left[1-\left(\frac{100-H}{100}\right)^{8}\right] \tag{5}$$

where k_o is, in this case, the log wetting rate at the normal temperature of 21.1°C.

Fourth, the effect of temperature on drying and wetting rates was assigned from laboratory evidence. The temperature effect in the original Tracer Index was deemed too weak, providing only a 15 percent increase in drying rate for a 20°F (11.1°C) rise in temperature, whereas laboratory tests on pine needles indicated a 50 percent increase. The function to accomplish this temperature effect is, for temperature in degrees Celsius,

$$k = k_o \times 0.581e^{0.0365T} \tag{6}$$

where k is either log drying rate (k_d) or log wetting rate (k_w) in units of log moisture content per day. In the published account of these laboratory tests (Van Wagner 1979), the temperature effect becomes a straight line when graphed as log k versus the reciprocal of absolute temperature. The relation in Equation 6 above is essentially equivalent and is illustrated in Figure 3.

In the first edition of tables of the FWI system (Canadian Forestry Service 1970 and 1972), the FFMC was presented as one main table in terms of H and W, with a subsidiary table for temperature correction. Although expedient then, the results were not quite true to the mathematics. In later editions, separate tables in H and W have been given for each range of T, thus expressing the equations in proper fashion.

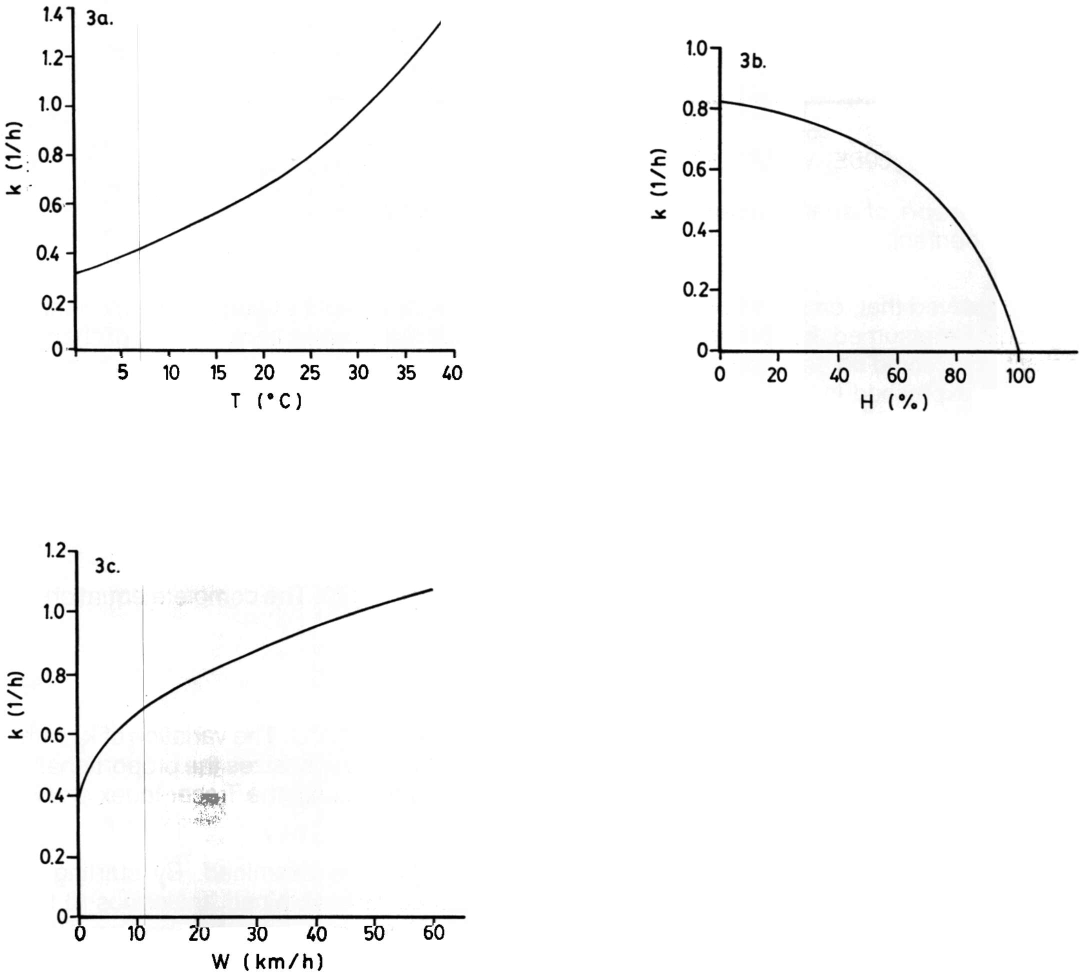

Figure 3. Variation of log drying rate k with T, H, and W in the FFMC: a) k vs T at constant H and W, b) k vs H at constant T and W, c) k vs W at constant T and H. Constant values are T = 21.1°C, H = 45%, W = 12 km/h.

Fifth, values of equilibrium moisture content E from the first step above were graphed, and the curves smoothed and partly modified in accordance with laboratory results for several kinds of forest litter (Van Wagner 1972a). In the original Tracer Index, values of E obtained by wetting were 1 to 2 percentage points lower than those obtained by drying. This hysteresis, also found in the laboratory, was retained in the present system. The new E curves, however, were made independent of wind speed, in contrast to the original. This was done partly for simplicity, and partly because in theory E should depend only on H and T.

This analysis of equilibrium moisture content (E), carried out for the original temperature class 60–80°F, was taken as valid for the normal temperature 70°F (or 21.1°C). Because the original Tracer Index showed no variation in E with temperature T, a temperature effect on E was therefore based on laboratory tests (Van Wagner 1972a). These indicated a shift of about 1 percentage point in E for every 10°F (5.6°C) change in T in the opposite direction.

The two curves of E *vs* H at the normal T (called isotherms), one for wetting and one for drying, were matched by an equation form supplied by J.A. Turner (Canadian Forestry Service, Pacific Forestry Centre), as follows:

$$E = a H^{b} + c\, e^{(H-100)/d} \qquad (7)$$

where a, b, c, and d are constants. To this basic form, the temperature effect was applied as an additive based on 21.1°C. Also, to provide for the convergence of both equations at zero when H = 0, an additional correction term, taking effect as H approaches zero, was designed. The complete equations for E in terms of H and T then emerge as

$$E_d = 0.942H^{0.679} + 11e^{(H-100)/10} + 0.18(21.1-T)(1-e^{-0.115H}) \qquad (8a)$$

$$E_w = 0.618H^{0.753} + 10e^{(H-100)/10} + 0.18(21.1-T)(1-e^{-0.115H}) \qquad (8b)$$

where E_d is the equilibrium moisture content obtained by drying from above, and E_w the equilibrium moisture content obtained by wetting from below, in percent moisture content based on dry weight. These are illustrated in Figure 4.

