

Fire danger rating in the United States of America: an evolution since 1916*

Colin C. Hardy^{A,C} and Charles E. Hardy^B

^AUSDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 US Highway 10 West, Missoula, MT 59808, USA.

^BRetired. Formerly of Northern Forest Fire Laboratory (now called the Missoula Fire Sciences Laboratory), USDA Forest Service.

^CCorresponding author. Email: chardy01@fs.fed.us

Abstract. Fire scientists in the United States began exploring the relationships of fire-danger and hazard with weather, fuel moisture, and ignition probabilities as early as 1916. Many of the relationships identified then persist today in the form of our National Fire-Danger-Rating System. This paper traces the evolution of fire-danger rating in the United States, including discussions of significant developmental milestones, innovative instrumentation, and a succession of analogue fire-danger meters, or calculators. Although the primary theme of this paper is an historical review of pioneering efforts leading up to our current state-of-knowledge, a common thread throughout this paper is the desire by every generation of developer to achieve a ‘purely analytical system’. A national system was first introduced in 1964. The current system used throughout the USA was implemented in 1978, with optional revisions added in 1988. We present this evolution within the context of three periods of development: first, the pioneering efforts initiated at the Priest River Experiment Station in northern Idaho; second, the implementation of a national, standardised fire-danger-rating system; and third, spatially explicit delivery systems that provide a national view of weather and fire potential, which include national fire-danger and weather maps and satellite-derived maps that reflect the state of live vegetation across the United States.

Introduction

‘Our danger measuring system may have its weak spots, but the best watch in the world will not show time accurately if you do not wind it.’

H. T. Gisborne, 1948

Harry T. Gisborne’s remarks on the need for vigilance, maintenance, and consistent interpretation of the fire-danger-rating system in the United States came just a year before his death in the field while investigating the fatal burnover of twelve young firefighters at Mann Gulch, central Montana, USA (Hardy 1977). By the time of his death in 1949, Gisborne had already spent 27 years developing and implementing his vision of a fire-danger-rating system. Was Mann Gulch another ‘unwound watch’?

Our objective in this paper is to review the significant pioneering efforts, begun in 1916, that framed the development of fire-danger research in the USA. This historical work provides the context within which we discuss the evolution of fire-danger rating, with particular focus on activities in the Northern Rockies, USA, as a ‘case study’. We follow the historical review with a discussion of new innovations and research that continues to lead fire-danger rating towards the long-held goal of a ‘purely analytical’ system.

Background

In the beginning, the number and magnitude of forest fires in District One (now Region One, or Northern Region) of the

newly formed US Forest Service dominated nearly every aspect of the agency. How could these well-intentioned resource management personnel accomplish any meaningful planning when huge fires continually sabotaged their progress? The 1910 fire, which consumed over three million acres and killed seventy-eight firefighters, was an event that raised national awareness (Pyne 2001). Several more moderate fire years during the period of 1910–1920, culminating in the extreme year of 1919, caused the agency to realise that a deliberate, science-based strategy would be needed to both explain and predict fire activity in the western USA, hopefully leading to options by which the number and size(s) could be reduced.

The main concern was for the forests west of the Continental Divide. At that time, the eastern forests of the District were commonly referred to as the ‘asbestos forests’; fires there were less dramatic, the value of timber east of the Divide was considerably less, and those grasslands were for cows and would grow back readily after a fire. The earliest focus was on the area extending from Western Montana across Northern Idaho, a region coincident with pioneering forest research based out of the Priest River (Idaho) Forest Experiment Station, founded by the Forest Service in 1911 (Hardy 1983).

Meteorological and climatic data were being acquired and archived at Priest River as early as 1913. By 1916, scientist J. A. Larson determined that the weather and climate data he had been collecting for silvicultural studies could be exploited

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for the study of fire hazard and liability – perhaps the earliest formulation of ‘fire-danger rating’.

Finally, in 1922, the agency assigned the first person to work specifically on forest fire research – a forester from Oregon named Harry T. Gisborne was assigned to District One, located in Missoula, Montana. Gisborne soon found that there was utter chaos in describing the relative fire hazard in various portions of the western part of the District. Line officers employed a variety of creative tactics to describe their fire hazards in order to acquire extra firefighting forces. Help was given to the loudest of the ‘squeaky wheels’, or to those favourites of the upper echelons. Some formal and consistent method was clearly needed to measure, evaluate, and interpret the actual degree of fire danger upon which manager’s assignment of resources was based. In response to the chaos Gisborne observed, the vision he formed was for a simple set of numbers that fire managers could communicate in a ‘common language’ to anybody, whether a woodworker, a settler, a ranger, or an administrator in the District Office. Motivated by his intense desire to mitigate this chaos, Gisborne installed fire weather stations in three forests (Kaniksu, Clearwater, and Nezperce) before the end of his first season on duty (1922).

Exploration and discovery

In just eight intensive years of mostly single-handed field studies, Gisborne was able to learn and describe the basic influences on fire and their relationships to fire potential and behaviour. Included in an extensive collection of nearly fifty papers and articles published by Gisborne between 1922 and 1930 are pioneering pieces on duff and fuel moisture (Gisborne 1923, 1924), weather (Gisborne 1922, 1925, 1927*b*), lightning (Gisborne 1926, 1927*a*), and early syntheses of fire-danger rating (Gisborne 1928, 1929). With this new knowledge, and after many discussions with resource managers and on-the-ground personnel, Gisborne determined that three parameters could be used to describe the current fire potential (fire-danger) situation: the moisture of the fuels, wind velocity, and relative humidity.

Instrumentation and measurement

Duff Moisture Hygrometer

Methods and instruments for measuring wind velocity and relative humidity were well known and widely available, but the need for daily measurements of fuel moisture for duff and ‘slash and branchwood’ presented a new challenge. An early development by Gisborne’s staff was the Duff Moisture Hygrometer, which consisted of a strand of rattan fibre enclosed in a perforated metal tube with the tip placed just under the top of the duff. The rattan stretched or shrunk according to the amount of moisture and, when attached to a needle pointer and calibrated, it indicated duff moisture as a percentage of oven-dry weight. The Duff Moisture Hygrometer was later abandoned because calibration was difficult, and uniform placement was not easy.

