WORLD METEOROLOGICAL ORGANIZATION

SPECIAL ENVIRONMENTAL REPORT No. 11

Systems for evaluating and predicting the effects of weather and climate on wildland fires

by
W. E. Reifsnyder

Prepared in co-operation with the United Nations Environment Programme (UNEP)

WMO - No. 496

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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NOTE

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FOREWORD

For many years, the application of meteorology to forestry has been an important activity of the WMO Commission for Agricultural Meteorology. The need to establish a forest-fire danger-rating system and a fire-weather forecasting system that can be utilized by Member countries has been well recognized by the Commission.

Following the recommendations of the UN Conference on the Human Environment at Stockholm in 1972, WMO, with the help of a consultant, prepared a report on "Research needs in forest meteorology". At its sixth session in 1974, the WMO/FAO/Unesco Interagency Group on Agricultural Biometeorology reviewed this report and proposed a project on forest fires and their relationship with the human environment. Subsequently, a sub-project on Atmospheric Aspects of Forest Fires was submitted by the Food and Agriculture Organization and WMO to the United Nations Environment Programme. The report contained in the present publication was prepared as part of the sub-project by Professor W. E. Reifsnyder of Yale University, New Haven, U.S.A. It deals with systems for evaluating and predicting the effects of weather and climate on wildland fires. It was decided to publish this report in the WMO "Special Environmental Reports" series.

It gives me great pleasure to place on record the gratitude of the Organization to Professor Reifsnyder for the time and energy he has spent in preparing this publication, which will, I am sure, be received with interest by meteorologists and foresters.

D. A. Davies

D. A. Davies
Secretary-General

SUMMARY

Fire, a natural feature of many of the world's ecosystems, causes extensive damage to forests in many areas. The initiation and subsequent development of forest fires from ignition sources depend to a large degree on meteorological and climatological factors.

In some countries, specialized services based largely on meteorological observations and forecasts have been developed for the purpose of reducing the damage caused by forest fires by providing warnings of impending fires.

This report contains a discussion on the general principles of forest-fire forecasting and presents proposals for the development of a universal fire-danger-rating system. In Annex II, several existing fire-danger-rating systems are described and compared.

RESUME

L'incendie, phénomène naturel de bien des écosystèmes du monde, cause, dans de nombreuses régions, des dégâts considérables aux forêts. L'origine et l'extension ultérieure de ces incendies de forêt à partir de sources inflammables dépendent, dans une large mesure, de facteurs météorologiques et climatologiques.

Dans certains pays, on a mis en place des services spécialisés fonctionnant en grande partie sur la base d'observations et de prévisions météorologiques, qui s'efforcent de réduire les dommages causés par les incendies de forêt, en donnant l'alerte lorsqu'il y a menace imminente d'incendie.

Le présent rapport passe en revue les principes généraux de la prévision des incendies de forêt et formule des propositions visant à mettre au point un système universel de classification des risques d'incendie. On trouvera à l'Annexe II une description et une comparaison de divers systèmes existants de classification des risques d'incendie.

РЕЗЮМЕ

Пожары являются естественным проявлением многих экосистем в мире, нанося значительный ущерб лесному хозяйству во многих районах. Начало и последующее распространение лесных пожаров от источника загорания в значительной степени зависит от метеорологических и климатологических факторов.

В некоторых странах вводится специализированное обслуживание, основанное, главным образом, на метеорологических наблюдениях и прогнозах, для целей снижения ущерба, вызываемого лесными пожарами, путем предоставления предупреждений надвигающихся пожаров.

В данном отчете обсуждаются общие принципы прогнозирования лесных пожаров и выдвигаются предложения по развитию универсальной системы оценки пожароопасного состояния лесов. В приложении II описываются и сравниваются некоторые существующие системы оценки пожароопасного состояния лесов.

RESUMEN

Los incendios, uno de los azotes naturales que afectan a gran número de ecosistemas en el mundo, causan enormes estragos en los bosques de multitud de regiones. El origen y ulterior desarrollo de esos incendios forestales a partir de focos de combustión dependen en gran medida de factores tanto meteorológicos como climatológicos.

En algunos países se han creado servicios especiales, basados en gran medida en las observaciones y predicciones meteorológicas para evitar los daños causados por los incendios forestales, facilitando para ello avisos para la prevención de incendios incipientes.

En el presente informe se exponen los principios generales utilizados para establecer esas predicciones y se formulan propuestas para la creación de un sistema universal de clasificación de riesgos de incendios. En el Anexo II se describen y comparan varios de los sistemas existentes de clasificación de riesgos de incendios.

1. INTRODUCTION

Fire is a natural part of many of the world's ecosystems. Indeed, many wildland ecosystems depend on fire for their regeneration and maintenance. But fire also, from man's point of view, exerts destructive influences on many ecosystems. Organic matter is consumed, trees are killed, and soil is exposed to the erosive power of rainfall. The delicate nature of the balance between man and the wildland environment is perhaps nowhere more evident than in the relationship between man, fire and the environment. Man often needs to use fire in manipulating the wildland ecosystem, but unwanted wildfire can destroy the values he has worked so hard to protect and develop. Recognizing this, the United Nations Environment Programme (UNEP) has undertaken several programmes to further the understanding, use and control of wildland fire for the protection of man's environment. In particular, UNEP asked the Food and Agriculture Organization of the United Nations (FAO) to employ a consultant to prepare a long-term programme of work aimed at:

(a) Identifying areas where the forest ecosystems are more susceptible to fire;

(b) Elaborating a methodology for the assessment of a fire-danger index, using meteorological observations in combination with the characteristics of existing vegetation and the prevailing topographic conditions;

(c) Encouraging countries to develop and/or improve fire-detection systems and to strengthen firefighting organizations and techniques;

(d) Promoting regional co-operation on forest-fire control by improving the exchange of information on techniques and equipment, by encouraging co-operative research work on fire behaviour and fire intensity, according to fuel types and on other related problems, and by exploring the feasibility of mutual aid, including the pooling of human resources and means;

(e) Identifying basic ecological research requirements of the effects of forest fires on the ecosystem in collaboration with Unesco.

The consultant (Mr. Carl Wilson) submitted his report, "Detection and control of forest fires for the protection of the human environment: Proposals for a global programme", to FAO and UNEP in May 1975. The World Meteorological Organization (WMO) was asked by UNEP to prepare a report on forest-fire danger-rating systems and forest-fire-weather forecasting in support of objective (b). This section of the report summarizes the work and recommendations of the consultant employed by WMO. In furtherance of the project, the consultant visited forest-fire and fire-weather experts in Western Europe, Australia and New Zealand during the period 10-28 March 1975; in Scandinavia during the period 28-31 October 1975; and in the U.S.S.R. from 14-18 December 1975. In addition, the consultant corresponded with a number of experts in North America and Western Europe. The people whom he visited and contacted are listed in Annex I. A summary of fire-danger-rating systems used in the countries visited is contained in Annex II.

2. GENERAL BACKGROUND

2.1 Relationship of weather and climate to wildland fire behaviour

Given a complex of fuels in a wildland environment, the way that a fire develops and burns from an ignition source depends largely on meteorological and climatic factors. The general structure of vegetation in an area is largely determined by the climate of the area, particularly such factors as temperature, precipitation and radiant energy input. The phenological development of plants in a vegetation complex depends in considerable measure on the seasonal progression of climatic elements. Extended periods of low precipitation, low humidity and high temperature produce conditions in which dead vegetation (and even to some extent living material) becomes highly flammable. Thus, in many regions, a well-defined "fire season" is established. Thus the role that weather conditions play in determining the potential severity of forest fires has long been recognized. As early as 1913, forecasters of the U.S. Weather Bureau were authorized to issue fire-weather warnings (Williams, 1916). These were primarily forecasts of impending dry and windy weather.

Development of specific information on the relationship between weather variables and fire behaviour received great impetus from the work of Harry T. Gisborne in the United States and J. G. Wright in Canada during the 1920s (Gisborne, 1925; Wright, 1932). These men pioneered the development of systems for integrating weather variables into single index numbers that could be used to predict the behaviour of fires and the difficulty of controlling them. Their work in the development of forest-fire-danger ratings and "fire-danger meters" formed the basis for much of the subsequent work that went on not only in North America but elsewhere in the world.

3. STATEMENT OF THE PROBLEM

3.1 Distribution of fires and fire weather in space and time

As stated earlier, fires can burn in wildland fuels when antecedent and present weather have brought a sufficient quantity of fuel to a dry and flammable state. All that is needed is a source of ignition; this can be produced either by lightning or by man. Fires occur in nearly every vegetation type in the world, with the possible exception of the tropical rain forest. Even here, however, fire is used in land clearing and shifting agriculture. Only a few forests in the world are so continuously wet that fires are virtually impossible.

The physical laws that control the behaviour of wildland fires are the same everywhere on Earth. It can be assumed, therefore, that it is feasible to develop a generalized system for predicting the behaviour of fires in any vegetative complex subject to burning and to predict the weather variables that influence such behaviour.

