

RESEARCH IN THE MEASUREMENT OF FOREST FIRE DANGER

by
H. W. Beall

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Fifth British Empire Forestry
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FOREWORD

This is the second publication in our series of reprints of early fire research papers. These reports contain much basic information on fire research techniques but unfortunately they have been "out of print" for many years. Thus, they have not been available to fire control personnel. For this reason, the Forest Fire Research Institute has undertaken a program of reprinting some of these early reports.

The author of Research in the Measurement of Forest Fire Danger is well known to foresters throughout the world. Herbert W. Beall was born in Ottawa in 1908 and received his early education at Lisgar Collegiate. He attended Queens University and the University of Toronto where he graduated B.Sc.F. in 1932.

As a student, Mr. Beall worked on fire research projects with Mr. J. G. Wright at the Petawawa Forest Experiment Station. After graduation, he joined the Forest Service of the Department of the Interior as an assistant to Mr. Wright in forest fire research. In 1941 he joined the RCAF, serving with radar units in the U.K. and Middle East. He left the RCAF in 1945 with the rank of Squadron Leader and returned to the Dominion Forest Service as Chief of the Forest Protection Division. In 1952 he was made Chief of Forestry Operations Division, Department of Northern Affairs and National Resources, responsible for the administration of shared-cost agreements with the provinces under the Canada Forestry Act. In 1961 he was appointed Director, Administration Branch, Department of Forestry, and in 1965 was named Special Adviser to the Deputy Minister, a position he still holds.

D. E. Williams
Director
Forest Fire Research Institute

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RESEARCH IN THE MEASUREMENT OF FOREST FIRE DANGER

INTRODUCTION

During the past twenty years, forest fires in Canada have burned a combined area roughly equal to four-fifths that of the Island of Great Britain. The direct loss sustained by the Canadian people as a result of these fires has been conservatively estimated at one hundred million dollars - a figure which does not include the less tangible, but no less real, effects of fire on stream-flow, erosion, soil fertility, wild life, scenic beauty and recreational value. During the period covered by these statistics a considerable portion of Canada's forested lands, and a large proportion of the accessible areas in which man-caused fires are most prevalent, were under some form of organized forest protection. In earlier years, for which (perhaps fortunately for the public conscience) reliable records are not available, forest fire damage may well have reached far more formidable proportions.

Enough has perhaps been said, without the aid of further statistics, to explain the emphasis which has been placed upon forest fire protection during the formative stage of Canadian forestry. Successful forest management cannot be practised without adequate assurance that depletion from destructive agencies will be held to small and reasonably well-defined proportions. That such assurance is still lacking in Canada is indicated by the fact that standing timber is not as yet regarded as an insurable risk.

FIRE-CONTROL PLANNING AND FIRE-DANGER MEASUREMENT

Systematic planning of the allocation of man-power and facilities for forest fire control, so as to achieve as far as possible a maximum of protection effectiveness without waste of expenditure, has been made necessary by (a) the size, complexity, and cost of the fire-control organizations which have been developed during the past quarter of a century, and (b) the great variation in fire danger, largely dependent on weather conditions, which occurs during a fire season.

Principles of forest fire control planning were evolved on the North American continent, more particularly in the United States of America, some fifteen years ago, by several investigators, among whom Hornby ^{10/} achieved notable success. Hornby's work made it possible to specify, for the Northern Rocky Mountain Region, the state of preparedness to be maintained by the protection force according to each of seven classes of fire danger, the danger class being determined by means of an integrating meter developed by Gisborne ^{8/}.

The close relationship between forest fire danger and weather conditions had, of course, long been recognized, and research workers both in the United States and Canada had devoted considerable attention to the production of an objective system of fire-danger measurement. Hornby's eminently practical application of danger-rating methods added impetus to the development of danger-rating systems which should be reliable, unbiased, and hence acceptable as a basis for the planned deployment of protection forces in anticipation of the outbreak of fire.

In Canada, an intensive study of the relationship between weather and forest flammability was begun in 1929 by Wright ^{13/}, at the Petawawa Forest Experiment Station (Ontario) of the Dominion Forest Service. This work to some extent paralleled, although with several important differences, Gisborne's highly successful investigations in the Northern Rocky Mountain region of the United States, begun some years earlier. Notable progress was made by these and other workers in both countries during the ten years preceding the war. By 1939, fire danger ratings were in practical use in three Canadian provinces and in the National Parks of Western Canada. During the war drastic curtailment of all phases of forest fire research became inevitable. Work was resumed by the Dominion Forest Service in 1946, and investigations are now in progress in both Eastern and Western Canada.