Finally, the drying phase of the FFMC now works as follows. If yesterday's moisture content (m_o) turns out to be higher than E_d, a drying regime prevails and the present day's moisture content (m) is found from

$$m = E_d + (m_o - E_d) \times 10^{-k_d} \qquad (9)$$

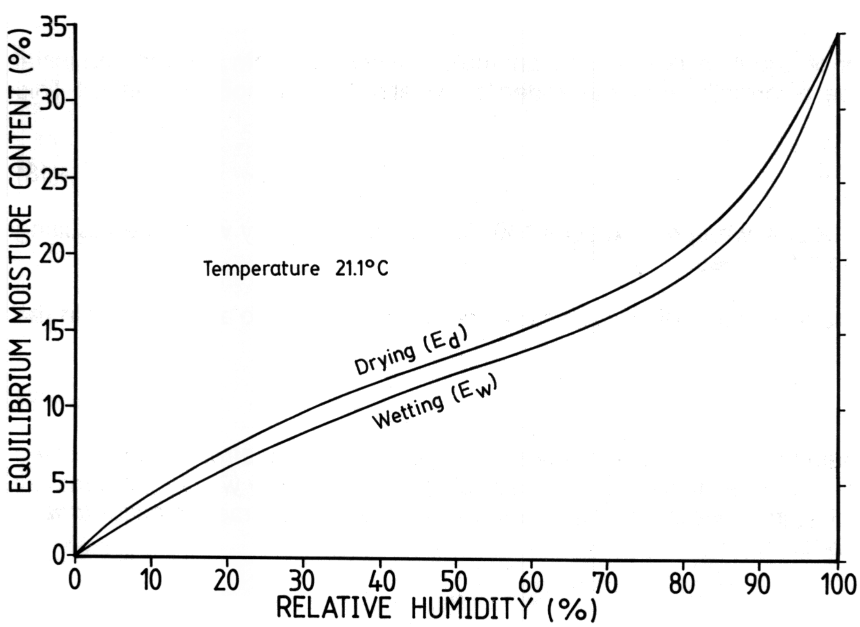

Figure 4. Isotherms of equilibrium moisture content E vs *relative humidity H at 21.1°C.*

If m_o turns out to be less than E_w, m is found from

$$m = E_w - (E_w - m_o) \times 10^{-k_w} \tag{10}$$

where k_d or k_w is the appropriate log drying or wetting rate obtained from Equation (5). If m_o lies between E_d and E_w, no change is assumed, and $m = m_o$.

RAINFALL PHASE

Next, the effect of rainfall on the Tracer Index was examined. The original rainfall table was analyzed for increase in moisture content per unit of rain. It was observed that this quantity decreased a) with increasing rainfall amount, and b) with increasing initial moisture content m_o. In other words, as the amount of rainfall increased, a smaller proportion of it was held by the litter; also, the higher the litter's initial moisture, the less rain it could absorb. For earlier versions of the FWI system, J.A. Turner supplied a set of three equations, for different ranges of rain amount, that matched the original rainfall table well. These operated on the code value. For the new version, a rainfall routine was required that operated on moisture content itself, rather than on code value. A new equation was therefore developed in the form

$$\Delta m/r = c\, e^{-b/(250-m_o)}\, (1-e^{-a/r}) \tag{11}$$

where Δm is increase in m due to rain r, and a, b, and c are constants. The 250 represents the maximum value of moisture content in the previously described FF scale. The rainfall effectiveness $\Delta m/r$ is decreased by the first bracketed term with increasing m_o, and by the second bracketed term with increasing r.

The constant c was first set as the limit of $\Delta m/r$ as m_o and r approach zero. For the standard FFMC fuel load of 0.25 kg/m^2, the first millimetre of rain should, therefore, cause a rise of 400 percent in m. This value was reduced to 42.5 to match the original Tracer Index rainfall table and Turner's equations, implying that the maximum effectiveness of rain in wetting litter is only about 10 percent and decreases from there.

Trials with other coefficients produced the following equation:

$$\Delta m/r_f = 42.5\, e^{-100/(251-m_o)}\, (1-e^{-6.93/r_f}) \tag{12}$$

The 251 appears in place of 250 in order to prevent division by zero should m_o ever equal 250; r_f is net rainfall, described below in Equation 14. When converted to code values, this equation's results match the output of the previous equations within one or two points over a wide range of rain amount and initial moisture content, with a slight exception explained below.

Because the behavior of Equation 12 is slightly anomalous when both rain amount and initial moisture content are large, a corrective term was added for use at high initial moisture content. This correction equals

$$0.0015\, (m_o-150)^2 r_f^{0.5} \tag{13}$$

It is added to Equation 12 only when m_o exceeds 150, and comes into play when the resulting FFMC code value is about 5 or less.

Finally, the amount of rain to be used in Equations 12 and 13 was reduced to allow for loss in the overhead canopy. Thus

$$r_f = r_o - 0.5 \tag{14}$$

where r_f is net rain amount and r_o is observed rainfall in the open, in millimetres. In other words rainfalls of up to 0.5 mm are to be ignored for purposes of the FFMC. In dry weather, the rainfall equations are not used. The increase in moisture content due to rain is assumed to occur always before the day's drying begins.

This completes the description of the Fine Fuel Moisture Code in its new version. It is also well recognized that fine fuel moisture content undergoes a strong wavelike diurnal variation. After the fuel is moistened by rain, this diurnal wave is superimposed on the general day-to-day trend until day-to-day equilibrium has been achieved. The FFMC thus describes the afternoon state only (forecast from noon observations), and other means are required to deal with fine fuel moisture at other times of day. Muraro et al. (1969) designed such a scheme, further developed into a Diurnal FFMC Table by Van Wagner (1972b). More recently, a computerized method depending on hourly (or at least frequent) weather data around the clock has become available (Van Wagner 1977).

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 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 wetting phases, it performed a useful function in the next two systems of danger rating.

When work began around 1970 on the first version of the FWI 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 because 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 60 × 40 cm in area set in the forest floor, and to weigh them daily. The DMC represents duff layers about 7 cm deep and 5 kg/m^2 in dry weight. Because a published description already exists (Van Wagner 1970a), only an outline of its structure is presented here.

SCALE

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

$$P = c\,[\log (M_{max} - E) - \log (M - E)] \tag{15}$$

where c is a scale constant, P is code value, M is moisture content, and E is the equilibrium moisture content. M_{max} was set equal to 300, and E to 20. The actual scale equation in natural logarithms for the chosen moisture limits of 300 and 20 percent was then

$$P = 244.72 - 43.43 \ln (M - 20) \tag{16}$$

This scale is illustrated in Figure 5. 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 unit of rain is inversely proportional to the amount of a rainfall.