3.2 Relationship to forest and wildland management

As a prerequisite for the development of fire-danger and fire-weather forecasting systems, it is necessary to establish the uses to which such systems will be put. The level and intensity of wildland management will determine the

interest in and need for the rating and predicting of fire danger and fire weather. These management criteria will determine the nature of the systems developed, their complexity and sophistication, the type and size of organization developed to implement the systems, and so forth. The following non-exhaustive list of management criteria and activities is illustrative:

(a) Protection of life and property in wildland environments;
(b) Protection of the commercial value of the forest resource;
(c) Protection of watersheds from fire-accelerated erosion;
(d) Protection of high-value plantations;
(e) Controlled use of fire for forest regeneration;
(f) Controlled use of fire for fuel reduction;
(g) Use of fire in land clearing and vegetation-type conversion.

The first step in establishing a fire-control plan must therefore be a statement and analysis of the fire-related management objectives. This in turn will imply the nature and level of fire-weather-forecasting services required and the kind and complexity of fire-danger-rating system needed to further the objectives of the fire-control plan. In terms of a fire-danger-rating system, possibilities range from a simple ignition index that will estimate the likelihood that fires can start and burn from natural or man-originated sources, to a multilevel system that will predict fire behaviour, difficulty of control, manpower requirements, and so forth. In terms of fire-weather forecasting, activities may range from fire-weather warnings, produced by a central meteorological office, to fire-weather-forecasting services provided to fire-control personnel at the scene of existing wildfires or controlled burns. The two systems thus involve a hierarchy of sub-systems and services that are implemented at a level appropriate to the expressed management requirements.

3.3 Hierarchy of fire-danger-rating systems

Discussion of the various levels of a fire-danger-rating system and the management uses to which the various components may be put is facilitated through examination of the structure of the U.S. National Fire Danger Rating System (Deeming et al. 1974). Although this was developed specifically for the U.S. system currently in use, it can be used as the basis for analysing systems presently used elsewhere and can be used as the basis for developing a system for universal application (Figure 1). The meteorological elements that are inputs to this scheme relate either to the moisture content of various sizes of dead fuels* or to wind speed.

* In this scheme, fuels are ordered according to their time rate of response to moisture changes. A one-hour timelag fuel is one that achieves 62 per cent (1/e) of its equilibrium moisture content after a step change in ambient humidity. In the natural fuel complex, this represents fine fuels such as dry grass, individual conifer needles or hardwood leaves, small twigs, and the surface of the litter layer. Ten-hour timelag fuels include large twigs, branches with characteristic diameters of one to three centimetres and the surface litter layer of two centimetres depth. One-hundred-hour timelag fuels include branch material from three to eight centimetres in diameter and litter layers from two to ten centimetres deep.

Level 1: Ignition. An ignition index indicates the ease with which fine fuels can be ignited from a simple ignition source such as a match, cigarette, or lightning strike. It can be used by the forest manager as a measure of the likelihood that wildland fires would start accidentally from the activities of man in wildland areas. From a meteorological point of view, it is dependent primarily upon the moisture content and temperature of the fuel particle.

Level 2: Occurrence. The occurrence index is defined as a number related to the potential fire incidence within a specific area. It is related to the number of potential ignition sources within the area and to the ignition index. It gives the forest manager an indication of the relative number of fires that may occur in the rated area. It can be used, for example, as a guide to the level of detection services required.

Level 3: Spread index. A spread index predicts the forward rate of spread of a fire in a particular fuel type on a particular slope when subjected to specific meteorological conditions. It can be used as a guide to estimate the time that deliberately-set controlled fires will take to cover the area within a controlled burn. It can be used to estimate the speed with which control lines must be built in order to contain a fire.

Level 4: Energy release. The energy-release index, as its name implies, indicates the combustion rate and heat output in a given fuel type for a given complex of fuel-moisture contents. It indicates how close to the fire edge fire-control crews can work and thus may be used as a guide to effective attack methods.

Level 5: Burning index. The burning index is defined as a number related to the contribution that fire behaviour makes to the potential amount of effort needed to contain a fire in a particular fuel type within a rating area. It can thus be used to estimate the number of fire-control personnel, kind and quantity of suppression equipment, and so forth.

Level 6: Fire load. The fire-load index, combining the burning index and the occurrence index, indicates the potential fire-control job that may be faced by a forest manager in an area on a particular day. It provides an indication of the likely total fire-suppression effort required on an area to meet the stated forest-management objectives.

Level 7: Seasonal severity. The seasonal severity index is a seasonal summation of fire-load indices and is useful as an administrative tool for apportioning suppression forces and services among various units of a wildland area.

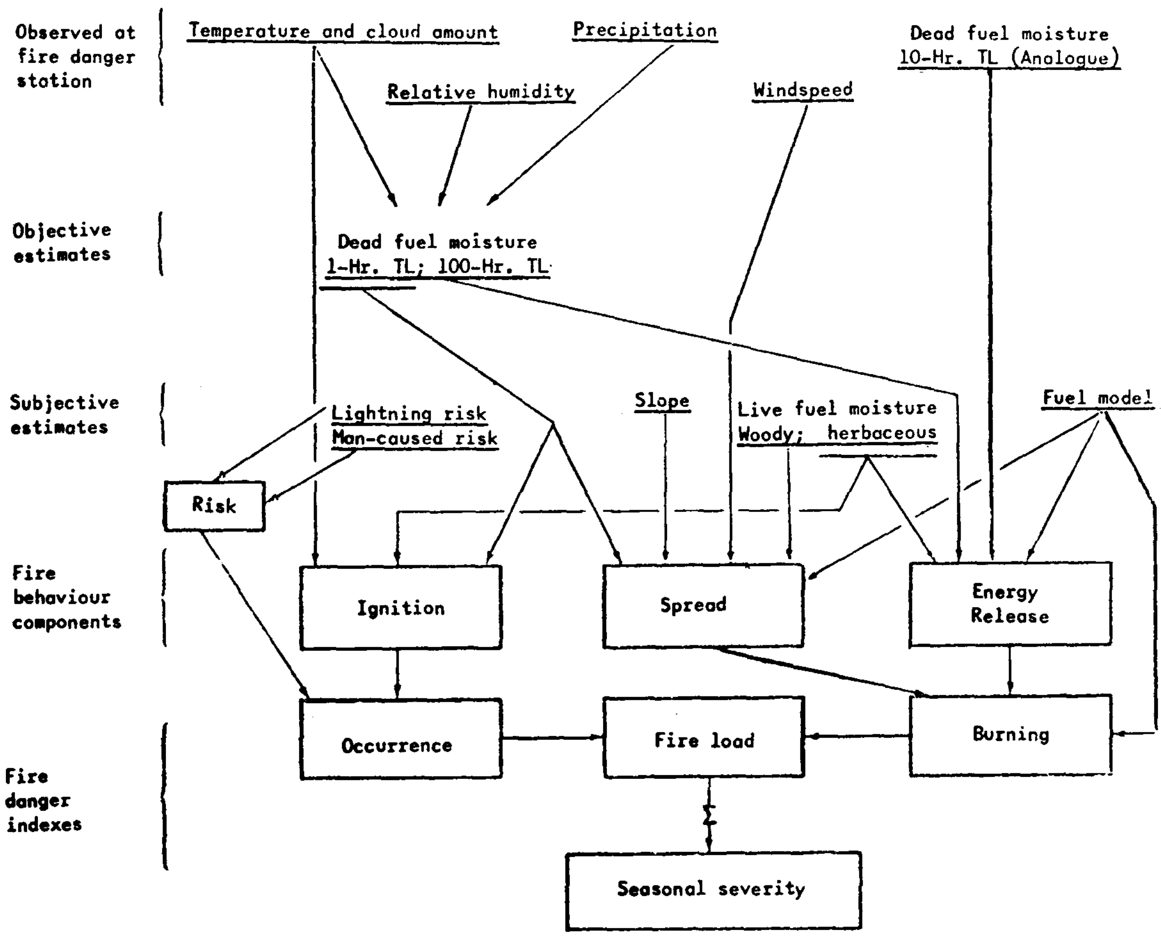

Figure 1 - Structure of the National Fire Danger Rating System in the U.S.A. (Source: Deeming et al., 1974)

Obviously, not every forest-fire-control organization will need to utilize all of these indices. Developing organizations will start at a low level in the hierarchy and add components as their needs develop. Specific recommendations for such development are made in Section 4.2.

3.4 Hierarchy of fire-weather-forecasting services

As with fire-danger-rating systems, a hierarchy of fire-weather services can be established. Specific services can be provided by a national weather service according to the needs of the forest-fire services and the capabilities of the weather service. The following presents a logical hierarchy of such services.

Level 1: Fire-weather warnings. At the very minimum, a weather forecast office that has responsibility for fire-weather services should be prepared to issue forecasts of dry and/or windy conditions that may occur during fire seasons. Depending on

the arrangement with the forestry service, these warnings can be issued to the public or communicated directly to the forestry organization, or both. Liaison must be established between the forecast office and forestry service in order to establish the forecast criteria, modes of communication and so forth. In general, such forecasts will be prepared by the regular forecasting staff.