ELEMENTS OF FOREST FIRE DANGER AND THEIR EVALUATION

Definitions

Forest fire danger is defined by the society of American Foresters as: "The resultant of both constant and variable factors, which determines whether fires will start, spread, and do damage, and determines as well the difficulty of control. Covers both Risk and Hazard....." 11/

Fire risk refers to the probability of fire occurrence, and hence takes into account the prevalence of fire-starting agencies.

Fire hazard is a term used in the past with reference to the amount, character, arrangement, and moisture condition of the fuels, although a more restricted meaning is now advocated. 11/ In conformity with well-established practice in Canada, the Dominion Forest Service retains the term "hazard index" to designate a numerical rating in which are integrated the effects of fuel moisture and seasonal influences on the fire danger in a specific fuel type. It is thus to a large degree a measure of flammability or "the relative ease with which fuels ignite and burn." 11/

Factors of forest fire danger which are not generally treated as variable quantities in danger-rating systems include: (a) fuel conditions other than moisture content and seasonal changes; (b) accessibility; (c) exposure; (d) normal risk of ignition; (e) values protected, and the extent to which those values are susceptible to destruction by fire. Such "constant" factors should, however, be taken into account when the fire danger is measured in any given area; they affect the general level of the danger class but have little influence on short-term variations in fire danger.

"Variable" factors in the accepted sense include: (a) weather; (b) fuel moisture content, which for a given site is largely determined by weather; (c) season of the year, which influences vegetation and hours of daylight; (d) abnormal risks; and (e) visibility, in so far as it affects detection coverage. Risk and visibility have been included in some of the danger meters developed in the United States; they are not taken into account in the "Danger Index" given by Wright's method, which in its present stage is intended for use over rather extensive areas. Abnormal risks are generally specific to restricted localities, while the allowance to be made for visibility is to some degree governed by the character of the detection system. These factors may, however, be successfully integrated in the Wright System for use in specified areas 1/.

DEVELOPMENT OF THE WRIGHT SYSTEM

The Wright method of fire-danger measurement depends fundamentally on two relationships:

- (a) The relation between fire behaviour and the moisture content of the "critical" fuels, or materials in which fires usually start and spread.
- (b) The relation between fuel moisture content and the weather elements which control it.

Once these basic relationships have been determined experimentally for the principal fuel types of a region, and expressed by means of suitable tables, an estimate of the prevailing degree of fire danger may be obtained by daily observation of the appropriate weather factors only.

Fire-hazard investigations by the Dominion Forest Service were first made in the mixed red pine Pinus resinosa and white pine P. strobus type, in which the "critical" fuel was found to consist of the surface layer of leaf (needle) litter, or top-layer duff. The relationship between fire behaviour, observed by means of small test fires, and top-layer duff moisture content was established for this fuel type as follows:

<u>Moisture Content of Mixed Red and White Pine Top Layer Duff</u>	<u>Inflammability Zone</u>
<u>Per cent</u>	
24 and over	Nil
19 to 23	Low
15 to 18	Moderate
11 to 14	High
10 and under.....	Extreme

Wright devised a simple and practical evaporimeter to integrate the drying effects of wind, temperature and relative humidity. In order to be able to estimate, in dry weather, the daily change in duff moisture content, this change was correlated with the day's evaporation, the mid-afternoon relative humidity and the previous day's moisture content. To determine the increase in duff moisture caused by rain, the gain in moisture content was correlated with the amount and duration of each rain, and with the moisture content before the rain started.

These data formed the basis of the first forest fire hazard tables published by Wright in 1933 ^{14/}, in which duff moisture was represented by a "Tracer Index" which varied directly, rather than inversely, with the fire hazard. In all subsequent modifications of the Wright System the essential features of these original tables have been retained.