Fuel moisture sticks

During a 1923 field visit to experimental stations in Europe, J. A. Larsen had made the serendipitous observation at a site near Copenhagen that the foresters there were using a block of straight-grained wood as a literal analogue meter of fuel moisture. Following this innovative approach, Gisborne collected

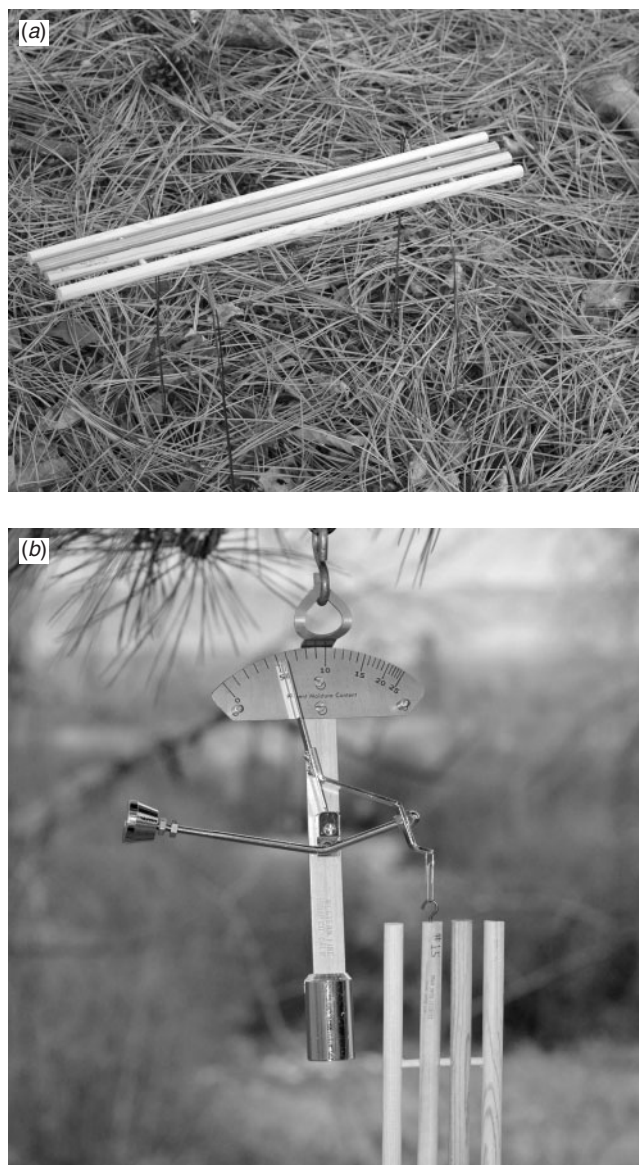


Fig. 1. The one and a half inch diameter ponderosa pine fuel moisture indicator sticks (a). Portable scales were used for weighing the sticks in the field (b).

twigs of several diameters, placed them into sets, and oven-dried them to determine moisture content as a percentage of oven-dry weight. He discovered that the twigs did not behave uniformly or consistently, so he resorted to ponderosa pine dowels (one-half inch seemed to be the most suitable diameter), and ultimately assembled sets of four dowels, trimmed to weigh exactly 100 g when oven dry (this greatly simplified the computations). He then wrote a tight set of specifications for the wood used so all sets would respond similarly (Fig. 1a) – what is to this day the standard manual method for measuring the small diameter, dead woody fuel moisture (Fischer and Hardy 1976).

Large log moisture

The influence of precipitation and drying on the moisture content of larger logs (10 to 12 inches in diameter) presented a more



Fig. 2. Gisborne at work on an early dead woody fuel moisture study, Priest River Experimental Forest.

difficult problem, however, and required several approaches initially explored by G. Lloyd Hayes in 1935 (Hardy 1977). Hayes and Gisborne installed electrodes along each side of several logs to relate electrical resistance (measured by an instrument called a 'Blinkometer') to moisture content. Gisborne also continued to evaluate the different sizes of logs and their response to precipitation and drying (Fig. 2). This work continued until 1940, when Hayes published his findings in his master's degree thesis (Hayes 1940). Brackebusch (1975) has summarised Hayes' findings: (1) the amount of rain per period was best correlated with the log moisture measured at 1-inch depths, (2) log moisture did not provide a usable index of seasonal, monthly, or current fire danger, (3) log moisture decreased continuously throughout the summer, almost without regard to midsummer rains, (4) the present (circa. 1940) fire-danger system is not sensitive to the cumulative effects of intensifying and constant moisture losses that occur between mid-July and mid-August, (5) the average moisture content of large logs can be used to determine its flammability, and (6) it may be possible to compute an index of inflammability of large logs using the amount of spring rain and the duration of the summer desiccation period. Following Hayes' recommendations, the large log moisture study was continued through 1960 using whole-log weighing procedures. Log diameters for the study were standardised at 6 inch, 10 inch, and 12 inch. Brackebusch (1975) completed a comprehensive analysis of the large-log moisture data collected during the 19-year period between 1942 and 1960. His conclusions generally agreed with those made in 1940 by Hayes: 'The large-fuel study did not produce a precise method for predicting fire season or fire activity, nor predicting the exact moisture content of large logs'. Nonetheless, he recommended a controlled-environment experimental design for future work.

Perhaps the most cogent and relevant conclusion from the large-log moisture studies was the admonition that potential severity and experienced severity are not always the same. Brackebusch (1975) reminds us in his discussion that two constantly changing factors unrelated to weather or climate can significantly influence experienced fire severity: human activity and efficiency of fire control.

Weather instruments

The aggressive increase in establishment of new fire-danger weather stations was so rapid that the supply of instruments



Fig. 3. Gisborne using one of the visibility meters he designed with his staff.

became a major problem. USA Weather Bureau (USWB) rain gauges and anemometers were used at first, but they were in short supply and were also quite expensive. Gisborne and his crew promptly set forth to acquire, engineer, or adapt a group of very inexpensive but relatively accurate instruments for measuring fire-related weather and fuel conditions.

Scales for weighing fuel moisture sticks

- Triple beam and Harvard balances: these were widely available shelf items, but were moderately expensive.
- Swinging beam scale: these hung on the side of the instrument shelter (Fig. 1b); the R-6 Scale was produced by the Pacific North-West Experiment Station; the Appalachian Scale by the South-East Forest Experiment Station.

Precipitation

- This modest rain gauge was made from a section of galvanised stove pipe fitted with a bottom and a calibrated funnel (US\$1.25, compared to USWB's US\$25).

Wind

- An old time service station Pennzoil advertising rotating sign, calibrated by driving down a road and counting the revolutions per minute (US\$3, compared to USWB's US\$80).
- The 'Stewart': a commercial four-cup anemometer, top mounted in an electrical conduit outlet box (US\$4.75). Others were soon developed, but none were as inexpensive as this.

Visibility

- Several rather complex devices were developed: first, using visibility of 'small smokes' as a measurable indicator; and later using 'skyline ridge' visibility. One such device designed by Gisborne and his staff is shown in Fig. 3.