Level 2: Fire-danger forecasts. If a forest-fire service has an operational fire-danger-rating system, the forecast office may be charged with the responsibility of either forecasting the danger rating directly or forecasting the specific weather elements that are used in calculating the fire-danger rating. These forecasts may be prepared either by the regular shift forecaster or by the forecasters of a special fire-weather unit. In the former case, shift forecasters should receive some specialized training in the rating system used and in the special requirements of the fire services. Forecasts of other meteorological elements important in determining the severity of wildland fires may also be required. These elements may include lightning, Föhn winds, frontal passages, and so forth. Special forecasts may also be required for specific fires or for controlled burns. Close collaboration between the forecasting unit and the forest-fire services is required.

Level 3: On-site forecast services. A forestry organization that has a highly developed fire-control organization may require the services of a fire-weather unit operating at the site of existing fires or of planned controlled burns. Fire-weather forecasters with special training may take mobile observation and forecast units into the field to operate with the forest officials managing control operations on large fires, whether planned or wild. This requires a forecasting unit with special training and skills in forecasting local winds and other local phenomena important in fire behaviour and fire control, as well as the forecasting of routine meteorological events. Specialized communications and observing equipment are necessary, mounted in mobile offices which can be towed or driven to a fire site. Personnel associated with such units will normally have routine fire-weather-forecasting duties as well and will frequently engage in research on fire-weather forecasting during non-fire seasons.

4. PROPOSALS FOR THE DEVELOPMENT OF UNIVERSAL SYSTEMS OF RATING FIRE DANGER AND FORECASTING FIRE WEATHER

4.1 General

As indicated previously, FAO and UNEP have proposed a global programme for the "detection and control of forest fires for the protection of the human environment". In preparing the basic documentation for this proposal, a FAO con-

sultant, Carl C. Wilson, visited a number of countries in southern Europe, Central America and Africa. Although a detailed study of fire-danger-rating systems and fire-weather-forecasting systems was not included, the report made a number of recommendations. Because of their relevance to this report, the recommendations are quoted in full. Only a few of the countries visited had sophisticated fire-danger-rating and fire-weather-forecasting systems.

4.1.1 Mediterranean region

For the Mediterranean region, the report proposed "the installation in each participating country of a new fire-danger-rating system (possibly a national FDR system from Australia, Canada or U.S.A.) for trial use in pilot districts. Evaluation should be conducted for at least three years." The necessity for a strong fire-weather-forecasting system was also recognized. The report proposed "the establishment and operation of a central fire-weather-forecasting centre with arrangements for appropriate communications facilities similar to the World Weather Watch. The purpose of this centre is to provide fire-weather forecasts on a routine basis and special warnings of strong winds, drafts, and similar adverse fire weather to forestry and/or fire organizations in participating countries." It also recommended that there be established, on a world-wide basis, a system for evaluating fire climates.

4.1.2 Central America

For the Central American region, FAO proposed "establishing a Fire Weather Forecasting and Research Centre at the International Airport in (Toncontin) Tegucigalpa, Honduras. This facility now serves as the principal aviation forecasting headquarters for Central America. With a new charter and some additional staff assistance, it probably could conduct both research and development studies as well as meet the forecasting requirements. Weatherfax and other teletype facilities are now installed. In addition, if Tegucigalpa is to serve as headquarters for the Regional Programme Leader for Central America, this unit could also assist in implementing and operating a standard fire-danger-rating system in 'pilot districts' in respective countries."

4.1.3 Africa

Few, if any, countries in the fire-prone savannah region of Africa have utilized any kind of fire-danger-rating system. Nor is there any central fire-weather-forecasting unit with the capability of forecasting critical weather conditions. The report recommended "the installation of a basic structure of a fire-danger-rating system for use in the proposed 'pilot districts' in each country. Evaluation should be conducted for not less than three years." It also proposed "the establishment and operation of a central fire-weather-forecasting centre at the regional programme headquarters and suitable arrangements to be made to communicate forecasts within that country and to participating countries. This centre could also conduct studies directed towards improving forecasts of such critical fire conditions as the dry Haboob winds in the Sudan."

As implied by these recommendations, the FAO report proposed the establishment of at least three regional programmes, each composed of a number of national and intra-regional projects, aimed at the development and implementation of integrated fire-management systems for the vegetative fuel types of primary regional importance. Implementation of a fire-danger-rating system and co-ordination with the fire-weather-forecasting unit would be effected by the Regional Programme Leader at each of the centres.

The World Meteorological Organization recognizes that these proposals are a step forward in the establishment of a forest-fire danger-rating system and a fire-weather-forecasting system that can be utilized by Member countries. It should be noted that the FAO recommendations apply specifically to three regions of the world only. Although these three regions have critical wildland fire problems and therefore should receive first attention, countries in other areas may also need systems appropriate to their conditions. In the sections that follow, the recommendations are general and not specifically oriented to any of the three regions listed. However, the recommendations contained herein can be implemented in these areas as the regional programmes develop. Other nations desiring to implement the recommendations can do so without the establishment of a regional centre as called for in the FAO proposals.

4.2 General recommendations

Development and utilization of a fire-danger-rating system and a fire-weather-forecasting system are essentially open ended and can be pursued to any level appropriate to a particular nation's or region's needs and to the quantity and quality of its technicians and scientists. For a nation with a small forestry department and perhaps a single weather-forecasting centre, the level of initial operations must necessarily be low. That is to say, the level of activity in rating and forecasting fire danger should be appropriate not only to the magnitude of the fire problem but also to the size and capabilities of the forestry and meteorological organizations.

4.3 Constraints

In developing the specific recommendations contained in the next section, a number of assumptions and constraints were observed. The major ones are described below.

4.3.1 The systems should have universal application. Since fires everywhere burn subject to the same physical laws, it should be possible to develop systems that can be applied anywhere. Although this establishes the possibility of developing universal systems, the desirability rests on other grounds. First of all, the task of developing a separate system for each nation or for separate areas within each nation (as typified by the early development of fire-danger-rating systems in the U.S.A.) is wasteful of scientific and technical talent. Development of separate systems would also delay the process in many areas where other tasks may have higher priority. Development of a single system for rating fire danger and fire climate

will permit the inter-comparison of fire hazards on a world-wide basis. This will permit rational studies of the allocation of fire research and fire-suppression efforts by national, regional, and United Nations agencies.

4.3.2 The systems should be flexible and adaptable to a variety of administrative and governmental structures. The proposed systems should not be keyed to the way any particular nation organizes its forestry and meteorological services. If possible, the meteorological parameters specified should be those that are normally produced by a forecast centre.

4.3.3 The proposed systems should be simple and easy to apply. A panel of experts reviewing the FAO proposals (see section 4.1) stressed the need for simplicity in formulating and using the fire-weather-forecast system and the fire-danger-rating system. Obviously, a system can be as complicated as needed, but at the start it should be easily usable and understandable by field personnel. Otherwise, it simply will not be used.

4.3.4 The systems should be hierarchical in nature. As implied in Section 3.2, various fire-control organizations will need systems of different levels of sophistication. The proposed systems should permit an orderly and logical transition from one hierarchical level to another. Each level should represent something added to the level below, rather than something substituted for it and replacing it. Some substitution may of course be necessary as scientific understanding of the meteorological influences on fire behaviour increases. But if the underlying hierarchical structure is sound, such substitutions can be made with minimal disruption to the operation of the system.

As a start of the development of rating and forecasting systems, primarily for use by developing countries without such a system, four tasks are proposed. These are:

(a) Development of a system for evaluating fire climate;
(b) Development of an ignition index;
(c) Development of a rate-of-spread index;
(d) Development of a fire-weather-forecasting system.

4.4 Development of a fire climatology

A useful fire climatology can be based either on the actual occurrence of wildland fires in an area or on the concurrence of meteorological and vegetational conditions necessary for wildland fires to occur. Both approaches can and should be used in developing a fire climatology where none now exists. Comparisons between the two will then indicate those seasons of the year during which fires can be expected and which fire-management plans must be implemented.

The FAO report emphasizes that the first step in developing a fire-management plan is to collect and evaluate existing statistics on forest fires, including all unwanted grass, brush and forest fires. The national forestry organization should collect, on a continuing basis, data on the occurrence, cause, location

and final size of every fire in the designated protection area, at the very minimum. Insofar as is possible, meteorological information appropriate to each fire should also be collected. At the minimum, this should include wind speed, relative humidity, temperature, and cloud amount, when the fire is burning most vigorously. Observations from the fire area or the closest standard weather observing station should be used. More complete information, including a sample report form, can be found in the FAO publication entitled "Elements of forest-fire control" (1953).