Further investigation showed that the observed flammability in a fairly wide range of fuel types and regions could be correlated with a single tracer index based on a moderately fast-drying fuel, almost as closely as with the moisture of the "critical" fuel, in each site individually. It became increasingly evident, too, that a knowledge of the moisture content of the "critical" surface fuels alone was not enough; moisture conditions in the deeper, heavier, and slower-drying materials, such as humus, moss, and large windfalls had an important influence on fire-suppression difficulty in certain fuel types. An index of cumulative drought conditions was therefore developed, based on moisture content determinations in these "heavy" fuels, observations of fire behaviour, and fire-report analysis. It is now believed that indexes of fire behaviour for a very wide range of fuel types and exposures may be derived, by multiple correlation, from one "weather-sensitive" index representing the light surface fuels, and one "sluggish" index for slow-drying materials.

The development of fire-hazard tables for a variety of fuel types 12/, 18/, 19/, made possible the preparation of a regional "administration hazard index" table for Eastern Canada, the values in which were obtained by weighting hazard indexes for individual types in proportion to the area of each type within the region. Provision was also made for seasonal influences, and for the effect of wind velocity on fire behaviour. These improved fire-hazard tables, published between 1938 and 1940, were adapted locally for use in the provinces of Quebec 5/ and New Brunswick 6/.

In the 1946 edition 2/, the Wright tables have been considerably simplified without impairing their reliability. The most important alteration has been the substitution of direct observations of wind, temperature, and humidity for evaporation readings, thereby permitting the danger and hazard indexes to be calculated several hours earlier in the day than formerly, with fewer observation times. The number of instruments needed is also reduced; the evaporimeter required special manufacture and proved quite sensitive to site conditions with respect to the effect of over- or under-exposure to the wind. Hazard index tables for four fuel types of major importance have been included, as well as three regional danger index tables, in provisional form, for use in Eastern and Mid-western Canada, and on the East Slope of the Rocky Mountains. The term "danger index" replaces "administration hazard index" as used in the 1940 tables.

COMPARISONS OF FIRE-DANGER RATING SYSTEMS

It is not the purpose of this paper to compare in detail the various methods of fire-danger measurement which have been developed and successfully applied on the North American Continent. As far as the writer has been able to ascertain, however, certain principles and procedures have been quite generally recognized and adopted, while on other points there appears to be considerable diversity of opinion. A brief summary of the two viewpoints may be of interest to those engaged in similar research in other parts of the Empire.

1. Matters on which agreement is fairly general:
 - (a) Factors of surface fuel moisture, wind velocity, condition of vegetation, and season of the year should be included in fire-danger tables and meters. (Fuel Moisture may be measured either directly or indirectly).
 - (b) The desirability of making some provision for the cumulative effect of sustained dry weather on the moisture content of deep or heavy fuels.
 - (c) The measurement of weather factors and use of fuel moisture indicators in open sites, rather than under forest canopy, in order to facilitate the standardizing of site conditions.
 - (d) The use of two or three fixed times for daily observations when the greatest accuracy is desired. (Some investigators 2/, 2/ however, consider that a single set of observations is sufficient for practical purposes if the hour be suitably chosen.)

2. Matters on which no general agreement exists:

- (a) The inclusion of such factors as temperature, relative humidity, visibility and special risks in danger meters and tables.

The measurement of humidity is essential, and some allowance for temperature appears to be desirable, when fuel moisture is indirectly derived from weather observations. The necessity for including visibility and risk elements depends largely on local conditions; e.g., the prevalence of dry lightning storms.

- (b) The nature of the "control" to be used in the basic evaluation of forest fire danger.

Personal judgement of experienced officers, analysis of past fire records, and direct observation of experimental and actual fires, have all been used, and probably all three methods have been employed to a greater or lesser degree by the majority of investigators. The degree of emphasis placed on different methods has, however, varied widely. The Wright System has been largely based on the observation of small test fires, supplemented by actual fire observation, fire-report analysis and purely subjective estimates.

- (c) The employment of slide-rules, movable scales, or tables for the practical application of the data.

Most of the danger meters in use in the United States are in slide-rule form, whereas users of the Wright System seem to have found the tabular presentation more acceptable.

- (d) The measurement of fuel moisture by direct weighing of samples of a suitable material, or indirectly by correlation with the weather factors once the basic research has been completed.

The fuel moisture indicator sticks devised by Gisborne ^{7/}, belong to the former class, and with some variations these sticks are now in quite general use in the United States, and by the British Columbia Forest Service. The indirect method, which is employed in the Wright System, is used in Canada east of the Rocky Mountains and to a limited extent in the United States.