Integrating the inputs: the first fire-danger meter

In his quest for a means of compressing the trio of factors into a common language, Gisborne happened onto a Kodak Exposure Meter, which combined light, exposure time and lens opening into a single set of values. By substituting his inputs (fuel moisture, wind velocity, and relative humidity) for those

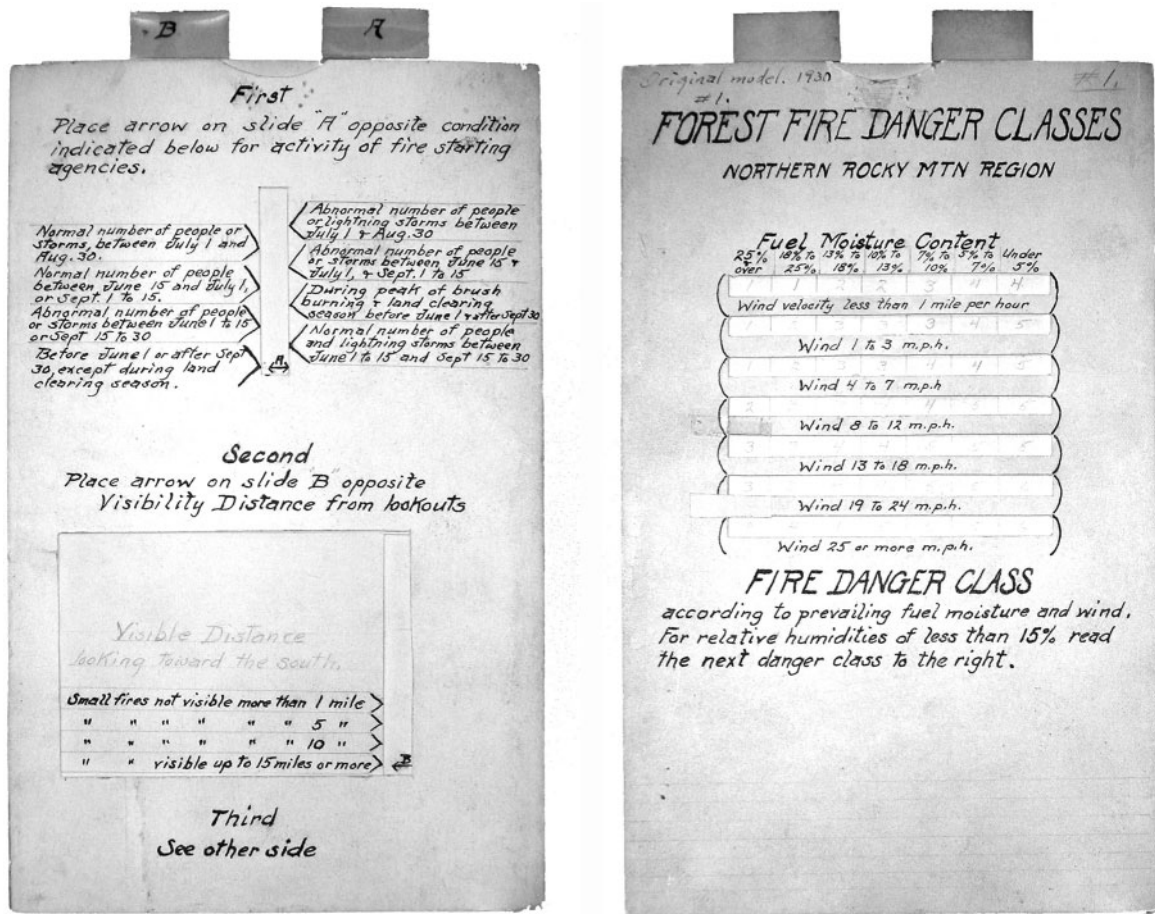


Fig. 4. Front (left) and back (right) of Gisborne's original Model One fire danger meter.

of the photographic parameters, he had the basics for the first fire-danger meter.

But how was he to express the relative importance of fuel moisture, wind, and humidity? Clearly, the relationships of these three components were not simply linear. Not only did he need to successfully integrate these three components into his fire-danger meter, but he also faced the equally intimidating challenge of getting potential users to accept this new tool. Being both an accomplished and practical scientist, Gisborne knew that in those early days nearly all personnel in the Forest Service were also seasoned firefighters. He, therefore, selected a few trusted and experienced men from both administration and research, took them to the Priest River Experimental Forest in Northern Idaho, set each up with a blank meter and asked each to draw a set of curves to express his idea of how these three factors should fit together. Gisborne then organised the data into a composite set of curves, normalised to express relative fire danger within a range of 1 to 6. The outcome of that effort became the structure for the Fire-Danger Meter, Model One (Fig. 4). Gisborne also included adjustments in the fire-danger meter to account for both human and lightning-caused ignition risks. Because Western Montana and Northern Idaho were still being settled, there was considerable risk of ignitions from human activities – clearing of ‘stump ranches’, slash burning, and railroad construction. These on-the-ground risk factors were characterised in the fire-danger meter

as a ‘land clearing class’ – the relative number of people in the woods, brush burning, and land clearing activities. Finally, the fire-danger class was adjusted by a detection-probability factor, expressed simply as ‘visibility distance’, which was based on an estimate of the distance a small fire could be seen from a lookout.

Use of this new ‘common language’ tool was accepted and its use spread quickly; the acceptance of which was a result largely of Gisborne’s constant consultation and integration of advice from experienced and respected foresters. Gisborne’s strategy was effective in making it ‘their meter!’

Although the popularity of this tool and its principles encouraged adoption in several other regions, it was not long before certain components were modified to suit their apparent regionally specific needs. For example, in the south-eastern USA, the half inch fuel moisture sticks were replaced by basswood Venetian blind material – ‘Appalachian slats’ – in an attempt to represent the greater abundance of fine fuels. Unfortunately, this and other localised adaptations ultimately diminished the ‘common language’ Gisborne had so hoped to promote.

Eight generations of the fire-danger meter

Within the Northern Rockies, USA, a continuous effort to improve the initial Model One fire-danger meter resulted in at least seven additional versions of the concept. Gisborne’s