In many areas of the world it may be possible to use imagery from the Earth Resources Technology Satellite (ERTS) to determine not only seasonal progression of fires but also the amount of area burned. Deshler (1974) used ERTS imagery to study grass fires in the grass and savannah area of tropical Africa. He was able to plot maps that showed the extent of burnt area at approximately two-week intervals. It is recommended that the regional centres proposed in the FAO report establish pilot projects to determine the feasibility of using this methodology for determining the length of fire seasons and the magnitude of the fire problem in suitable areas.

Several climatological methods exist for the determination of fire areas and fire seasons. Reifsnyder (1962) suggested that correlations could be developed between fire occurrence statistics and climatic classifications such as the commonly used Koeppen system. The major Koeppen designations, ranked in order of descending fire-weather severity, are as follows: Cs, Cw, Cf, Dw, BS, Aw, Af, ET, EF and BW. Kerr et al. (1971) have also suggested a modified Koeppen classification for the evaluation of fire climates.

Inasmuch as burning conditions are produced by the drying of fuel (largely the result of high temperatures) and counteracted by precipitation, a simple climatic diagram based on these two elements can be interpreted in terms of the fire season. Batchelder (1967; 1966) used the following scheme to evaluate dry periods in a study of spatial and temporal patterns of fire in the tropical world. Monthly mean temperatures and monthly total precipitation are plotted on the same graph in which ten Celsius degrees are scaled the same as 20 millimetres of precipitation. On these scales, periods during which the temperature line exceeds the precipitation line are considered "dry" periods. Batchelder developed a simple sector diagram (in which months of the year correspond to hours on a clock face) on which dry periods and periods in which wildland fires are common are plotted. He constructed these diagrams for numerous weather stations in tropical areas and plotted these on vegetation maps. Although inconsistencies can be noted, the simplicity of the system and the ready availability of the basic meteorological data commend it to wider application. It is recommended, therefore, that several pilot projects be established to test further the validity and usefulness of the procedure.

A somewhat more sophisticated system has been developed by Fosberg and Forman (1974), utilizing calculations of the equilibrium moisture content (emc) of forest fuels. Meteorological observations of temperature and relative humidity made during the time of highest fire danger (usually 1400 h or 1500 h, local time) are used to calculate equilibrium moisture content, emc. These values are then averaged over suitable periods, either monthly or for the duration of the normal fire season. Maps of average emc are plotted and isopleths of constant emc drawn. Climatic boundaries are then drawn to delineate relatively uniform fuel-moisture regions.

Another system, developed by C. C. Chandler of the U.S. Forest Service, has been recommended for publication and distribution in the FAO report. This utilizes climatological data that are normally available in published reports, including monthly averages of daily maximum temperatures, daily minimum temperature, dewpoint temperature, and monthly precipitation and number of days in each month with greater than 2.5 mm precipitation. It requires substantial computation and has been programmed for digital computer. Unfortunately, full computational procedures have not been published yet. It is recommended that a pilot project be undertaken to evaluate and compare the Chandler, Fosberg and Furman, and Batchelder methodologies.

4.5 Development of an ignition index

The single most important wildland fire-danger index for a nation developing a wildland fire-management system is one which will indicate the likelihood that a wildland fire will start when a source of ignition such as a cigarette, debris fire or a lightning strike is present. Wildland fires normally start in fine dead fuels such as dry grass or leaf litter. The drier the fuels, the more likely an ignition source will start a fire. The moisture content of the fine dead fuels depends on the temperature of the fuel particle and on the relative humidity of the air immediately in contact with it. Fine dead fuels respond very quickly to changes in ambient temperature and humidity conditions. However, if the grass and herbaceous vegetation are only partially cured, the effective moisture content of the fine fuels is raised, because of the high moisture content of the green living material.

One existing rating system, the US National Fire Danger Rating System (NFDRS), includes a component which estimates the moisture content of fine fuels less than seven millimetres in diameter. (These are the so-called one-hour timelag fuels indicated in Figure 1.) Because equilibrium moisture content of a fine fuel depends on whether the fuel particle is undergoing a drying or wetting phase, an assumption must be made as to the régime to which the particle is being subjected. The NFDRS assumes a drying phase, inasmuch as high fire danger normally occurs in the afternoon after the fuels have been drying from a morning moist condition (Fosberg and Deeming, 1971). Although a specific drying régime was utilized in the preparation of the tables (that appropriate to a continental climate) it is likely that the system will work reasonably well anywhere, certainly as a first approximation. The meteorological elements required for estimating the ignition index are air temperature and relative humidity, measured in a standard weather shelter, and the state of the weather (whether sunny or cloudy). Thus, calculations can be made based on standard meteorological observations. The time of observation should be close to noon.

It is recommended, therefore, that the ignition component of the US National Fire Danger Rating System be adopted for trial use as an ignition index. Details of the computation and tables are contained in Annex III. Pilot studies to evaluate the adaptability of this system to various parts of the world should be undertaken by the regional centres proposed in the FAO report.

4.6 Development of rate-of-spread index

The rate of spread of a fire in a given fuel complex depends on wind speed and slope, in addition to fuel-moisture content. Also, the moisture content of heavier fuels influences both the intensity of a fire and its forward spread.

These are fundamental fire-behaviour parameters which are important not only to the control of wild fires but also in the behaviour of fires set for management purposes. Consequently, it is desirable that the danger rating be interpretable directly in terms of forward spread of fire.

The Australian system (McArthur, 1967; Cheney, 1968) fits these criteria. It was developed for eucalyptus forests in Australia and has been applied successfully in the subtropical climates of Australia and in eucalyptus and pine plantations in Zambia (FAO, 1971). It should be noted that the McArthur system is based on more than one thousand experimental fires, permitting direct interpretation in terms of rate of spread. It is recommended that the McArthur system be adopted for evaluation in pilot studies by the regional centres. The system can be described briefly as follows. Use is made of standard meteorological measurements of temperature, relative humidity, dewpoint, wind speed and rainfall as basic input parameters. Fine-fuel moisture is determined implicitly through the measurement of temperature and relative humidity. Moisture content, such as a thick litter layer, of medium and heavy fuels is kept track of through a "drought-index"* book-keeping system utilizing rainfall amount, days since rain, and maximum air temperature. Wind speed is included as a major influence on rate of spread and rate of combustion (Figure 2). According to McArthur (personal communication), the resultant index number is "a relative number denoting the combined evaluation of the flammability of forest fuels, rate of spread and behaviour of fires in such fuels, for specific combinations of fuel-moisture content, herbaceous stage and wind velocity. The index is on a logarithmic scale of 1-100 and provides a linear relationship between rate of spread, ignition probability and suppression difficulty. Fire size and damage potential are a power function of the index." It can be interpreted directly in terms of rate of forward spread and flame height for various quantities of fine dead fuel, ranging from five to twenty-five tonnes per hectare.

It should be noted that the US NFDRS is capable of evaluating a danger rating for an essentially infinite variety of fuel types in which fuel amounts are distributed among fine, medium and heavy fuels. At present, the system has been adapted to eight different fuel types (called fuel models) representing typical fuels found in the United States. Development of this system should be monitored for possible application in other regions, inasmuch as it appears to be highly adaptable to any fuel complex and any climatic régime. In its present form, it may be difficult for a forestry organization unfamiliar with fire-danger-rating systems to implement it because of its relative complexity.

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* An explanation of the drought index and its calculation is given by Keetch and Byram (1968). This bulletin, together with those by McArthur (1967) and Cheney (1968), should be consulted for details on implementing the McArthur system. A rough estimate of the drought index for use with the McArthur meter (Figure 2) can be made as follows: No drought: rains every three to seven days; grass green; 0-100. Mild drought: little rain for two to three weeks; grass yellowing or fully dead; 101-250. Severe drought: little rain in past 30 days; grass dead and brittle; 251-400. Extreme drought of two months or more duration: 401+. Further information can be obtained from the Director, Forest Research Institute, Forestry and Timber Bureau, Canberra, ACT 2600, Australia.