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

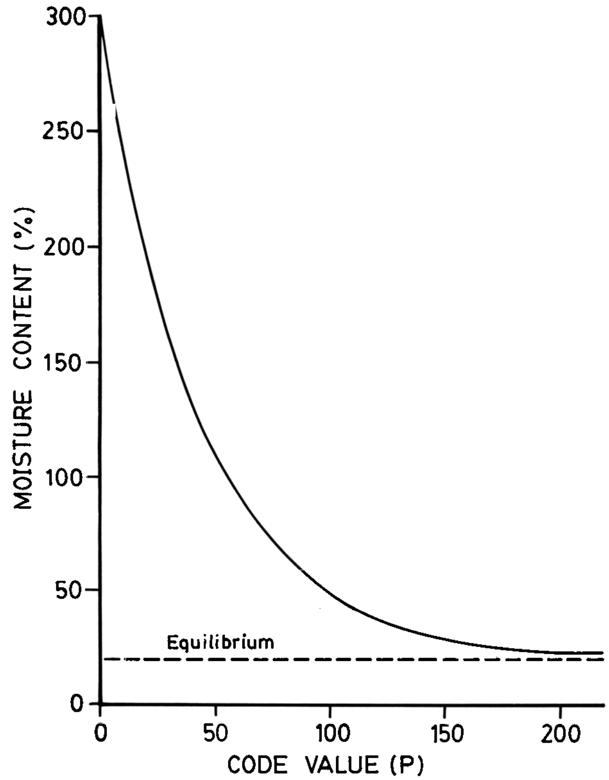

Figure 5. Graph of scale linking DMC to duff moisture content.

In other words, the duff layer retains a greater fraction of a light rainfall than 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

$$r_e = 0.92\, r_o - 1.27 \qquad r_o > 1.5 \tag{17}$$

where r_e is net rain amount and r_o is observed rainfall in the open. In any event, rainfalls of up to 1.5 mm are ignored for purposes of the DMC, and Equations 17 and 18 (below) are not used unless r_o exceeds that amount. The moisture content after rain (M_r) is given by

$$M_r = M_o + 1000\, r_e/(48.77 + br_e) \tag{18}$$

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:

$$b = 100/(0.5 + 0.3\, P_o) \qquad , P_o \leq 33 \tag{19a}$$

$$b = 14 - 1.3 \ln P_o \qquad , 33 < P_o \leq 65 \tag{19b}$$

$$b = 6.2 \ln P_o - 17.2 \qquad , P_o > 65 \tag{19c}$$

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 percent.

3) The log drying rate K is proportional to temperature, becoming negligible at about −1°C.

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

5) The daylength, 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

$$K = 1.894\,(T + 1.1)(100 - H)\,L_e \times 10^{-6}$$

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

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

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

Table 2. Daylength factor L_e in Duff Moisture Code

Month	L_e	Month	L_e
January	6.5	July	12.4
February	7.5	August	10.9
March	9.0	September	9.4
April	12.8	October	8.0
May	13.9	November	7.0
June	13.9	December	6.0

THE DROUGHT CODE

BACKGROUND

The Fine Fuel Moisture Code covers only the thin surface layer of fast-drying material, whereas the Duff Moisture Code applies to organic layers of moderate depth and 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 System 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 to follow the moisture state of a particular slow-drying forest fuel. Because soil loses moisture exponentially, such an index 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 18 cm deep and 25 kg/m^2 in dry weight. Deep duff layers of a similar nature under balsam fir forest at Petawawa and upland black spruce in northern Quebec have also been found to match the DC well in drying rate (Van Wagner 1974). 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[1] 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.

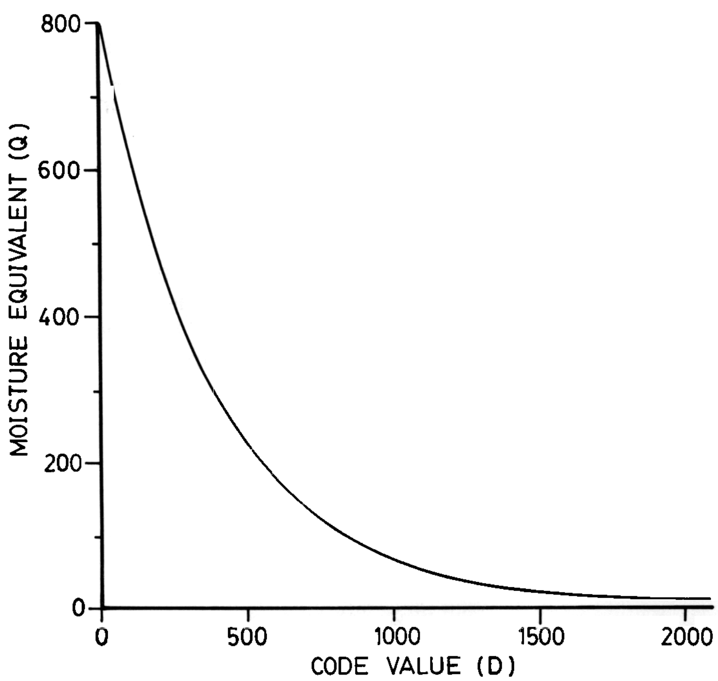

Figure 6. Graph of scale linking DC to its moisture equivalent Q.

[1]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 Internal Rep. A–34.

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 of the moisture equivalent Q, the chosen scale equation is

$$D = 400 \ln (800/Q) \tag{22}$$

where D is the current DC. The constant 400 represents the maximum theoretical moisture content of the fuel represented by the DC. 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 (Figure 6).

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

$$r_d = 0.83\, r_o - 1.27 \qquad , r_o > 2.8 \tag{23}$$

and $$Q_r = Q_o + 3.937 r_d \tag{24}$$

Rainfalls of up to 2.8 mm are ignored for purposes of the DC; Equations 23 and 24 are not used unless r_o exceeds that amount.

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:

$$V = 0.36\,(T + 2.8) + L_f \tag{25}$$

The seasonal daylength adjustment L_f is listed by month in Table 3. Because the scale length of the DC is in a sense one-half that of the original SMI (see Equation 22), the value of V is halved 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

$$D = D_o \text{ (or } D_r) + 0.5\,V \tag{26}$$

OVERWINTERING

The timelag of the DC, 52 days in standard weather, is long enough that the amount of precipitation during winter may affect the season's starting value. In other words, the assumption that melting snow always saturates the DC fuel layer cannot be counted on. Following the procedure of Turner and Lawson (1978), the DC starting value is computed from

$$Q_s = a\,Q_f + b\,(3.94 r_w) \tag{27}$$

where Q_f is final fall moisture equivalent (from final D by Equation 22),
r_w is winter precipitation in millimetres,
Q_s is starting spring moisture equivalent, and
a and b are constants.

The value of D corresponding to Q_s may then be found by Equation 22. This procedure now constitutes an integral aspect of the DC and its computation. The values of a and b are set according to the judgment of each agency and its advisors. Experience so far is that an overwinter adjustment is almost never necessary in eastern Canada, but will be needed occasionally in certain western regions as described, for example, by Alexander (1982).

Table 3. Daylength 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

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 behavior, preferably frontal fire intensity in terms of rate of energy output per unit length of fire front (after Byram 1959). From the experimental fire program at Petawawa there were available some 22 documented fires in pine stands, for which the Danger Index was known and the intensity could be calculated. Some fires burned in a jack pine stand, some in a mixed red pine and white pine stand, and some in a red pine plantation. These were all plotted on semilog paper as log intensity versus D–scale Fire Danger (Figure 7), in which the D–scale is shown extended beyond its normal limit of 16. (This work and the following scale development were based on the English–unit intensity in British Thermal Units per second–foot; however, an SI unit scale in kilowatts per metre is added to Figure 7 for comparison). The resultant grouping gave reasonable cause for assuming the D–scale to be a logarithmic function of intensity, according to the broken line in Figure 7.