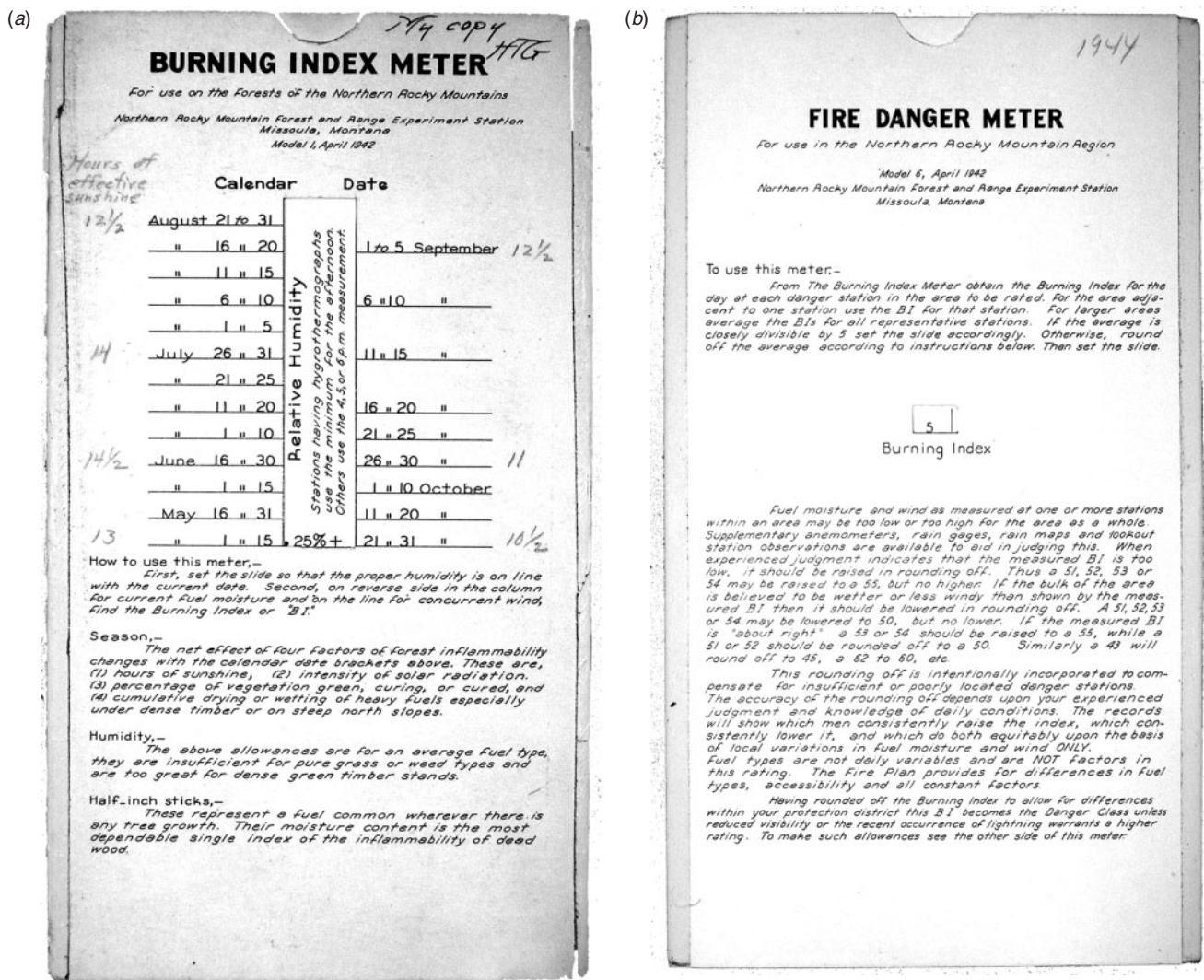


Fig. 5. (a) The Model Six BI meter incorporates season, humidity, wind speed, and fuel moisture. (b) Calculations in the Model Six FD meter are initiated by the BI, as first determined from the BI meter.

core idea for a fire-danger meter evolved through eight different models over a period of nearly twenty-five years. Although development and adaptation of some of the models was underway in other regions of the country, in this paper we use the work in and for the Northern Rockies, USA, as our frame of reference. Managers and researchers worked hand-in-hand as these meters changed and evolved, which resulted in eager adoption and implementation by managers of successive models of the meter – these managers were clearly leaders at the early adoption of new science and technology. During the period 1931–1954, seven different variants of the fire-danger meter were developed and tested in rapid succession.

Model Two Meter: 1931. Described potential fire behaviour in terms of fire danger classes, ranked from 1 to 7.

Model Three Meter: 1933. Removed land clearing, lightning in the last two days was tied to an actual calendar date, visibility distance was modified, a factor was introduced to reduce the rating if humidity exceeded 15%, the number of danger

classes increased from 6 to 7, organisation according to fire-danger class was added.

Model Four Meter: 1934–1937. Number of people in woods was deleted, the next higher wind class was used if fuel moisture below 5%.

Model Five Meter: 1938–1941. The factor for land clearing was re-instated, threshold visibility distances varied between eastern and western forests, fire danger now ranged from 1.0 to 7.4. A new addition was ‘action commensurate with fire-danger class’ (which relates in general terms to Table 10-1-c, briefly described later in this paper).

Model Six Meter: 1942–1953. This model consisted of two meters: Burning Index (BI) and Fire-Danger (FD) meters. The two meters comprising Model Six are illustrated in Fig. 5a (BI) and Fig. 5b (FD). The BI Meter included calendar date, relative humidity, fuel moisture, and wind, with the resulting BI scaled numerically from 1 to 100. The FD meter weighted BI with visibility (Fig. 6a) and lightning (Fig. 6b). Land clearing and the recommended ‘action commensurate

with fire-danger class' were both eliminated. A narrative interpretation was added for practical purposes, emphasising that BI and FD are relative ratings, the use of which was 'an administrative matter'.

Model Seven Meter: 1954. Lightning and visibility were dropped, but this model survived for only one year. A seasonal severity factor was prematurely included but did not

satisfy actual conditions, which led to immediate revisions and subsequent release of Model Eight.

Model Eight Meter: 1955. This model contained an improved Seasonal Severity factor and served from 1955 until a National Fire-Danger-Rating System was conceived in the mid 1960s (Fig. 7).

Early lessons and new fire-danger-rating principles

Shortly after the Model One meter and supporting weather observations had been implemented, an unusual situation developed. In 1934, a relatively active fire season, critical but highly localised conditions developed. The new fire-danger-rating principles and tools were proven both accurate and valuable, but this was only acknowledged in retrospect. On the night of 10 August, twelve fires started near where the Selway and Lochsa Rivers joined to form the middle fork of the Clearwater River; ten of the twelve were promptly controlled and contained. But no fire-fighting resources were left to hit what became the 'big one': the Pete King-McLendon Butte Fire. Readings from the fire weather station installed the previous summer at the Pete King Ranger Station clearly indicated that extreme fire weather was building there. Gisborne was screaming to everyone he could contact that, 'boy, we really got a blow-up situation on the Selway'. In addition, C. S. Crocker, the acting supervisor of the Selway Forest, was also crying for pre-suppression reinforcements, but his Forest could not secure the funds to hire supplementary crews. Regrettably, agency administrators were not persuaded by what they felt was, perhaps, either an error in the local fire-danger estimate or an anomaly at a scale too small to warrant additional resources. Forty-three days later, it was snow on the 22 September that finished off the quarter million acre fire.