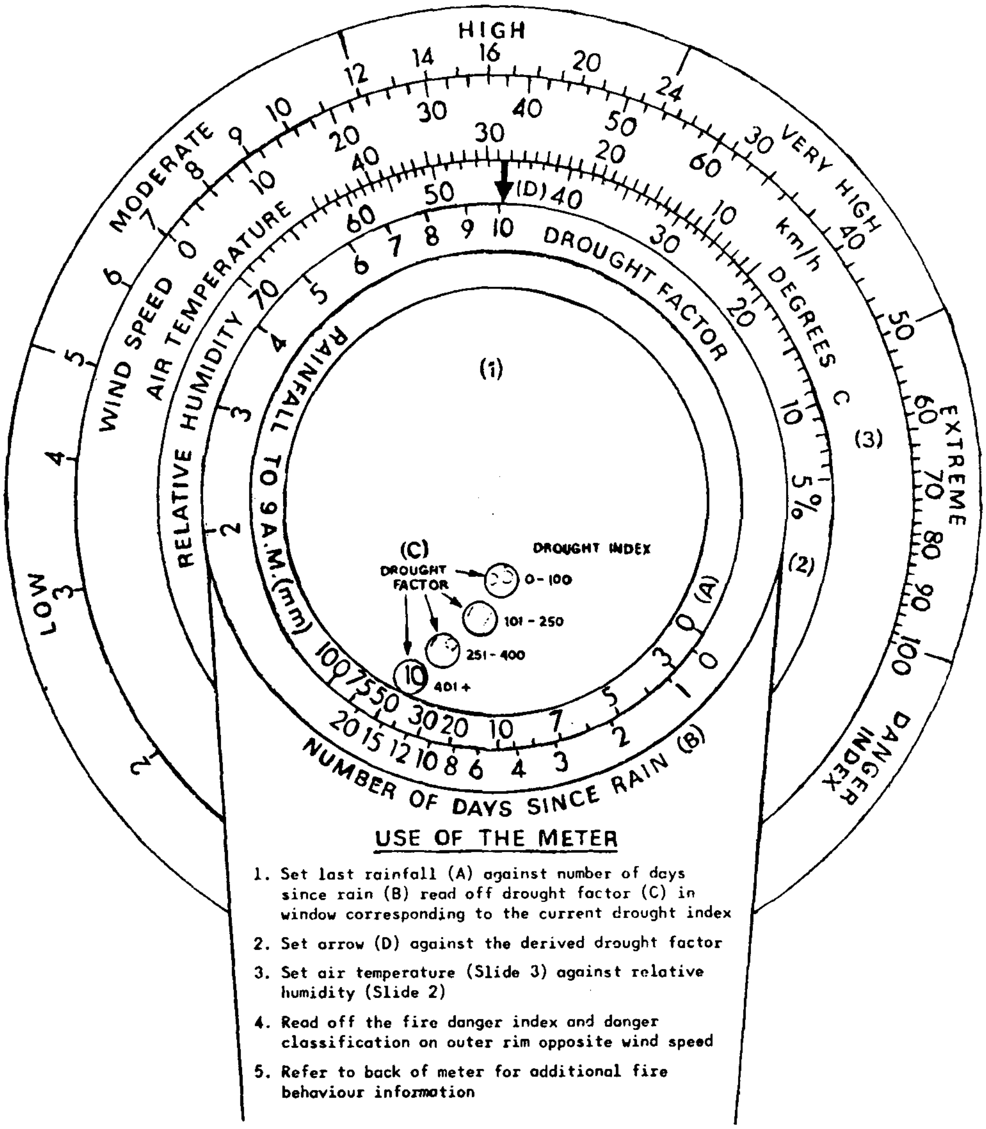

Figure 2 - Forest-fire danger-rating meter

4.7 Development of a fire-weather-forecasting system

In many ways the problems involved in establishing an integrated fire-weather service are more easily solved than those associated with establishing a fire-danger-rating system. Meteorological services are well developed in most regions of the world. At the beginning, the addition of a fire-weather-forecasting service involves little more than a few tasks added to the duty forecaster's work-load. As the demand for specialized fire-weather services increases, the problems become more complicated. It is to the first stage of providing fire-weather services that this report is addressed. Many of these problems are considered in detail in

WMO Technical Note No. 42, referred to previously. The operation of the fire-weather-forecast system in many countries is also discussed in that Technical Note. Any organization attempting to develop a fire-weather-forecasting system should refer to this earlier Technical Note since the present publication does not repeat the material contained therein. There are, however, several aspects in the development of a forecasting system that should be emphasized. These include the nature of the forecast issued, division of responsibility between forestry and meteorology organizations for issuance of fire-weather warnings, communications, and research and development. It must be emphasized that a successful fire-weather-forecasting service depends, inter alia, on a high level of co-operation between the two services. For example, forecasters should understand the use to which their fire-weather forecasts are being put; on the other hand, foresters should know that the quality of the fire-weather services they receive may depend in considerable measure on the quality of meteorological data they may be required to furnish to the Meteorological Service.

4.7.1 Types of forecast

Forecasts will either be routine forecasts of the weather elements influencing fire behaviour or ones used in calculating fire-danger rating. They may also be special forecasts of extremely hazardous conditions either for existing wildfires or planned controlled burns. The exact nature and format of the forecasts will, of course, depend on the specific needs of the fire-control organization and will have to be determined by consultation between the two organizations.

In any case, the forecaster should be trained in local climatology and should receive some special training in fire weather and fire behaviour. An excellent reference for this is the manual entitled "Fire weather - A guide for application of meteorological information to forest fire control operations", published by the U.S. Forest Service (Schroeder and Buck, 1970). Although written primarily for fire-control personnel, and therefore containing much elementary meteorology which will appear to forecasters as over simplified, it provides information on those meteorological and climatic elements which are important in fire management.

If the network of standard weather-observing stations in protected areas is sparse or non existent, it may be necessary to establish a network of specialized fire-weather-observing stations. These will generally be installed and serviced by the national Meteorological Service but operated by the national forestry service. The basic reference on observing practices is the WMO Guide to Meteorological Instrument and Observing Practices. For special problems in establishing and operating a fire-weather-observing station, the "Fire-weather observers' handbook", published by the USDA Forest Service, should be consulted (Fischer and Hardy, 1972).* The observers, normally forestry service employees, should receive training and instruction in the use and maintenance of the instruments. It is important to the success of the fire-weather service that observations made at fire-weather stations be of high quality. It is worth expending considerable effort to ensure this high quality.

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* A section on fire-weather observations is being prepared for the WMO Guide to Agricultural Meteorological Practices.

4.7.2 Division of responsibility between the organizations

The Meteorological Service will normally prepare forecasts of fire-weather elements on a schedule determined by agreement with the forestry service. The forestry service will then prepare the fire-danger-rating forecast, issue public fire-weather warnings, and in general take appropriate administrative actions based on the data and forecasts supplied by the Meteorological Service. In some countries, public fire-weather warnings are issued by the Meteorological Service itself. However, unless there is a special fire-weather-forecasting unit in the Meteorological Service, it may be more efficient to leave this to the forestry officials. This, however, is often a matter determined by law.

4.7.3 Communications

Communications, both in the sense of physical facilities and of administrative procedures, are of great importance to the effective operation of a fire-weather service. Although telephones and radio provide easy and quick communication between officials in separated offices, teletypes supply hard copy that is less subject to error in interpretation and also furnishes permanent records. Efficient channels for communicating fire-weather warnings to the public broadcasting media should be established and operated so as to ensure rapid and timely dissemination of warnings.

In the inter-personal sense of the term, effective communication between the producers and users of fire-weather-forecast information should be strongly encouraged. Joint seminars and training sessions for fire-weather forecasters and fire-control personnel should be held periodically. Informal exchange visits should also be encouraged and forecast offices and the fire-control administration offices should, if possible, be located near to each other. It is extremely valuable to arrange for fire-weather forecasters to visit the scene of ongoing fires. This is the most effective way for them to learn how their forecasts are put to use on actual fires and to learn of the importance of local meteorological phenomena in determining fire behaviour. Such visits will greatly enhance the ability of forecasters to produce useful forecasts. Reciprocal visits of fire-management personnel to forecast offices may also be useful but of lesser importance.

4.7.4 Research and development

Although most nations just establishing a fire-weather-forecasting system may not be in a position to establish also a research unit oriented to fire-weather-forecasting problems, forecasters should always maintain a kind of "research attitude" towards their work. They should be encouraged to develop research projects related to their forecasting tasks and time should be made available for their pursuit. Fire-weather forecasting is still a developing field and every fire-weather forecaster has an opportunity to advance knowledge in this field. Local conditions influencing fire weather and fire behaviour will always require special study. These include such phenomena as local winds, Föhn winds, topographic influences on fire danger, and so forth. Special attention should be paid to the study of meteorological factors associated with large or disastrous fires. Forecasters should be encouraged to attend appropriate courses in local universities.

At a higher level of organization and activity, specialized fire-weather-forecasting units should be established in appropriate meteorological offices. In particular, the proposal in the FAO report for the establishment and operation of a central fire-weather-forecasting centre (in the Mediterranean region), with arrangements for appropriate communications facilities similar to the World Weather Watch, is endorsed. The purpose of this centre would be to provide fire-weather forecasts on a routine basis and special warnings of strong winds, droughts and similar adverse fire weather to forestry and other fire organizations in participating countries. Such a unit would serve as a prototype for developing similar units in other regions of the world. However, this should not prevent any country from developing its own fire-weather-forecasting service to a level appropriate to its needs.

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A N N E X II

COMPARISON OF SEVERAL FIRE-DANGER-RATING SYSTEMS AND FOREST-FIRE WEATHER-FORECASTING SYSTEMS

The following are brief descriptions of forest-fire-danger-rating systems currently in use in several countries in various regions of the world. In addition, comments are made on the nature of the fire-weather services provided by the various national Meteorological Services. "Forecasting for forest-fire service", WMO Technical Note No. 42 (Turner et al., 1961) describes a large number of fire-danger-rating systems in considerable detail. However, several of the systems described in that Technical Note are obsolete and no longer in common use. To some extent, the comments that follow will bring that information up to date. The reader is referred to the original Technical Note for information on the structure and use of the systems not covered in this report.