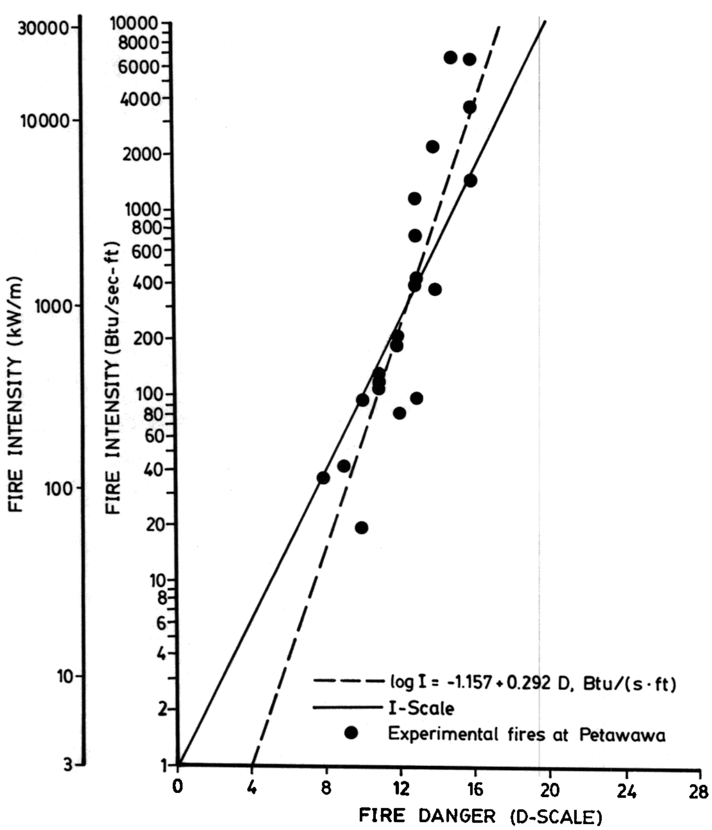

Figure 7. Graph of I–scale and the relation between the intensity of experimental fires and D–scale.

A modified line was now required to represent a generalized intensity interpretation of the D–scale, on two grounds:

1) The three most intense fires in Figure 7 were in the red pine plantation, judged to be more flammable than the so-called standard fuel type; therefore the upper portion of the line was shifted right.

2) The zero in Canadian fire danger rating is traditionally a condition wet enough that fires will not start and spread in even the most flammable fuel types; therefore the required line should pass through the origin of the D–scale, and the lower portion of the line shifted to the left.

The solid line in Figure 7, crossing the broken line at moderate intensity and reaching 1 Btu/(s–ft) at D–scale zero, was named the I–scale, and formed the link between the old and new systems of danger rating. Another desirable result of this adjustment is that the proportion of zeros can be kept below some reasonable level, say 20 percent of days, at locations with average fire climate in Canada.

Furthermore, it was decided to leave the new scale open at the top. This was in keeping with its concept as a function of frontal 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 becomes more severe. There is no artificial upper limit such as existed in the old system.

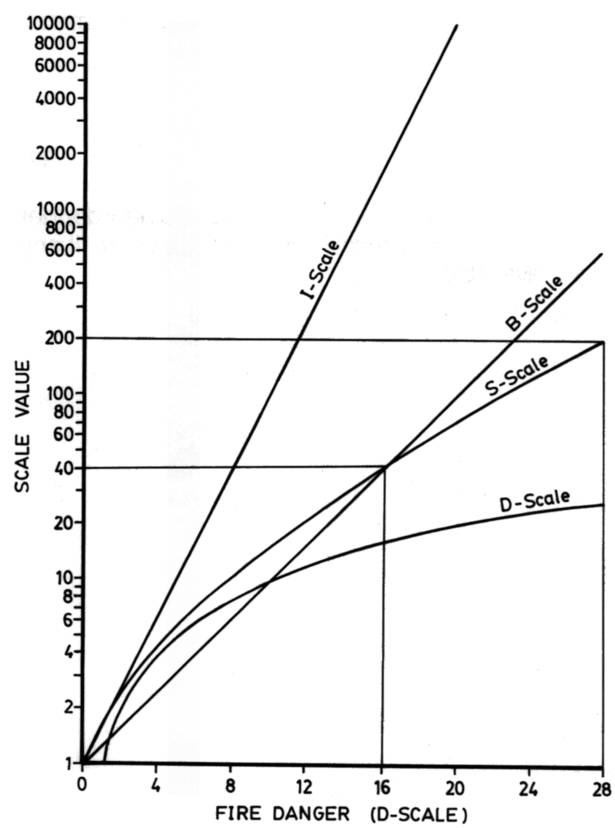

Figure 8. Four danger scales (I, B, S, and D) all graphed against D–scale, showing the two design points for the S–scale.

Since the I–scale values (Btu/[s–ft]) 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 developed called the S–scale, designed to equal 40 at D–scale 16 and 200 at D–scale 28. It yields values higher than the D–scale throughout its whole range; in practice, a level of 100 will occasionally be exceeded in Canada, but 200 will almost certainly never be reached. The FWI was recast on this scale, whose relations to the I–scale, B–scale, and D–scale can be seen in Figure 8.

Equations for these various scales are

$$= 10^{0.2D} = e^{0.461D} \qquad (28)$$

$$B = 10^{0.1D} = I^{0.5} = e^{0.230D} \qquad (29)$$

$$\begin{aligned} \ln S &= 0.614\ D^{0.647} = 1.587\ (\ln B)^{0.647} \\ &= 1.013\ (\ln I)^{0.647} \end{aligned} \qquad (30)$$

The above equations are all for I–scale in terms of British Thermal Units per second–foot. A pair of equations for conversion between S–scale and I–scale when fire intensity is in kilowatts per metre, the accepted present-day units, is given below.

$$\ln S = 1.013\ [\ln(0.289\ I)]^{0.647} \qquad (31)$$

$$\ln\ (0.289\ I) = 0.980\ (\ln S)^{1.546} \qquad 32)$$

Equations 28 to 32 constitute a formal but somewhat artificial link between the old and new danger scales and fire intensity. The intensity link in particular should be recalibrated specifically to fit any fuel type for which enough fire behavior data are available.

THE INITIAL SPREAD INDEX

BACKGROUND

It would have been easy to take the three moisture codes, together with wind (for its direct effect on the fire), and process them 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.