Gisborne's prediction of the 1934 blow-up situation caused even the Forest Service's Washington office leaders to take unprecedented action. It was the beginning of many spin-offs

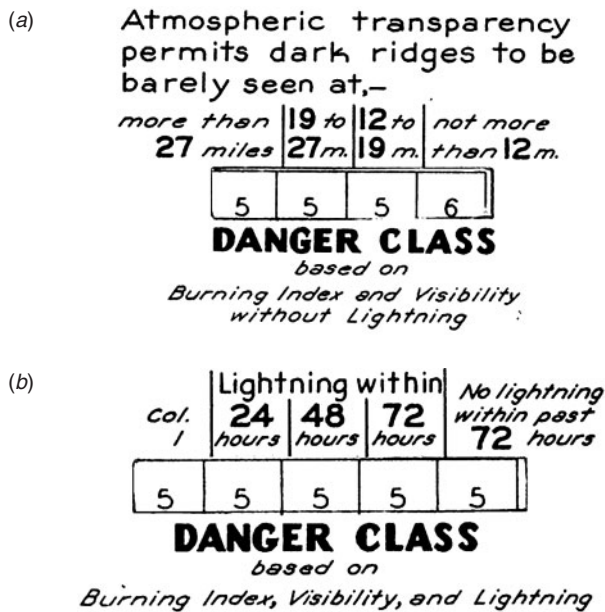


Fig. 6. Two adjustments to Danger Class are made on the backside of Model Six: (a) if no lightning has occurred in the past 72 h, simply adjust FD by visibility; (b) if lightning has occurred, adjust FD by time since last lightning.

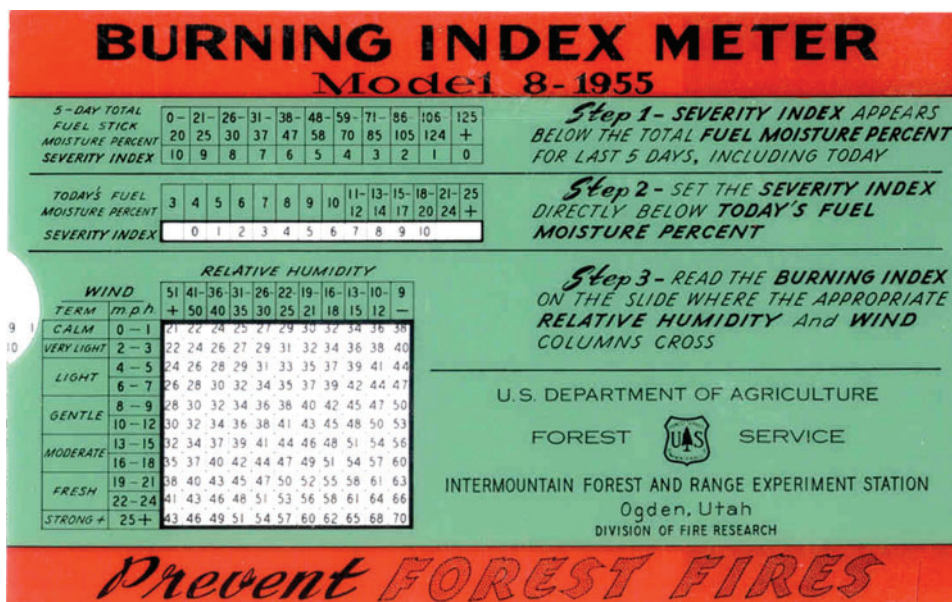


Fig. 7. The Model Eight meter served from 1955 until a NFDRS was conceived in the mid 1960s.

based on the use of fire-danger-rating principles. These early principles are listed below, as are several contrasting examples of current practices.

Fire control economics

This concept suggests that fire control decisions should be primarily based on the principle of ‘cost plus loss’, as opposed to the 1935 decree of control by 1000 am the next day for all fires. Although the concept of cost plus loss was recognised as both intuitive and feasible, the aggressive ‘10-AM’ policy prevailed nonetheless.

Agency policies today provide the opportunity, if not the imperative, to implement appropriate management response (AMR), which includes values at risk and suppression capability. The policy and implementation guidelines for AMR are presented below with respect to the 10-AM policy.

Fire control planning

The notion of fire planning validated Lloyd Hornby’s major endeavour, ‘Hornby’s principles of fire control planning’ (Hornby 1936). Hornby’s principles considered concentration (loading) by fuel types, rate of fire occurrence, rate-of-spread, and fire danger as fundamental, measurable factors of the fire job.

Quite recently, new analytical tools and data have been developed to support better fire-control planning based on parameters that mirror Hornby’s original principals. Probability distributions integrated into an actuarial approach now comprise a suite of experimental wildland fire decision analysis tools, as presented below in the section on ‘Calculating the probabilities’.

Statistical analysis of fire records

The assessment of fire records to support the development of future fire-danger actually started in 1931, but was given credence after the 1934 Pete King–McLendon Butte fire incident.

Software (FireFamily Plus) is now available for summarising and analysing daily weather observations and computing fire-danger indexes based on the National Fire-Danger-Rating System (Bradshaw and McCormick 2000).

Mapping fuel type, seen-area, and transportation plans

Much of these new mapping efforts were accomplished with CCC and emergency funds, and were field implementations of Hornby’s ‘principles’. The ‘seen-area’, for example, is simply the area or extent one can see from a specified lookout or vantage point.

The availability of modern Geographic Information System (GIS) tools for spatial analysis and mapping has made this job part of standard operating procedures for many managers. Viewshed analysis tools capable of deriving ‘seen-area’ using digital elevation data are common to many GIS applications. And now, nationally consistent and locally relevant maps of vegetation, fuels, and other attributes are becoming available for the entire United States through the LANDFIRE project (Rollins and Frame 2006).

The 10-AM policy

Gisborne emphatically said this 1935 policy was extremely counter to Hornby’s planning objectives, deeming the policy ‘an

uneconomic expression, impossible to justify in low value or ‘little injury’ types of vegetation’. Nonetheless, they were forced to modify and adapt Hornby’s objectives to fit this new policy.

Federal agencies today have significant decision-making authority with regards to how and when to respond to a wildland fire. If an approved fire management plan is in place, the response by federal agencies to wildland fire is based on ecological, social, and legal consequences of the fire. The AMR to a fire is dictated by the circumstances under which a fire occurs, and the likely consequences on firefighter and public safety and welfare, natural and cultural resources, and values to be protected (USDA Forest Service and US Department of Interior 2001).

Table 10-1-c

Prepared by Clarence Sutliff, Division of Fire Control in the Northern Region headquarters, this widely used table was based on the Ranger District’s current fire danger, which triggered employment and mobilisation of pre-suppression forces as a percentage of the Ranger District’s ‘Worst Probable Fire Danger’ limit (Fig. 8).