The various forest-fire-danger-rating systems in current use can best be discussed and compared by references to some comprehensive conceptual framework which relates the relevant physical factors to various aspects of fire behaviour and to the managerial aspects of fire control through a selected group of index numbers. The diagram describing the basic structure of the US National Fire Danger Rating System (NFDRS) provides such a framework (see Figure 1). Since this diagram will be used as the basis for discussing other systems, the US system will be described first.

UNITED STATES OF AMERICA

In the past decade, the US Forest Service has developed a single unified fire-danger-rating system to replace the eight or more that were in use in various sections of the United States. According to the developers of the system (Deeming et al., 1974), its basic philosophy can be described as follows:

(a) The system should consider only a fire which is not behaving erratically, but spreading, without spotting, through fuels which are continuous on the ground;

(b) The system should provide a measure of that portion of the potential job of containment which is attributable to fire behaviour;

(c) The length of the flames at the head of the fire is assumed to be directly related to the contribution which fire behaviour makes to the job of containment;

(d) The system should attempt to evaluate the "worst" conditions in a rating area;

(e) The system should provide ratings which are physically interpretable in terms of fire occurrence and behaviour and these evaluations could then be used alone or in combinations, giving the systems the flexibility needed to deal with the entire spectrum of fire-control planning and dispatch problems;

(f) Ratings should be relative, not absolute, and should be linearly related to the activity being evaluated.

In the current version, only meteorological elements which are routinely observed with standard instruments are used. These include temperature, relative humidity, precipitation and wind speed. The only non-standard observation is the percentage of dead or cured vegetation in the fine-fuel complex, although an analogue is permitted for estimation of one component of fuel moisture. The measured meteorological elements are related to the moisture content of three size classes of fuel, representing fine, medium and heavy fuels. Taken together with slope and fuel type (idealized as a "fuel model" in the system), these elements largely determine three basic characteristics of fire behaviour: ease of ignition, rate of spread and rate of combustion or energy release.

The fire manager, however, is more likely to be interested both in the number of fires likely to occur in his district and in the difficulty of controlling each fire that does occur. The occurrence index is derived from an ignition component, together with the risk of fires due to either lightning or human causes. Difficulty of control, presented as a burning index, involves those factors contributing both to the rate of spread and to the rate of combustion or energy release. Multiplied together, the occurrence index and the burning index produce a fire-load index which indicates the total amount of fire-suppression activity likely to be required in a particular district on a particular day. Summing these over a fire season leads to a season severity index which can be used to compare the total suppression effort likely to be required in various districts.

The fire behaviour components are based on mathematical models verified primarily through laboratory experimentation. For example, calculation of fuel moisture is based on diffusion theory, except for medium fuels where the use of a fuel analogue (fuel-moisture sticks) is recommended as an option. Fine-fuel moisture content is predicted from current weather conditions; heavy-fuel moisture is predicted from rainfall data and current temperature, cloudiness and relative humidity, using a book-keeping procedure.

Fire-danger calculations are made by the Forest Service, based on meteorological observations made by the National Weather Services, though it is more common to use weather observations made by Forest Service personnel at special fire-danger stations. The National Weather Service provides the Forest Service with current weather data and predictions of the basic meteorological variables. Forecasters with special training in forecasting fire weather provide special forecasts during periods of high fire danger as well as localized forecasts for specific wild fires or planned controlled burns. A number of mobile units is available and fire-weather forecasters are frequently sent to the scenes of major fires.

The National Weather Service also provides fire-weather services to the various State forest-fire organizations responsibile for fire control in areas outside the National Forests. Although procedures vary considerably among the several States, most follow rather closely those established by the Forest Service.

CANADA

The Canadian Forest Fire Weather Index (Canadian Forestry Service, 1970; Van Wagner, 1974) is also a national index, providing a uniform scale for rating fire-weather severity all across Canada. It is "related to the ease of ignition of wild-fires, and is a relative measure of expected fire behaviour and daily fire-control requirements". Like the US system, it includes estimates of the moisture contents of three classes of forest fuel together with the effect of wind on fire behaviour. Meteorological requirements are for temperature, relative humidity, wind speed and rain, all measured once daily. Two fire-behaviour indices are calculated: an initial spread index (corresponding to the spread component of the US system) and a fire-weather index (corresponding to the burning index of the US system). The fine-fuel-moisture code, which is a numerical rating of the moisture content of litter and other cured fine fuels in a forest stand, can be used as an indicator of the relative ease with which fires will ignite. This corresponds to the ignition component in the US system.

The Canadian system is based on fifteen thousand outdoor test fires (Van Wagner, personal communication 1975). It is based on a standard fuel type, a normalized jack or lodgepole pine forest. It does not include the effect of slope.

AUSTRALIA

In Australia, the fire-danger-rating system developed by A. G. McArthur (McArthur, 1967) is used nearly universally and may soon become standard throughout the country. It corresponds most closely to the burning index of the US system. Two classes (fine and heavy) of fuel are considered for evaluation of fuel-moisture content. Fine-fuel-moisture content is estimated from current values of air temperature and relative humidity. Heavy-fuel moisture is estimated from a drought index based on a book-keeping system developed in the U.S.A. (Keetch and Byram, 1968). In this system, the effect of rainfall on fuel moisture is increased by the amount of rain and diminished by the number of days since last rain. Wind speed is included, as in the American and Canadian systems.

The Australian system is based on a large number of experimental fires (more than 1 000 according to McArthur) and produces an index number related directly to the expected behaviour of fires burning for an extended period in high eucalyptus forests, carrying a fuel quantity of 12.5 tonnes per hectare and travelling over level to undulating topography. Conversion tables are included for application to other fuel loadings and for steeper slopes. According to an analysis by Van Wagner, the Canadian and Australian systems are structurally very similar. He has stated: "Although developed for quite different ranges of fire weather, and fairly different fuels, the similarities between the Australian and Canadian indices are more apparent

than the differences".* The system has also been used successfully in eucalyptus and pine plantations in Zambia (FAO, 1971). There is, therefore, good reason to expect that the system would work satisfactorily, at least as an initial attempt, in other forested regions of the world.

In Western Australia, a system developed by Peet (1965) for the jarrah forests is used. This system uses air temperature and relative humidity to estimate moisture content of fine fuels; a rainfall/drying book-keeping procedure is used to estimate moisture content of the leaf litter. Wind speed is added to give a measure of expected rate of spread. The system was developed for a fuel loading of approximately seven and a half tonnes per hectare and a conversion table is included for application to other fuel loadings. The system was based on some 130 experimental fires. It corresponds to the spread component of the NFDRS.

In Australia, the Bureau of Meteorology produces routine fire-weather forecasts. (In 1972, the Bureau prepared 28 200 such forecasts.) There are no special fire-weather units and forecasts are prepared by the meteorologist on duty. Meteorologists may occasionally be sent to especially large fires, but there is no regular mobile service.

In many of the states, the Bureau of Meteorology calculates the fire-danger rating and issues forecasts of the rating. In order to obtain information on the state of curing of grass and herbaceous vegetation, the Bureau has developed a system of co-operators who routinely mail post cards with this information directly to the Bureau.

Although the issuing of burning bans is normally reserved to the state forestry departments, in at least one state (South Australia) the Bureau of Meteorology is charged with this responsibility.

Although the Bureau does not maintain specialized fire-weather-forecasting units, forecasting personnel work closely with forestry officials on fire-weather problems. The Bureau accomplishes a considerable amount of research on fire weather and fire-weather forecasting.

NEW ZEALAND

The New Zealand Forest Service uses a fire-danger-rating system which appears to be based on the system formerly used in the south-eastern United States. It uses fuel-moisture sticks made from "Pinus radiata" to estimate fine-and medium-fuel-moisture content, a drought index based on precipitation and temperature to keep track of heavy-fuel-moisture content, relative humidity, air temperature and wind speed. In terms of the US National Fire Danger Rating System, it corresponds most closely to the energy-release component for a single fuel type.

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* Memorandum from C. E. Van Wagner, 20 May 1975

The Forest Service is responsible for keeping track of fire weather and has the statutory responsibility for imposing fire bans.

The New Zealand Meteorological Service prepares routine forecasts of elements which enter into the calculation of the forest-fire-danger index. The Service also produces specialized forecasts for planned controlled burns, and forecasts a ventilation index used by forestry personnel to minimize the air pollution from smoke. The two services are jointly responsible for operating fire-weather-observing stations.

Although there is no specialized fire-weather service, a number of meteorological service personnel have done research projects on fire weather and fire-behaviour/weather interactions.