Indicator sticks possess an important advantage in that observations may be missed for one or more days without detriment to subsequent records. By the Wright System a small error may be introduced for two or three days after such omissions. On the other hand, the latter method requires less equipment, is better suited to the interpretation of weather forecasts in terms of fire danger, and is not subject to error through weathering or other progressive changes in the hygroscopic material. Such errors tend to be cumulative, rather than self-correcting as is the case with the Wright method.

The writer would suggest that certain indirect methods of fuel moisture measurement tried in the past might have met with more general acceptance but for two reasons:

- (i) In these early investigations an attempt was made to determine the most probable value of fuel moisture content associated with a given combination of weather conditions, without direct reference to the fuel moisture content at the last preceding observation. Wright, however, recognized that the change in moisture content from the previous day's value, under given weather conditions, can be determined with a much higher degree of accuracy.

(ii) The methods of correlation analysis usually employed in such studies have not been sufficiently flexible to express adequately the complex joint functional relationships involved, and at the same time to eliminate the effect of the rather high degree of inter-correlation which exists between the weather elements themselves. In the investigations conducted by the Dominion Forest Service, the graphic method described by Ezekiel ^{4/}, with certain refinements suggested by Professor T. W. Dwight of the University of Toronto, and some further modification in the present study, was successfully employed. Details of the statistical treatment thus evolved have not yet been published.

In so far as the practical measurement of surface fuel moisture is concerned, there would appear to be little difference in the reliability of the methods developed by Gisborne and Wright. As might be expected, the degree of correlation between the values given by the two methods is high. Data obtained in 1940 at Kananaskis in a comparison of Douglas fir fuel moisture indicator sticks, as used by the British Columbia Forest Service, with the Wright tracer index, showed that the percentage moisture content of the former could be estimated from the latter with a probable error of ± 0.68 per cent moisture content at tracer index values of 100 or more - that is, within the range in which a state of inflammability normally exists in typical surface fuels. The correlation index, calculated from the same data was 0.92.

RESEARCH TECHNIQUES EMPLOYED

A complete description of the field procedures used by the Dominion Forest Service in fire-danger research is beyond the scope of this paper. Many of the instruments and methods described by Wright 13/, 15/, 16/ twelve and fifteen years ago are still employed. Some of the more important modifications and newer developments might, however, be mentioned.

EXPERIMENTAL FIRES

The conduct and observation of small test fires to determine the prevailing degree of fire hazard, are performed in substantially the same manner as described by Wright. These small tests are well suited to most homogeneous and finely divided fuels, such as leaf litter and some grasses and mosses. Comparison with actual forest fires in such fuels has shown that this type of test fire provides a reliable indication of large-fire behaviour, except in the litter and mosses associated with certain stands of spruce Picea spp. and fir Abies spp. where the tests are indicative of susceptibility to ignition from standard fire-brands only.

In the case of heterogeneous and scattered fuels such as logging slash, windfall and most kinds of shrubs and herbaceous vegetation, test fires on trenched plots from 10 to 30 feet square have been employed. Observations of crown-fire behaviour have (not unnaturally) been confined to actual forest fires when opportunity permitted.

MEASUREMENT OF FUEL MOISTURE CONTENT

Basic moisture content determinations in all natural fuels are made by the oven-drying of samples. The metal sampling boxes are approximately 4 1/2 inches in diameter and 3 inches deep, with friction-fitting covers. Materials are dried at 212° F. in the same boxes in which they are collected. The laboratory equipment used has been described by Wright ^{13/}.

The sampling error in most fuels is rather high, especially after a light rain. The order of reliability of duplicate samples in top-layer pine duff, for moisture contents up to 60 per cent, is indicated by the following table, which is based on a series of replicate samples:

MIXED RED AND WHITE PINE

Per Cent Moisture Content of Top Layer Duff	Standard Error of the Mean of Duplicate Samples Per Cent Moist. Content
10	± 1.2
20	± 1.8
30	± 2.5
40	± 3.1
50	± 3.7
60	± 4.4

In order to minimize the effect of sampling errors, alternative indicators of fuel moisture are also employed wherever possible. These may be either natural fuels or other hygroscopic materials, the moisture content of which is determined in situ, usually by weight. In the case of surface

leaf litter, small twigs, etc., the natural fuels are unsuitable, owing to lack of uniformity, rapid decomposition, and the difficulty of separating newly fallen material from the original sample.