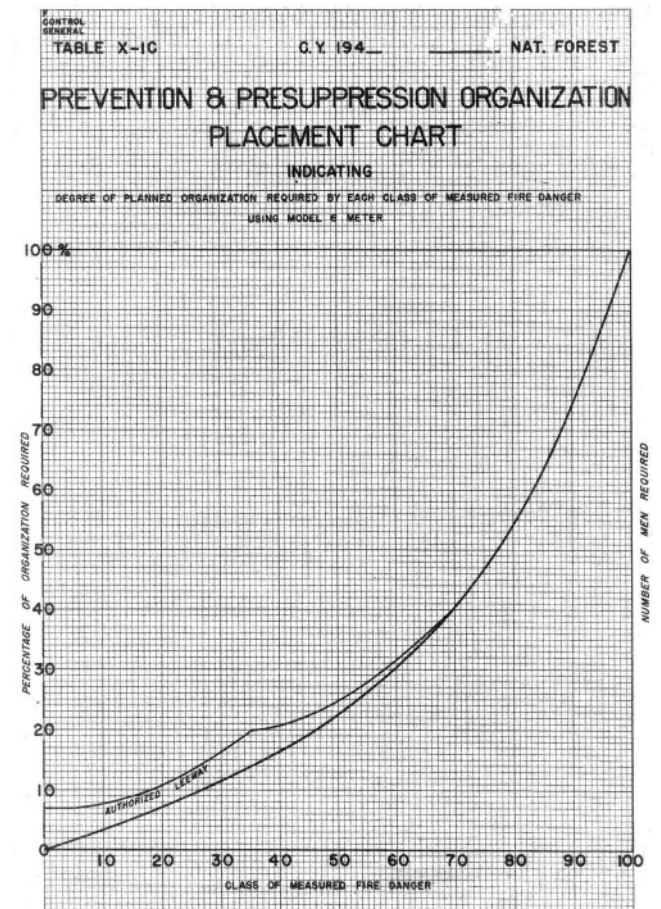


Fig. 8. The graph titled ‘Table 10-1-c’, developed in the 1940s, related the required presuppression organisation (shown on the vertical y-axis as ‘Percentage of Organisation Required’) to the relative ‘Class of Measured Fire Danger’ (the x-axis). The area between the upper and lower curves was considered ‘authorised leeway’.

Current practices are not dissimilar to this. Now, requests for within-season augmentation of firefighting resources are based either on the potential for abnormally severe fire behaviour, or where there is fire activity outside the normal fire season. A local or regional need for this 'severity funding' is determined and documented by using fire-danger analysis software, precipitation and/or drought indices, relative live fuel moisture, and long-range weather outlook(s) – many of these tools and approaches are briefly discussed later in this paper.

Calculating the probabilities

This protocol involved predicting the behaviour of a fire to support estimates of the forces needed to control that fire. Years later it was updated to involve both rate of spread and resistance to control.

We now know this activity to be a common function of a Fire Behaviour analyst or Long-Term analyst on most wildland fires. Analysts can now generate spatial fire spread probability distributions using high-end computing hardware and algorithms (Finney 2006), which can be integrated with rapidly generated values at risk data to improve strategic fire suppression planning (Calkin 2006).

Altitude and aspect

Data gathered from a perpendicular swath cut across a canyon from one ridge to another showed that, under certain conditions, the mid-slope environment (micro-climate) differs from either the ridge top or the canyon (or valley) bottom – a phenomenon termed the 'thermal belt'. This factor was thereafter included in the calculation of probabilities.

By 1936, Gisborne and his cadre of associates realised that in order to acquire more reliable information, there was considerable new research to be done that could only be executed inside an enclosed chamber with controlled conditions. Ten years after his death, his dream finally came true. Three new state-of-science fire laboratories were constructed in the late 1950s through to the early 1960s in Macon, Georgia; Missoula, Montana; and Riverside, California. These new laboratories provided sophisticated facilities such as wind tunnels and combustion chambers, where wind, air temperature and relative humidity could be manipulated and controlled. To exploit the unique and sophisticated new facilities, they were staffed by personnel highly trained in specific disciplines, making it possible to produce a National Fire-Danger-Rating System and extend its uses in many new ways.

A nationally consistent fire-danger-rating system

By 1958, as many as eight regionally specific variants of the initial fire-danger-rating principles had been implemented across the USA, including a variety of regional fire-danger meters styled after the predecessors developed first for the Northern Rockies. At the 1958 national meeting of the American Meteorological Society, a truly 'national' fire-danger-rating system was proposed, where the question was asked: 'Can one uniform fire-danger-rating system be developed and put into practice throughout the United States?' (Hardy 1958). In a presentation and paper on the subject, the reasons why this should be done

were discussed, followed by suggestions on how to accomplish it (Hardy 1958):

Why?

- To facilitate cooperative action between the various agencies.
- To ensure that increasingly mobile firefighters are able to evaluate burning conditions in terms and figures that mean the same thing as in their home region.
- To assure that fire prevention warnings (statements of fire danger) mean the same to people in all forest areas.

How?

- A problem analysis approach will be taken – follow the Forest Service Research branch's Research, Development, and Application (RD&A) Program approach.
- Indexes will be obtained that are based ONLY on common aspects of fire behaviour.
- All weather will be measured uniformly.

Over a period of time in 1958, several actions were taken that led to initial efforts at formulating and developing a national system. A joint committee comprised both fire management and research personnel determined that a national system was feasible, and a team was formed to implement the program. Less than a year later, work on the project was initiated. Early work relating to the 'spread phase' included two indexes: one for fires in the open, one for fires in a closed canopy. Preliminary work on the 'spread phase' was completed by 1961, tested in 1962 and 1963, and in 1964 the 'spread phase' of the system was issued in the Forest Service Handbook under section 'FSH 5109.11' (Deeming *et al.* 1972). Although field use of these 'spread phase' indices was being explored by fire managers, a small community of fire scientists (several of whom were ultimately conscripted to the National Fire-Danger-Rating Research Work Unit) found the subjectivity and lack of analytical foundation to the indices troublesome.

Creating a national system

Nearly ten years after the first formal proposal to develop a National Fire-Danger-Rating System (NFDRS), the USDA Forest Service established the National Fire-Danger-Rating Research Work Unit in Fort Collins, Colorado, which was dedicated to the development and implementation of a truly national fire-danger-rating system. Although the unit was officially chartered in 1968, considerable research and development had been accomplished in the decade leading up to 1968. Members of the new work unit were aware of the pioneering work being done by Richard Rothermel at the Fire Laboratory in Missoula, Montana to develop a mathematical model that produced quantitative values of spread and intensity. They felt quite strongly that Rothermel's work should be utilised in a new fire-danger system. Consequently, Rothermel's subsequent work (through 1972, at least) was directed towards the creation of a fire behaviour 'engine' for the NFDRS, which '... will display the [quantitative values of spread and intensity] on a relative scale in the form of indexes' (Rothermel 1972).

In the history and background provided in the 1972 Forest Service Research Paper describing the completed NFDRS

(Deeming *et al.* 1972), the authors enumerate the criteria by which the system was to be developed:

1. An operational system could be delivered by 1972.
2. The architecture of the system would be designed to readily accommodate new knowledge in the future.
3. The system would be delivered as a complete and comprehensive package.
4. Risk would be evaluated by subjective criteria, recognising the ultimate preference for a much more objective approach as new science became available.
5. The ultimate goal was for a system that was 'purely analytical', based on the physics of heat transfer, moisture dynamics, and fire behaviour.