FRANCE

The fire-danger-rating system currently used in the Mediterranean region was developed by the national Meteorological Service (Bordreuil, Lombardo and Orieux, 1962; Orieux, 1974). It is based on two variables: an estimate of cumulative drought (i.e. soil moisture) and the speed of the wind. Drought is estimated through a book-keeping procedure wherein daily drying is calculated using a modified Thornthwaite evapotranspiration formula, which in turn is based on temperature and day-length. Depending on the dryness of the soil, actual evapotranspiration is reduced by a negative exponential function. Daily calculations of estimated soil moisture are made by adding rainfall and subtracting actual evapotranspiration, to a maximum of 150 mm of water.

Discriminant analyses based on the number of fires per day lead to equations of the form:

$$F = a + bR - cV - fV^2 + dN + eQ$$

where F is a highly positive number when the risk of fire occurrence is small and a highly negative one when the risk is great; R is the soil moisture estimated as above; V is the wind speed; N is the number of days since last rainfall; Q is the amount of the last rainfall; and the small letters are empirically-determined coefficients (Barescut, 1976).

The system does not correspond directly to any of the indices of the U.S. NFDRS, but combines wind speed with 100-hour (or greater) time-lag fuel moisture. This corresponds most closely to the NFDRS burning index for very heavy fuels.

Fire-weather forecasts are prepared and disseminated twice daily during the fire season by the Regional Meteorological Centre at Marignane. In addition to bulletins transmitted directly to the forest-fire services, warning bulletins are broadcast on television and radio. During the fire season, information notes are issued, describing the development of the fire climate and indicating those regions in greatest danger from potential fires. Special forecasts are prepared for specific wildfires, and meteorologists are occasionally sent to the scene of especially large and dangerous fires.

Although there is no specialized fire-weather service, a number of meteorological service personnel have done research projects on fire weather and fire/behaviour/weather interactions.

WEST GERMANY

Baumgartner et al. (1967) developed an ignition index which is used in Bavaria. It is based on a balance between precipitation and evaporation and was developed through a statistical analysis of past fire records. It is apparently the only system currently in use in any part of the West German states.

The German Weather Service does not provide specialized fire-weather-forecast services. The Bavarian Office of Fire Fighting prepares forecasts based on their accumulated experience. However, fires are not a major problem in the country. During a recent ten-year period in Bavaria, less than one tenth of one per cent of the area was burned and the average fire size was just over one hectare.

UNION OF SOVIET SOCIALIST REPUBLICS

In the U.S.S.R., the forest fire-danger-rating system in use today was developed by Nesterov (1940, 1960). It has been revised slightly since its introduction in 1938. The current version used by the Hydrometeorological Service is expressed by the equation:

$$G = \sum^{n} T\ (T - T_d)$$

where T and T_d are the air temperature and dew-point temperatures respectively, in degrees Celsius at 1500 h, local time. The summation extends over n days since the last precipitation of at least three millimetres. The index, G, is reduced to zero when at least three millimetres of rainfall occur, and the summation process begins anew.

An alternative method for calculating the cumulative fire danger is expressed in the equation:

$$G = K\sum^{n} T\ (T - T_d)$$

where K is an index number which takes into account the effects of rainfall. With five millimetres precipitation in the previous 24 hours, K = 0. With no precipitation, K = 1; and the index is scaled proportionately for intermediate amounts of rainfall.

Numerical ratings are classified into five fire-danger classes, as follows:

G	Fire-danger class	Description of fire danger
1 - 300	I	Nil
301 - 1000	II	Low
1001 - 4000	III	Medium
4001 - 10 000	IV	High
10 000	V	Extreme

A rating system is basically a drought index and corresponds most closely to the energy-release component of the US system. The state of curing of the herbaceous vegetation, not explicit in the Nesterov system, is taken into account by local forestry personnel.

The danger index is calculated daily by a special section in the Hydrometeorological Service Office in Moscow (Katz, Guser and Shabunina, 1975). Synoptic charts are prepared each morning for the entire Soviet Union, based on the 1500 h data of the previous day. These show areas of the country in each of the fire-danger classes. Duplicated synoptic charts are distributed each day to various forestry, agricultural and civil defense organizations (about fourteen in Moscow).

Local charts are also prepared in each of the 34 regional forecast centres throughout the country. These are based on synoptic conditions prevailing at noon, local time, and show in greater detail the areal distribution of fire danger prevailing in the immediate area of the regional centre. They are sent to the local forestry offices.

Each regional centre prepares three-day forecasts of fire danger. The Moscow office also prepares a 30-day forecast, based on prognoses developed by the long-range forecasting section. These are issued by the 25th of each month for the following calendar month.

It is recognized that the Nesterov index does not take into account local variations of fire danger caused by topography and vegetation types. Regional centres are encouraged to develop local variations of the index scale to suit local conditions. However, no weather-observing station is operated specifically to obtain weather data used to calculate the index. Although wind speed is not included in the Nesterov system, fire-weather forecasts contain warnings of high winds.

The fire season lasts from April through October, depending on the disappearance and reappearance of snow cover. The Central Office prepares the daily charts from May until autumn snowfall occurs, usually in October.

The danger index is used at the local level for scheduling fire-detection reconnaissance flights and for determining the state of preparedness of suppression forces.

Co-operation between meteorological personnel and forestry officials is furthered by an annual meeting in Leningrad. At the regional level, meteorologists are occasionally called upon to visit the scene of major fires to provide on-the-spot fire-weather information.

SWEDEN

The fire-danger index is based on one developed by A. Angström in the 1940s (Angström, 1942). This related the rate of spread of fire in the surface litter to air temperature and relative humidity. As used today by the Swedish Meteorological and Hydrological Institute (SMHI), the index is expressed as:

$$B = 3.3 - 5R + \frac{T}{10}$$

where R is the relative humidity (expressed as a fraction from 0-1) and T is the air temperature in degrees Celsius. The index is calculated using readings taken at 1300 h local time. The calculated index is classified into a five-class scale, as follows:

B	Fire-danger class	Fire danger
1.4	1	Very low
1.5 - 2.4	2	Low
2.5 - 3.4	3	Moderate
3.5 - 4.4	4	High
$\geq$4.5	5	Very high

The fire season starts in March or April after the snow cover has melted. The number of fires reaches a maximum in April. These are mainly grass fires. However, in these spring months the B index may be abnormally low because of low temperatures, even when the relative humidity is low enough to permit fires. At these times, an index based solely on relative humidity is used, as follows:

Relative humidity (per cent)	B	Fire danger
70	1	Very low
61 - 70	2	Low
51 - 60	3	Moderate
41 - 50	4	High
⩾ 40	5	Very high

A forecast of the afternoon fire index is made by the duty forecaster prior to 0800 h each day, based on computer-plotted charts of the previous day's fire danger. The chart includes index values and relative humidities for approximately 150 stations throughout Sweden, calculated from the 1200 GMT weather observations. Areas covered with snow and areas having "considerable" precipitation during the previous two days are given a rating of zero. The forecast for the current day is then used to predict the fire danger for that afternoon.

At 0800 h, the fire-danger prediction is broadcast on radio for public information along with the regular weather reports. In case of high fire danger, special warnings are prepared and broadcast on radio and television.

The fire-danger predictions are used for scheduling aerial detection patrols. However, SMHI is not called upon to provide specialized fire-weather forecasts for existing fires.

In addition to the forecasts prepared by SMHI, many local forestry organizations utilize the "Riskindikator" to indicate current state of fuel flammability. This device consists of two wooden disks, exposed to the air, and which are weighed continuously to indicate their moisture content. They are similar in function and response to the fuel-moisture sticks used in the United States.

The Angström index, as modified by SMHI, corresponds closely to the ignition component of the US system. It should correlate with occurrence of fires but less well with fire behaviour since it does not include the effects of wind or fuel type.

FINLAND

Until recently (May 1975) fire danger in Finland was rated by a system developed by M. Franssila (1958). It is based on the empirical probability that a fire will occur as a function of the relative humidity measured at 1400 h, provided that the previous two days had negligible rainfall.

Currently, a rating system is used which includes a number of meteorological variables in addition to the Franssila index. It is based on forest-fire statistics for the years 1959-67 and corresponding weather observations from 28 stations throughout Finland. The resulting multiple regression equation is:-

$$B = aR + bT + cU + dN + eE + fP + gK + h \sin \alpha + i \cos \alpha$$

where: B is the so-called BC-index and is constrained to vary between 0 and 10;

R is a two-valued variable indicating occurrence or non-occurrence of significant rainfall in the previous two days;

T is the current day's temperature at 1400 h;

U is a summation of six current and past days' 1400 h relative humidity;

N is a summation of the previous six days' average cloud amount;

E is the sum of current and previous days' 1400 h humidity deficit;

P is a summation of values of the past six days' sea-level pressure at 1400 h;

K is the Franssila index calculated for the present day at 1400 h;

α is a factor depending on region and season.

The regression coefficients are calculated for each of twelve different fire-climate regions. An index value of less than 2.5 is considered to indicate minimal fire danger. At values of 2.5 or more, fire warnings are broadcast over radio and television, and a "fire-alarm" warning is issued when the index value reaches four.