The moisture content of most kinds of surface leaf litter has been successfully correlated with that of fuel trays containing untreated western white pine (*P. monticola*) match splints, the trays being placed on the surface of the duff. The splints at present used are approximately 1.4 inches long and 0.1 inch in diameter. Three hundred grams of splints (oven-dry weight at 212° F) are scattered uniformly in the 16- by 24-inch fuel trays described by Wright ^{13/}. The moisture content is determined in the field to within one per cent by weighing with a high-quality spring balance. Allowance for loss by decomposition is made after the splints have been oven-dried at the end of the season; extraneous material is carefully removed from the trays, if necessary, before each field weighing. All trays are rated against each other by exposure in an open site at the beginning and ending of the season, and erratic specimens (those whose average deviation from the mean exceeds 10 per cent of the mean moisture content) are rejected.

Fuel-tray frames are covered with marquisette netting, which is pre-treated with a solution of alum and sugar of lead, followed by creosote, to retard decomposition and discourage rodents. Excess preservative is removed by oven drying at 212° F. before the trays are prepared.

A fairly satisfactory indication of the moisture contained in the critical surface layer of certain mosses (Calliargon, Hylocomium and Sphagnum spp.) has been obtained by periodic weighing of 100 to 200 grams of oven-dry

natural material exposed in standard fuel trays. For the deeper layers of moss, as well as peat and humus, no successful indicator has yet been developed and reliance is placed on oven-dried samples. Spruce sticks 6 inches long and 1/4 to 3/4 inch square, from twenty-five to fifty of which are strung together on a flexible brass wire, have been used to indicate the moisture content of dead twigs and small branches on which they are hung.

Moisture content determinations in large dead branches and windfall material are made with the aid of an electronic moisture meter which gives good correlation with oven-dried samples, although its moisture range is rather limited. An alternative technique is also employed for large logs. The dry weight of a selected specimen is estimated from samples cut near the ends, and the centre of gravity of the log is determined. One end of the log is then supported on a knife-edge, while the other is suspended from a weigh-beam whose readings are corrected in relation to the centre of gravity. This moisture indicator is proving useful for the study of cumulative drought effects.

METEOROLOGICAL EQUIPMENT

Forest fire research stations operated by the Dominion Forest Service are equipped with apparatus for recording wind direction and velocity, temperature, relative humidity, pressure, sunshine, precipitation, and evaporation. With the exception of the evaporimeter, all instruments are of standard design, and the majority have been described by Wright ^{13/}.

RELATIONSHIP BETWEEN DANGER INDEX AND FIRE INCIDENCE

Analyses of the relationship between hazard or danger ratings computed by the Wright System and the occurrence and behaviour of actual fires have been made in various parts of Canada. The most comprehensive analysis of this nature available at the time of writing, with respect to the 1946 edition of the tables, was made as a check on the latter from data already compiled for the 1940 tables. These data related to 147 fires which occurred in Riding Mountain National Park (Manitoba) and Prince Albert National Park (Saskatchewan) during the years 1939 to 1944 inclusive. The danger index (re-computed by means of the new tables) at the weather station nearest to each fire on the day the fire started was noted, and the total area burned by each fire was tabulated. The average distance from the starting-point of a fire to the nearest weather station was 9 1/2 miles.

The results of this analysis are summarized in the table below. Differences from the figures obtained ^{3/} with the 1940 tables are generally small: the new tables, however, show a somewhat greater tendency to concentrate the large fires in "extreme" danger, and to include more small fires in the lower zones.

Degree of Danger	Fires Starting in each Degree		Area Burned by Fires Starting in each Degree		Average Size of Fire	Days of Danger in Average Fire Season		Average Frequency of Fires
	No.	p.c.	acres	p.c.	acres	No.	p.c.	
Extreme	67	46	261,839	77.7	3,908	9	6	1 per day
High	39	27	68,851	20.4	1,765	19	11	1 per 3 days
Moderate	27	18	6,115	1.8	226	45	27	1 per 10 days
Low	14	9	435	0.1	31	71	42	1 per 30 days
Nil	0	0	0	0	0	24	14	None
TOTAL	147	100	337,240	100.00		168	100	

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