Finally, the architects of the proposed system reiterated that the Rothermel spread model would become the computational basis of the NFDRS processor.

The NFDRS – 1972

The NFDRS was published and implemented nationally across the USA in 1972 (Deeming *et al.* 1972). The basic structure of the system included three levels of inputs: observations (weather variables, 10-h timelag dead fuel moisture sticks), objective estimates (1- and 100-h dead fuel moisture), and subjective estimates (fuel model, lightning and man-caused risk, slope, woody and herbaceous live fuel moisture). Subjective characterisation of live herbaceous fuels used ocular plot estimates along a transect, and involved periodic double-sampling (comparing subjective estimates to clipped and sorted vegetation) to 'calibrate' the observer's estimates of live-to-dead ratios used to compute percentage green. All inputs are then run through the processor to compute three primary fire-behaviour components:

1. *Spread component (SC)*: derived from Rothermel (1972), with a unique SC table for each of nine fuel-type groups (NFDRS fuel models).
2. *Ignition component (IC)*: represents the susceptibility of fine fuels to ignition.
3. *Energy release component (ERC)*: an expression related to the rate of heat release per unit area within the flaming front at the head of a moving fire.

These three NFDRS components are subsequently processed to derive three indexes to 'aid in planning and supervising fire control activities on a fire protection unit' (Deeming *et al.* 1972). Each of the three fire-danger indexes is normalised to a 0–100 scale:

1. *Occurrence index (OI)*: a number related to the potential fire incidence within a rating area.
2. *Burning index (BI)*: a number related to the potential amount of effort needed to contain a fire in a particular fuel type within a rating area.
3. *Fire load index (FLI)*: a number related to the total amount of effort required to contain all probable fires occurring within a rating area during a specified period.

The nominal 'reporting unit' for NFDRS outputs and indices is called the Fire-Danger-Rating Area (FDRA). Deeming *et al.* (1972) define the FDRA as: 'A geographical area where the fire

danger throughout is adequately represented by that measured at a single fire-danger station. It is relatively homogenous in climate, fuels, and topography.' FDRAs are the smallest spatial measure used to translate NFDRS outputs from a point source (such as a weather station observation) to a spatial area that can be used for operational and planning purposes. As areas of 'uniform fire danger', they are the footprint of NFDRS on the ground.

Updating the NFDRS – 1978

In the spirit of the 1972 criteria stating that 'the architecture of the system would be designed to readily accommodate new knowledge in the future', plans had been made during the initial development of NFDRS to update the system by 1978. Even though a companion criterion for the 1972 system prescribes a 'complete and comprehensive' system, an element of trial and error development, not dissimilar to that seen through eight generations of fire-danger-rating meters, was still at work. A process of updates to the science and processors within the 1972 NFDRS was undertaken in the mid-1970s, based on significant new emerging knowledge regarding combustion physics, wildland fuels, and factors that influence fire occurrence (Deeming *et al.* 1977). Specific issues and generalised changes made to the system included:

- *Poor responsiveness to drought*: Incorporation of a live vegetation moisture model and also larger dead fuels. A live fuel moisture model based on the seasonal cycle of the 1000-h fuel moisture was added (Burgan 1979). The previous method, based on 'subjective' herbaceous vegetation transects, was replaced by a more analytical and consistent algorithm based on weather parameters. This change reflects a move from a purely subjective estimate, to one based more firmly on observations or measurements of vegetation phenology.
- *Ratings lack sensitivity*: Eliminate the 0–100 scaling restrictions, making the range of index values open-ended.
- *Fuel models cannot adequately represent the range of fuel in the USA*: Increase from nine to twenty the number of NFDRS fuel models.
- *Cause of occurrence not distinguishable*: Create two distinct fire occurrence indexes: (1) lightning caused; (2) man [human] caused.
- *Seasonal changes in 'drying power' of the day is not reflected*: Weigh the predicted recovery of the moisture content of heavy fuels by day length.
- *The number of slope classes is too few for mountainous terrain*: Increase the number of slope classes from three to five; the mid-point of slope class five is 90%.

Comprehensive technical documentation of the 1978 system is available (Bradshaw *et al.* 1983). The generalised structure of the 1978 NFDRS is illustrated in Fig. 9 (taken from Andrews and Bradshaw 1991). Note that the diagram given in Fig. 9 is a simplified form of a much more complex version used to illustrate the entire system. Because they are rarely used, neither the ignition (occurrence) components nor the integrated index known as Fire Load Index (FLI) are shown in the simplified figure. These are now optional parts of the system because of the dependence of FLI on occurrence indices, which were overly subjective.

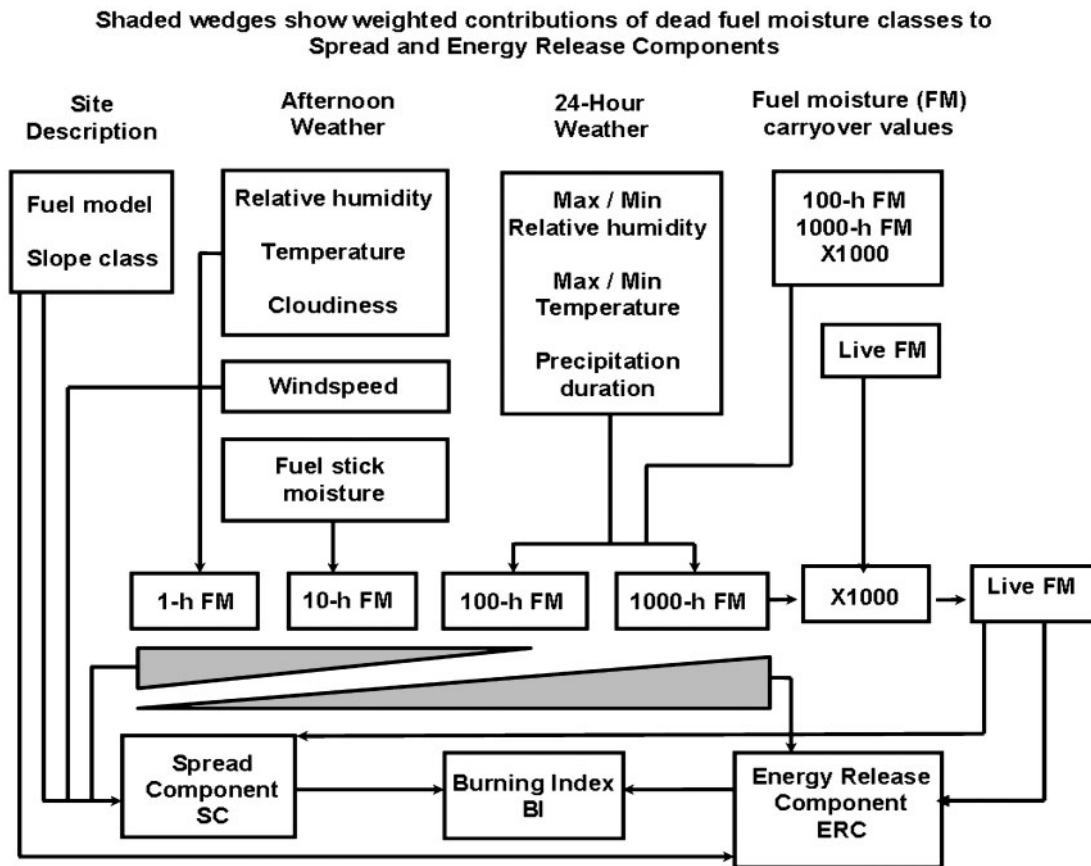


Fig. 9. Simplified diagram of the 1978 NFDRS structure, showing relationships between observations, intermediate calculations of fuel conditions, and key final indexes (from Andrews and Bradshaw 1991).