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 on fire spread. Its first function was to be an 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 total available fuel, the name was modified by prefixing "initial." In other words, the name refers not so much to the behavior of a fire during its early life just after ignition, but rather to the basic rate at which a fire will spread when the fine fuel is dry but further drying in depth is not well advanced. 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

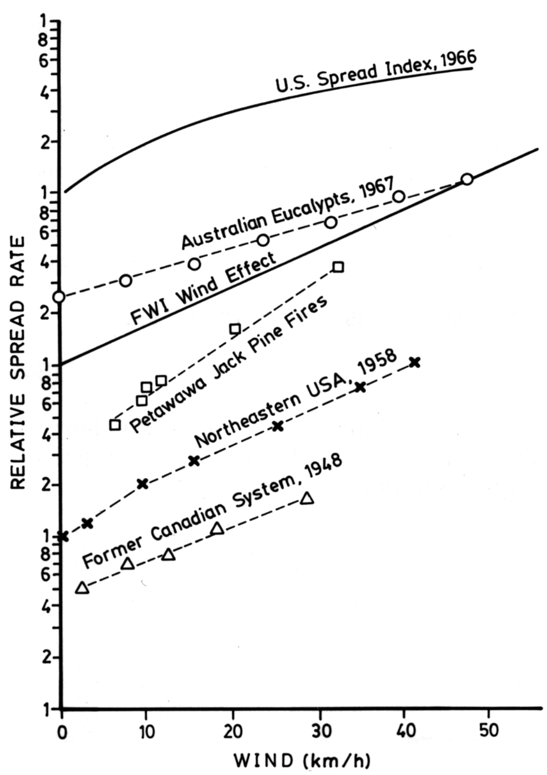

Figure 9. Effect of wind speed on relative spread rate in the ISI, along with wind effects from five sources. (Shape and slope of curves is relevant — their relative position is not).

at Petawawa. Some of these were graphed and described by Simard[2], and a few are shown in Figure 9, plotted on semilog paper as spread rate (or index) versus wind speed. 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 (U.S. Forest Service 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 Figure 9 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 method used in the systems shown in Figure 9 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-metre open wind, and this was adopted. The winds measured 1.2 m above ground in the forest during the Petawawa jack pine fires were multiplied by 5 for purposes of Figure 9. (This factor was obtained from a study of local wind speeds at different heights above ground.)

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

$$f(W) = e^{0.05039W}$$

where W is 10-metre open-wind speed in kilometres per hour. This function (see Figure 9) doubles the ISI for every 14 km/h increase in wind speed. It is fairly close to several published effects of wind on forest fire and matches fairly well the local 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 ISI 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 of FFM effect on fire spread yet exists. In contrast to the case of wind, however, empirical data have been collected over several decades by Canadian Forestry Service researchers on the effect of FFM on test fire behavior, all of which are embodied in the former system.

To derive an FFM function, f(F), 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 resulting function is a fairly straight descending line on semilog paper, four times as strong at 6 percent as at 16 percent FFM content, and flattening out gradually above 16 percent. It is shown graphed in Figure 10, with an Australian curve from McArthur (1967), an American curve from U.S. Forest Service (1966), and a curve from the previous Canadian system (Forestry Branch 1957). The empirical equation chosen as a reasonable fit is

$$f(F) = (91.9\ e^{-0.1386m})\ [1 + m^{5.31}/(4.93 \times 10^{7})] \qquad (34)$$

where m is fine fuel moisture content in percent, determined by Equation 2b. The second term on the right side of Equation 34 has been slightly modified from its original form in order to maintain compatibility of the ISI with the FFMC, whose changes were described earlier.

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

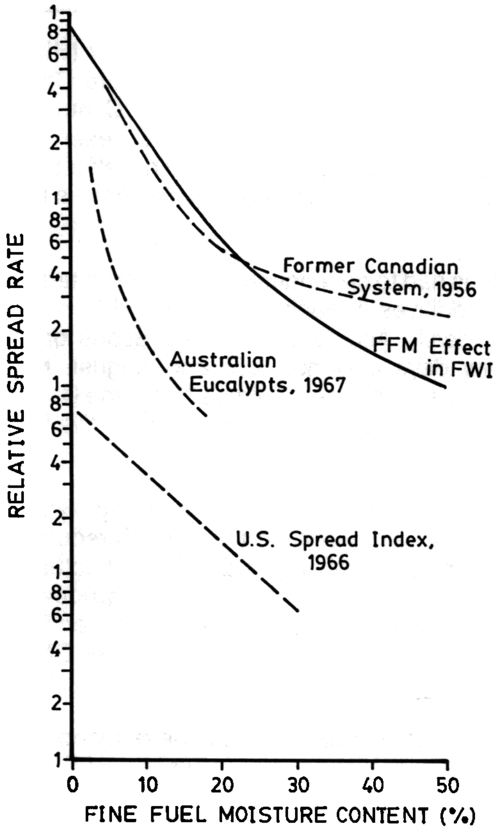

Figure 10. Effect of fine fuel moisture (FFM) on relative spread rate in the ISI, along with FFM effects from three sources. (Shape and slope of curves is relevant — their relative position is not).

THE ISI EQUATION

The ISI is merely the product of 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 — 13 km/h

Fine fuel moisture content — 6 percent

Old Drought Index — 25

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

$$R = 0.208\ f(W)\ f(F) \qquad (35)$$

where R is Initial Spread Index.

THE BUILDUP INDEX

The second of the two intermediates that lead directly to the FWI is the Buildup Index (BUI), formerly the Adjusted Duff Moisture Code; the BUI is a combination of the Duff Moisture Code (DMC) and the Drought Code (DC). Once it was decided to introduce the slow-acting 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 rendered 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, using nonrainy days in June, July, and August. 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 BUI) can be calculated, the DC must 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. Thus the reduced DC is almost always higher then 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 $2ab/(a+b)$. When the DMC and the reduced DC are combined in this way, the BUI is given by

$$U = 0.8\,PD/(P + 0.4D) \qquad , P \leq 0.4D \tag{36}$$

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

1) When the DMC is zero, the BUI 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 BUI is always greater than, but never more than double, the DMC alone.

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

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

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 BUI is simply a blend of two fuel moisture codes and retains their basic form, a logarithmic function of moisture content. A function was needed, therefore, to transform the BUI into a measure 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 the scales 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

$$\mathrm{DMC} = 13.0 + 2.92\ \mathrm{DRI} \tag{37}$$

(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 index structure, the average DMCs 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 85 on the DMC scale. Since the new danger system must handle rainless periods much longer than this, some justification for extrapolation was needed. In the original version of the FWI, 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 1972c).

Suppose that fire spreads by preheating and igniting the fine fuel layer only — say 0.25 kg/m^2. Any duff that contributes directly to frontal intensity must be ignited, therefore, 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 balance can be struck that will yield the weight of duff available as fuel for the fire-front. 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 (Figure 11). This theory, although incompletely secure, did 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 BUI that is used in the final equation. The equation for the original f(D) was, then