In use, the BC-index is calculated each day at 1430 h for all 52 standard weather stations, and results compiled and printed by computer analysis. Warnings are issued by the Meteorological Service after consultation with the Ministry of the Interior. Although the BC-index is not forecast explicitly, the duty forecaster evaluates the trend subjectively in preparing fire-weather warnings.

The BC-index is primarily an ignition index and corresponds most closely to the ignition component of the US system. However, it has some of the characteristics of the energy-release component, inasmuch as it includes the effects of the past six-days' relative humidity and cloud amount. It should be noted, however, that it was developed from statistics on actual fire occurrence and therefore includes the element of fire risk.

Meteorological observations (wind speed and direction, temperature, relative humidity, rainfall and thunderstorm activity) are transmitted daily from the Meteorological Service to the National Board of Forestry. In addition, special fire-weather-observing stations are operated by the Board of Forestry at about twenty locations, usually at fire-lookout towers. Twice-daily observations, including Riskindikator values (see previous section), are transmitted to dispatching centres in each forest-administrative district.

A N N E X III

IGNITION INDEX

(Adapted from Ignition Component of the
US National Fire Danger Rating System)

PURPOSE

The ignition index provides an index number related to the ease with which fine fuels (grass, herbaceous vegetation, pine needles, etc.) will ignite when exposed to a simple ignition source (match, cigarette, lightning strike, etc.).

RATIONALE

Accidental fires in wildland fuels normally start when a source of ignition comes in contact with the fine-fuel part of the fuel complex. Once ignited, these fuels can produce enough heat to ignite the heavier components of the fuel complex.

The major determination of the ease with which these fine fuels will ignite is their moisture content. This in turn depends primarily on the temperature of the fuel and the relative humidity of the air in contact with it. If such dead fuels are subjected to a constant temperature and relative humidity for an indefinite period, they will eventually reach an equilibrium moisture content. Although each type of fuel (such as grass or pine needles) has a characteristic curve of equilibrium moisture content as a function of temperature and relative humidity, the curves for the different fuels are quite similar and can be approximated by a single curve. The equilibrium moisture content also depends on whether the fuel is undergoing a drying phase or a wetting phase. Because fire-control personnel are normally concerned with the increasing flammability of fuels subjected to drying conditions, tables are constructed for such a drying phase. Although fine fuels respond quickly to changes in ambient conditions of temperature and humidity, the changes are not instantaneous and some programme of temperature and humidity changes must be assumed as a basis for calculating the fine-fuel moisture content at any particular time. For these tables, a drying régime typical of a continental climate is assumed. Although such a drying régime may not be typical everywhere, it can be used as a first approximation.

If all the fine fuels are completely dead (fully cured), the moisture content of the fine-fuel complex can be determined directly from observations of air temperature, relative humidity, and the state of the weather (whether sunny, cloudy, or raining). However, if some of the fine fuels are still living, their moisture content will be much higher (in the order of 100 per cent on a dry-weight basis), and the ignitability of a fuel complex, consisting of an intimate mixture of dead and living fuels, will be reduced accordingly. Therefore, some adjustment must be made for the percentage of the fine fuels which are green and living. With this corrected

fine-fuel moisture content and an observation of the state of the weather, an index number can be calculated which will relate directly to the ease of ignition of the fine fuels.

PROCEDURE

Table I - Fine-fuel moisture content of fully cured or dead fuels

In addition to the state of the weather, measurements of temperature in degrees Celsius and relative humidity in per cent taken in a standard weather shelter are needed. Enter the appropriate block of the tables (sunny, cloudy, or raining) with temperature and relative humidity and read the fine-fuel moisture content from the body of the table.

Table II - Fine-fuel moisture corrected for state of curing

If the fine fuels are not fully cured or dead, an estimate is needed of the percentage of these fuels which are green and living. This estimate can be made by eye, but should be representative of the fine fuels in the area being rated. The table is entered with this percentage and with the fine-fuel moisture content from Table I to give an estimate of the average or effective moisture content of the fine-fuel complex.

Table III - Ignition index

Table III is entered with this corrected fine-fuel moisture content and with the state of the weather at the time of observation to yield an index number - the ignition index. This number can be interpreted as the probability that an ignition source, dropped at random into the fine-fuel complex, will start a persistent fire. It can be used by fire-control personnel as an indication of the probable number of fires which will start, given a certain number of ignition sources. It does not indicate how vigorously a fire will burn or how fast it will travel, since these depend on other variables such as wind speed, nature of the fuel complex and so forth.

TABLE I

Fine-fuel moisture (per cent) - fully cured or dead

State of Weather	Temperature	Relative Humidity																				
	°C	0 → 4	5 → 9	10 → 14	15 → 19	20 → 24	25 → 29	30 → 34	35 → 39	40 → 44	45 → 49	50 → 54	55 → 59	60 → 64	65 → 69	70 → 74	75 → 79	80 → 84	85 → 89	90 → 94	95 → 99	100
SUNNY (Cloudiness 0-5/10)	-12 → -2	1	2	2	3	4	5	5	6	7	8	8	8	9	9	10	11	12	12	13	13	14
	-1 → 9	1	2	2	3	4	5	5	6	7	7	7	8	9	9	10	10	11	12	13	13	13
	10 → 20	1	2	2	3	4	5	5	6	6	7	7	8	8	9	9	10	11	12	12	12	13
	21 → 31	1	1	2	2	3	4	5	5	6	7	7	8	8	8	9	10	10	11	12	12	13
	32 → 43	1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	13
	44+	1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	13
CLOUDY (Cloudiness 6/10 or more)	-12 → -2	1	2	4	5	5	6	7	8	9	10	11	12	12	14	15	17	19	22	25	25+	25+
	-1 → 9	1	2	3	4	5	6	7	8	9	9	11	11	12	13	14	16	18	21	24	25+	25+
	10 → 20	1	2	3	4	5	6	6	8	9	9	10	11	11	12	14	16	17	20	23	25+	25+
	21 → 31	1	2	3	4	4	5	6	7	8	9	10	10	11	12	13	15	17	20	23	25+	25+
	32 → 43	1	2	3	3	4	5	6	7	8	9	9	10	10	11	13	14	16	19	22	25	25+
	44+	1	2	3	3	4	5	6	6	8	8	9	9	10	11	12	14	16	19	21	24	25+
RAINING	all	25+	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	.25+

TABLE II

Fine-fuel moisture corrected for state of curing

Fine fuel moisture (from Table I) Percent moisture content	Percent of fine fuels that are green and living								
	0 → 4	5 → 14	15 → 24	25 → 34	35 → 44	45 → 54	55 → 64	65 → 74	75 → 100
1		2	3	4	5	8	13	18	21
2	N	3	4	5	7	10	16	19	22
3	O	4	5	7	9	14	18	20	22
4	C	5	6	8	12	16	19	21	23
5	H	6	8	11	14	18	20	22	23
6	A	7	10	13	16	19	20	22	23
7 - 8	N	9	12	15	18	20	21	22	23
9 - 10	G	12	15	17	19	20	22	23	24
11 - 12	E	14	17	18	20	21	22	23	24
13 - 14		16	18	19	20	21	22	23	24
15 - 16		17	19	20	21	22	22	23	24
17 - 18		19	20	21	21	22	23	23	24
19 - 21		21	21	22	22	23	23	24	24
22 - 24		24	24	24	24	24	24	24	25
25 - 25+		25+	25+	25+	25+	25+	25+	25+	25+

TABLE III

Ignition index

State of Weather		Corrected fine fuel moisture content (from Table 2)														
SUNNY Temp. °C	CLOUDY Temp. °C	1	2	3	4	5	6	7 → 8	9 → 10	11 → 12	13 → 14	15 → 16	17 → 18	19 → 21	22 → 24	25 → 25+
-12 → -7	-12 → 4	88	75	64	54	46	39	30	21	14	9	5	2	0	0	0
-6 → -2	5 → 9	90	77	66	56	48	41	32	22	15	9	5	2	0	0	0
-1 → 4	10 → 15	93	80	68	58	50	42	33	23	16	10	6	3	0	0	0
5 → 9	16 → 20	95	82	71	61	52	44	35	25	17	11	7	3	1	0	0
10 → 15	21 → 26	98	85	73	63	54	46	36	26	18	12	7	4	1	0	0
16 → 20	27 → 31	100	87	76	65	56	48	38	28	19	13	8	5	1	0	0
21 → 26	32 → 37	100	90	78	68	58	50	40	29	21	14	9	5	2	0	0
27 → 31	38 → 43	100	93	81	70	61	53	42	31	22	15	10	6	2	0	0
32 → 37	44 → 48	100	97	84	73	63	55	44	32	23	16	11	7	3	0	0
38 → 43	49+	100	100	87	76	66	57	46	34	25	18	12	8	4	0	0
44 → 48		100	100	90	79	69	60	49	36	27	19	13	9	4	1	0
49+		100	100	92	80	70	61	50	37	28	20	14	9	5	1	0

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