$$f(D) = 0.626U^{0.809} + 2 \tag{38a}$$

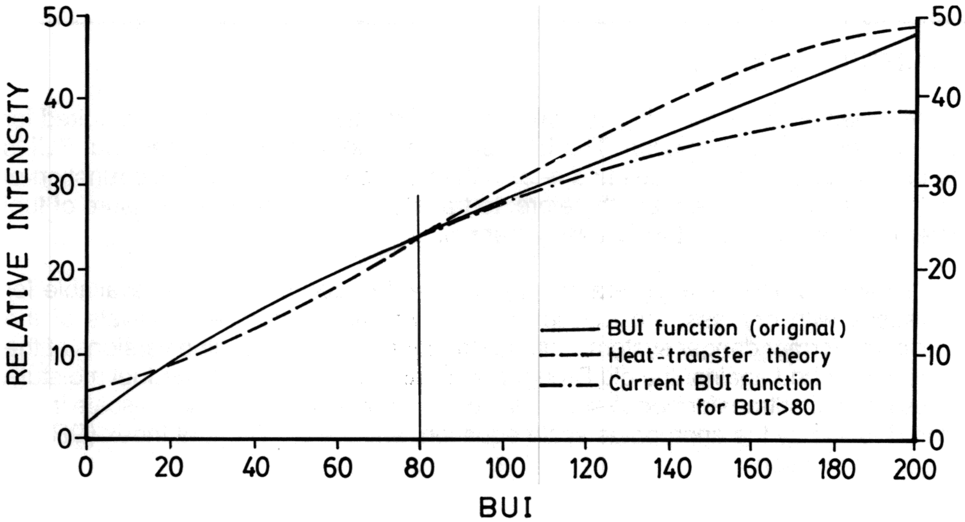

Figure 11. Effect of BUI on relative intensity in the FWI, showing new function above BUI 80, plus curve based on heat-transfer theory.

Although the theoretical curve in Figure 11 flattens off to a maximum value at high BUI, the chosen f(D), Equation 38a, did not, mainly because the theoretical form could not easily be adapted to the desired curve shape at low BUI. Subsequently, it was realized that Equation 38a allows the FWI to increase indefinitely with rising BUI, a condition not in keeping with the principle that there is a limit to the amount of fuel that can be engaged in the production of actual frontal intensity. A new equation was designed, therefore, to come into play at BUI 80 and eventually to level off at f(D) = 40. The FWI now reaches 90 percent of its potential value at BUI 160 and even an infinite BUI will yield no more than a further 10 percent increase. Analysis of the duff consumption data of Van Wagner (1972a) suggests that an f(D) of 40 is equivalent to about 2.5 kg/m^2 of duff consumption. Larger amounts, if consumed, are assumed to smolder behind the main fire front. Equation 38a is now used for BUI values up to 80; beyond that, f(D) is given by

$$f(D) = 1000/(25 + 108.64\, e^{-0.023U}) \qquad , U > 80 \qquad (38b)$$

This equation levels off, for considerations of scale, somewhat below the maximum of the theoretical curve, and is shown also in Figure 11.

THE FWI EQUATION

The functions required to calculate the FWI are now all at hand. The duff moisture function is given by Equations 38a and 38b. The reference constant, whose derivation was covered in the section describing the ISI, is already an integral part of the ISI. That constant was multiplied by 10 for convenience and, therefore, the ISI's value must be readjusted by the factor 0.1. The B–scale FWI is then given by

$$B = 0.1\, R\, f(D) \qquad (39)$$

The final S–scale FWI is then found from

$$\ln S = 2.72\, (0.434 \ln B)^{0.647} \qquad (40)$$

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[3] yields smaller and smaller values as the moisture codes decrease, but never a true zero. For general use, the FWI and its various system components are usually rounded to the nearest whole number; any FWI value of less than 0.5 will thus be reported as zero.

THE DAILY SEVERITY RATING

An optional additional component of the FWI System is the Daily Severity Rating (DSR). Severity rating was originally conceived by Williams (1959) to provide a measure of control difficulty in terms of the former fire danger index. It was recognized that the kind of scale appropriate for fire danger rating was not necessarily in direct proportion to the work required to suppress a fire. This nonlinearity with respect to control effort was pronounced in the former index and is still considerable in the FWI. Williams' (1959) formula was therefore adapted to fit the FWI by Van Wagner (1970b). The DSR is computed directly from the FWI by the equation

$$DSR = 0.0272S^{1.77} \tag{41}$$

The obvious effect is to weight the FWI sharply as it rises, in a manner deemed to reflect control difficulty in more direct proportion. The FWI itself is therefore not considered suitable for averaging and should be used as its single daily value only. Any averaging, whether spatially over a number of stations on a given day or at a single station over any period of time, is better accomplished through the DSR.

The DSR averaged for a whole fire season is termed the Seasonal Severity Rating (SSR), which can be used as an objective measure of fire weather from season to season, or fire climate from region to region. But it is, in itself, an incomplete measure of seasonal fire activity because the latter is also dependent on the ignition pattern and the control resources available.

[3]This is the standard equation to be used in calculating the FWI. It is not exactly identical to equation 30, which was calculated later at full precision.

CALCULATION

The codes and indexes of the FWI System may be determined either by computer or from tables. The basic form of the system is the standard set of equations. Most of these have been used in the present publication in explaining and illustrating the system's structure. The complete set is listed in Van Wagner and Pickett (1985), and includes several others designed to improve internal consistency in minor ways. The published set of tables (Canadian Forestry Service 1984) was derived from these equations.

Several historical computer programs have figured in the development of the FWI System and its use. The first was by Nikleva and Parent (1971). Others were designed by Simard (1970b), Engisch and Walker (1971), Kean (1975), and Kourtz (1980). The present official program (included in Van Wagner and Pickett 1985) processes the present equations to give the purest possible mathematical output, with no artificial constraints other than those required by the empirical nature of some of the equations. Although it is arranged to handle one station's weather data one season at a time, its mathematical routines serve as a standard of comparison, and may be incorporated as blocks into operational daily programs serving any number of stations.

A perennial problem in computation deserves mention. The traditional means of working out fire danger indexes in Canada in years past was by a set of manual tables; these by themselves formerly constituted the standard. The FWI System, however, is based on equations that can only be processed conveniently by computer. It is, of course, impossible to design a set of tables that will match the pure mathematical computer output all of the time. Great pains have been taken to make the tables as accurate as possible and to minimize bias in the average table output, but day-to-day error will occur to some degree in all codes and indexes. Most agencies now compute the FWI System output centrally and redistribute it to the individual stations. However, the tables are still in widespread use locally for quick answers as soon as weather observations are available. An agency then has two choices. It can adopt the mathematical output as standard, instructing any station that keeps a table record to adjust it occasionally to match the computer record. Or it can place the tables themselves in the computer, and adopt the table output as standard. Of course, this choice will be a matter of policy. Nevertheless, it is understood that whenever critical comparison or development is required the equation output is the true standard.

Since the FWI System depends only on weather readings and the date (by month), its output can just as easily be calculated from forecast weather to yield a forecast of fire danger. In cooperation with the Atmospheric Environment Service, most forest fire agencies now issue such forecasts up to 24 hours in advance of the standard noon determinations. Paul (1970), Pouliot (1974), and Nikleva (1975) have described operational procedures.

INTERPRETATION

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

$$I = HWR \tag{42}$$

where, in compatible units, H is heat of combustion, W is weight of fuel consumed per unit area, R is rate of advance, and 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 (Figure 7). Further, the ISI and BUI were designed to represent the factors R and W respectively in Byram's 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 therefore be thought of as embedded in the reference constant (see Equation 35).

Of course, owing to the distortion involved in the design of the S–scale, the FWI is not a direct proportional representation of frontal intensity. In fact another interpretation is possible. As shown in Figure 8, the S–scale is in a rough sense not unlike the square root of the I–scale, which represents fire intensity. But it is known (Byram 1959) that the flame length of surface fires is also approximately proportional to the square root of intensity. Thus, the FWI could in turn be pictured as roughly proportional to flame length, a useful visual measure of fire behavior.

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 fuel moisture codes may be relatively high or low in opposition to the other two. First, two or three good days' drying after heavy rain will produce a high FFMC while the DMC remains low. Second, muggy weather or light rain after a long dry period will produce a low FFMC while the DMC remains high. Third, the DC may rise or fall gradually while the other two codes fluctuate many times. As a result of this interplay, for instance, muggy calm weather after a considerably dry period will yield a moderate FWI. A sudden dry windy day will then cause the FWI to rise dramatically. The FWI is, in fact, considerably more variable from day to day than the old danger index on account of its stronger (but more realistic) wind effect.

All these considerations point to the impossibility of communicating a complete picture of daily fire danger in a single number. The other components of the FWI System are needed for full interpretation of the fire weather. The System can be pictured as a pyramid with the FWI at the top, and successively more components at each lower level:

First level — the FWI alone, with all effects combined as well a possible in a single number.

Second level — the ISI and BUI quoted separately, providing direct information on both spread rate and fuel consumption.

Third level — the FFMC, DMC, DC, and wind speed, all quoted separately, indicating the respective influences of surface dryness and wind on potential spread rate, and of medium and long-term dryness on potential fuel consumption.

A still lower level on such a pyramid might be the individual weather elements themselves plus, perhaps, the number of days since rain. But it is precisely because it is impossible to make sense out of such primary weather information that fire danger rating systems exist. The FWI System integrates weather effects, past and present, to yield far better measures of burning conditions and fire behavior potential than can be deduced from a simple collection of weather observations. The FWI alone is a suitable index for general public information. The ISI and BUI quoted separately are particularly recommended for general fire management usage, while the FFMC, DMC, and DC enter the picture for various special purposes. Wind speed is the primary weather factor of most direct current interest. Lawson (1972) has written an interpretation guide to the FWI System; it is aimed particularly at British Columbia but is generally applicable everywhere. He has also (Lawson 1977) produced a slide-tape presentation useful in training exercises.

CALIBRATION

No sooner was the FWI System put into practice throughout Canada than the question of how well its components would relate to various aspects of forest fire became of great interest. By calibration is meant the empirical correlations of system components with statistics of fire occurrence and fire size, rather than the prediction of individual fire behavior. Apart from many informal tests, formal large-scale studies have been published on the system's performance in Ontario, Alberta, and British Columbia. Stocks (1971), Turner (1973), Stocks (1974), and Kiil et al. (1977) have all analyzed several years' data from many stations. Their analyses show strong trends of fire activity with increasing severity of fire weather as portrayed by the FWI System's codes and indexes. Some principles that emerge from all these results are:

1) Fire occurrence is best related to the FFMC, the measure of fine surface fuel moisture content.

2) Fire area is best related to the ISI, which combines wind and fine fuel moisture, the two factors most responsible for fire spread.

3) Other system components may show good correlation with features of fire activity, depending on their information content. Thus, the FWI is a good indicator of all kinds of fire activity because it combines all factors in one number.

4) The BUI is a fair indicator of fire activity simply because dryness in depth contributes substantially to fire behavior. It reinforces any primary indicator.

5) Certain correlations may appear unfavorable, but this merely confirms that proper interpretation of any component is necessary. Thus, fire size may correlate negatively with the DC. If so, it will be because the DC rises slowly over the whole spring and summer, and will not reflect the common tendency for the most severe fire weather to occur early in the season. Use of the DC as a secondary rather than primary variable should correct this apparent anomaly.

Harrington et al. (1983) carried out a major study of how burned area in Canada relates to the FWI System, using weather data from 41 stations throughout Canada over the period 1953–1980. The best available burned area information was in the form of monthly totals by province and territory. The best linear correlations were with the DMC and the Daily Severity Rating (DSR); however, R^2 values were not particularly high. The probable reason is that fire danger and fire activity can vary considerably during a given month, and throughout a given province, so that monthly averages (or even extreme values) of any system component may bear a weak relation to the monthly burned area. The DMC performed best in this study probably because its timelag best matches the kind of weather trend necessary to produce good burning conditions on a monthly basis.

In all calibration work, the results are confounded by other factors, especially by variation in the number of fire-starting agents abroad in different kinds of weather, by the tendency of fire control effort to vary with degree of fire danger, and by the differences in fire control policy with latitude in certain jurisdictions. Such results will always require interpretation. Nevertheless, the ability of the FWI System to distinguish strongly the different degrees and aspects of fire danger has been well demonstrated.

Ultimately, the most desirable calibration of any fire danger index is in terms of the control effort needed per unit of fire perimeter. There is as yet no sound theory to link control effort with pertinent parameters of fire behavior, and the increasing variety of attack methods makes this a difficult problem indeed.

DANGER CLASSES

It is customary in fire danger rating to quote a danger class as well as or in place of an index number, especially for the general public. Although the FWI scale is uniform throughout Canada, the range of fire weather certainly is not. It makes sense, therefore, for each major jurisdiction to devise its own danger class system, assigning ranges in the FWI number scale to fit the regional pattern of fire weather. The following danger classes are in use in Canada: Very Low, Low, Moderate, High, Very High, and Extreme. Individual agencies generally use four or five of these six.

To develop a rational class breakdown, S.J. Muraro of the Pacific Forest Research Centre suggested the following procedure. First, compile a historical sample of FWIs over a number of seasons. Second, decide how many Extreme days should be allowed each season on the average, and set the lower limit of the Extreme class. Third, arrange the other classes on a geometric progression in terms of the I–scale, using a constant ratio of I–scale value from class to class. Finally, convert the I–scale values back to S–scale FWIs.

For example, suppose that FWI 30 has been chosen as the lower limit of Extreme. By Equation 32, the I–scale equivalent is 2309. The required constant ratio between classes (using all six) will then be the fifth root of 2309, or 4.706. Dividing 2309 successively by this number yields the lower limits of the other five classes. These are then converted back to S–scale FWIs by Equation 31, producing the following class ranges.

Danger class	I–scale lower limit	FWI range
Extreme	2309	30 +
Very High	491	17 – 29
High	104	9 – 16
Moderate	22	5 – 8
Low	4.7	2 – 4
Very Low	1.0	0 – 1

This mathematical procedure implies that the lower limit of the lowest class is 1, not 0. The zero value may then be added to its range to complete the picture.

This scheme provides a class structure that bears a progressive relationship to frontal fire intensity or flame length as portrayed by the FWI. Alternately, the FWI scale may simply be divided to provide some predetermined proportion of days in each class.

Simard and Valenzuela (1972) compiled distributions of fire weather and FWI System components for 364 individual stations across Canada, plus regional and provincial averages. Their data show that the severity of fire weather increases steadily from east to west across Canada, except that British Columbia includes within its borders both the wettest and driest forested areas in the nation. Furthermore, Simard (1973) incorporated these regional differences into a map of Canada that graphically portrays all this in the clearest possible way. A common fire danger system whose numerical values are constant with respect to weather but can be arranged in classes to suit the regional average weather is well suited to this national pattern.

LATITUDE

Latitude, along with time of year, influences the effective daylength and thereby the amount of drying that can be accomplished in any one day. The FWI System samples weather at one moment only, at noon LST, and the weather observations themselves tell nothing about daylength. The DMC and DC incorporate a daylength factor that changes month by month, but this trend can be valid, strictly speaking, at one latitude only. The FFMC incorporates no allowance for daylength. The effective range of latitude within Canada's forest is over 20°, and whether or not the FWI System should take this variation into account is a fair question. Some tests are described below.

Consider first the FFMC. Some average June hourly weather data from five stations at latitudes from 48° to 66°N were processed by the hourly FFMC computation described by Van Wagner (1977). The 1600 h FFMCs obtained by this method were compared with the standard FFMC worked from the noon observations; this latter presumably predicts the 1600 h actual value. The discrepancies, computed as 1600-hour value minus standard value, ranged from 1.1 at 48°N to 2.5 at 66°N, on base FFMCs in the high 80s. The correction, if it were desired, would be to progressively delay the standard observation time from 1200 h at lower latitudes to about 1400 h at higher latitudes. This is because the time of the maximum temperature and minimum RH in high summer is progressively later as latitude increases. However, the discrepancies were not judged serious enough to warrant officially recommending such revised procedures. The FFMC, in other words, measures the peak flammability condition reasonably well at all latitudes. Its diurnal range, however, does decrease markedly with latitude in high summer, meaning that fine fuel remains flammable for a longer proportion of the day as one proceeds north.

To test the DMC, theoretical daylength factors were computed for three latitudes 45°, 55°, and 65°N, and used to compute modified DMCs for the weather in a fairly dry season (actually 1967 at Lac la Biche). In comparison with the standard DMC, the output is tabulated below, based on six months, May to October.

	45°N	55°N	65°N	Standard
Season average	34.5	32.4	30.0	31.9
Maximum value	85	83	78	88

The standard version does not fit quite smoothly with the three special versions because its daylength factors were worked out empirically. Nevertheless, it represents the average case reasonably well. Several such tests were carried out, and the differences were again not judged serious enough to warrant supplying special DMCs for different latitudes.

The DC was tested in an analogous manner using the same season's weather data. The additive nature of the daylength adjustment in the DC produces higher differences than obtained with the DMC, especially toward the end of the season. The output of the three theoretical versions is tabulated with the standard DC below, again based on the six months from May to October.

	45°N	55°N	65°N	Standard
Season average	312	302	274	293
Maximum value	523	497	436	495

Again, the standard version was representative, and these variations were not judged great enough to warrant special DCs for different latitudes.

The three tests described above were computational only. True definitive testing for latitude effect would need field data, which are not yet available in sufficient quantity. In any event, because all three moisture codes are consistent with weather and its effect on regional fuels at any particular latitude, the problem of comparison among widely different latitudes will probably never become serious.

CONCLUSION

Because it was built up to represent fire behavior in a generalized standard fuel type, the FWI System will obviously have different meanings in different forest or fuel types. The initial interest was mainly in logging slash of different types (Muraro 1971, Quintilio 1972, Stocks 1972), but data linking spread rate with the FWI System in various forest and vegetation types has accumulated steadily. In fact the FWI System is just part of the larger Canadian Forest Fire Danger Rating System (CFFDRS), which now includes the Canadian Forest Fire Behavior Prediction (FBP) System, designed to provide quantitative estimates of fire behavior in particular fuel types. An interim version of this latter (Alexander et al. 1984) provides equations for predicting rate of spread in 14 vegetation and slash fuel types throughout Canada, as well as topographical adjustments and fire growth. It is on this line of work that further research and development will be concentrated in future.

It is apparent by now what "fire danger" in the Canadian context includes and what it does not. The CFFDRS incorporates the effects of weather (past and present), season, fuel moisture content, topography (for its effects on fine fuel moisture and on fire behavior) and fuel type on the rate of spread and energy output rate of forest fires. It does not (at least not yet) include the risk of fire as dependent on the presence of fire-starting agents, the effects of topography on access, or the general "difficulty of control" with respect to particular fire-fighting tactics. These latter are deemed to be part of some larger field, namely fire management in general.

The philosophy behind the development of the FWI System and the larger CFFDRS deserves a few final remarks. Throughout the nearly 60 years of work leading to the current system, the required information has been gathered in one or more of four different ways:

by random field sampling,

by controlled field experiment,

by laboratory experiment, or

by physics and mathematics.

The final development has always been based on data or information from two or more of these sources. Especially, the final analysis has always been in terms of the empirical field experience. Theory and laboratory results have been used to plan and analyze the field experiments but never to supplant them. The approach has thus been decidedly deductive rather than inductive throughout, and the success of the system may be attributed to this strategy.

Nevertheless, all who took part in developing the Fire Weather Index System 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. Therefore it is fully expected that, in keeping with the philosophy established by J.G. Wright and H.W. 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 management throughout Canada.

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APPENDIX I

SYMBOLS

SYMBOLS

All quantities used in the 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 of dry weight.

WEATHER

- T – noon temperature, degrees C
- H – noon relative humidity, percent
- W – noon wind speed, km/h
- r – rain in general
- r_o – rainfall in open, measured at noon, mm
- r_f – effective rainfall, FFMC
- r_e – effective rainfall, DMC
- r_d – effective rainfall, DC
- r_w – total winter precipitation, DC

FINE FUEL MOISTURE CODE (FFMC)

- m_o – fine fuel moisture content from previous day
- Δm – change in fine fuel moisture content due to rain
- m – fine fuel moisture content after drying
- E_d – fine fuel EMC for drying
- E_w – fine fuel EMC for wetting
- k_o – intermediate value of k
- k – log drying or wetting rate, log m/day
- k_d – log drying rate in particular
- k_w – log wetting rate in particular
- F_o – previous day's FFMC
- F – present day's FFMC

DUFF MOISTURE CODE (DMC)

- M_o – duff moisture content from previous day
- M_r – duff moisture content after rain
- M – duff moisture content after drying
- K – log drying rate in DMC, log M/day
- L_e – effective day length in DMC, hours
- b – variable in DMC rain effect
- P_o – previous day's DMC
- P_r – DMC after rain
- P – present day's DMC

DROUGHT CODE (DC)

Q	moisture equivalent of DC, units of 0.01 inch water
Q_o	moisture equivalent of previous day's DC
Q_r	moisture equivalent after rain
Q_f	final fall moisture equivalent
Q_s	starting spring moisture equivalent
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	present day's DC

INITIAL SPREAD INDEX (ISI)

$f(W)$	wind function
$f(F)$	fine fuel moisture function
R	present day's ISI

BUILDUP INDEX BUI

'esent day's BL

FIRE WEATHER INDEX (FWI)

$f(D)$	duff moisture function
B	FWI (intermediate form)
S	present day's FWI

SEVERITY RATING

DSR	Daily Severity Rating
SSR	Seasonal Severity Rating