The 1988 revisions to the NFDRS

After nearly ten years use of NFDRS across the USA, certain deficiencies in system performance for the eastern USA became apparent, and a special workshop was held to identify the problems and to formulate a program of work by which revisions could be made to the system (Gale *et al.* 1986). Out of that workshop came the charge to mitigate the identified deficiencies as quickly as possible, and to do so without relying on any new, long-term research. As was the case in the 1978 updates, the proposed 1988 revisions were aligned with the original vision that the system should accommodate new information or ideas as necessary. The 1988 revisions involved work on five priority issues (Burgan 1988):

- *Improve the response to drought in humid environments:* The Keetch Byram Drought Index (KBDI) (Keetch and Byram 1968), a popular drought index widely used in the south-eastern USA, was implemented both as a stand-alone index and as a driver to modify the amount of dead fuel available during drought conditions.
- *Provide flexibility to reflect greening and curing of live fuels:* The implementation of a user-entered season code and 'greenness factor' became an added user responsibility, adjustable at any time depending on changes in observed vegetation greenness. This addition provided more dynamic and smoother

changes in vegetation condition than the 1978 system could reflect.

- *Correct the identified issue overrating fire-danger in the autumn:* Changes provided for a smoother transition from spring and summer 'green', to late summer/autumn 'cured' live vegetation condition.
- *Correct the identified issue overrating fire-danger after rainfall:* Options for calculation of fine dead fuel moisture were implemented to mitigate the tendency of the system to compute fine dead fuel moistures that were too low. The wind-speed reduction factor was also modified to better reflect hardwood and mixed hardwood/conifer stands in the eastern USA.
- *Adjust the fuel models to better predict fire-danger in humid environments:* The above-mentioned changes necessitated modifications to all twenty NFDRS fuel models. To provide flexibility (for users in the eastern USA) and continuity (for other users), the user was provided the choice of either the original 1978 fuel models or the 1988 revised fuel models.

The 1988 revisions were changes and accommodations focused almost entirely on issues specific to application of the NFDRS to the eastern and south-eastern regions of the USA. While the overall system structure remained nearly unchanged, the adaptations were, nonetheless, a compromise to the founding principle of a nationally consistent fire-danger-rating system.

Table 1. Adjective classes, abbreviations and associated colours

Fire-danger-rating adjective class	Associated colour for signage and communications
Low (L)	Green
Moderate (M)	Blue
High (H)	Yellow
Very High (VH)	Orange
Extreme (E)	Red

This tension between a desire for national consistency and acknowledgment of varying climate and vegetation processes across the country continues to this day.

Delivery systems

Manual calculations, tables, and nomagrams

The initial release of the 1972 NFDRS relied on a manual, tabular method for entering the input data, calculating intermediate variables, and computing output components and indexes. The 10-Day Fire-Danger and Weather Record, form WS-D-9a, was a manual entry form comprised forty-one columns, of which over twenty were for inputting observations. Intermediate and final outputs were determined using an extensive set of tables and mathematical calculations. In 1977, a user’s guide was developed that covered the manual procedures for the 1978 update of the NFDRS (Burgan *et al.* 1977). The user’s manual replaced many of the original tables presented in the 1972 NFDRS system documentation with twenty-one highly innovative, multi-variate nomagrams to support the extensive computations required by the system.

The Adjective Class – communicating to the public

While the NFDRS provides a suite of components and indexes designed to inform a variety of fire management decisions, none of the outputs can be used directly as a means to communicate with the public or other non-technical customers. Towards this objective, Federal and State fire scientists and managers convened in 1974 to create a simple set of adjective descriptors of fire-danger that could be linked quantitatively to the NFDRS indexes (Helfman *et al.* 1975). A table of Adjective Classes (AC) was developed which relates AC to ignition component (IC) and a user-selected staffing index (derived either from ERC or BI, depending upon which works ‘best’ for a local unit). The five classes and their associated letter abbreviations and colours are given in Table 1. Five classes were invoked to provide an intuitive gradient between the lowest (low) and highest (extreme) values relative to a centroid value (high).

Most USA citizens and visitors recognise these five fire-danger-rating Adjective Classes because of their incorporation into the Smokey Bear fire prevention program, perhaps one of the most pervasive, recognised, and successful public information campaigns in the USA. In nearly every region of the USA, Smokey Bear can be seen pointing to one of the five fire-danger classes (Fig. 10).



Fig. 10. Smokey Bear program signs are used throughout the USA to display the current fire danger class using the five adjective classes.

Computerisation

AFFIRMS – Administration and Forest Fire Information Retrieval and Management System

Soon after implementation of the 1972 NFDRS, development of a computerised system began that would utilise a centralised computer system and software, simultaneously accessible from multiple remote field stations throughout the USA over a large network. The system was called AFFIRMS – Administration and Forest Fire Information Retrieval and Management System. The program description provided in the AFFIRMS user’s guide (Helfman *et al.* 1975) suggests six levels or scales of intended use:

1. *Field units:* entry of observed weather data.
2. *Fire weather forecasters:* display observed weather and enter fire weather forecasts and narratives.
3. *Forest or local area:* display fire-danger indexes computed from both observed and forecast weather.
4. *Regional or State:* monitoring of regional trends and conditions.
5. *Nationally:* displaying and comparing among groups of forests or regions.
6. *At all levels:* for distributing administrative messages between users.

Field users entered their local weather station observation, AFFIRMS computed the daily indexes, and then provided access to the observation data, indexes, and forecasts to any user across the entire national domain of the system. This approach allowed all users access to what was happening around them as well as in other regions – the key feature to a ‘national’ system. An automatic data archiving system was also included in AFFIRMS, which provided short-term archiving of all observations, computed indexes, and forecasts.

WIMS – Weather Information Management System

In 1993, the Weather Information Management System (WIMS) replaced AFFIRMS as host of the NFDRS (USDA

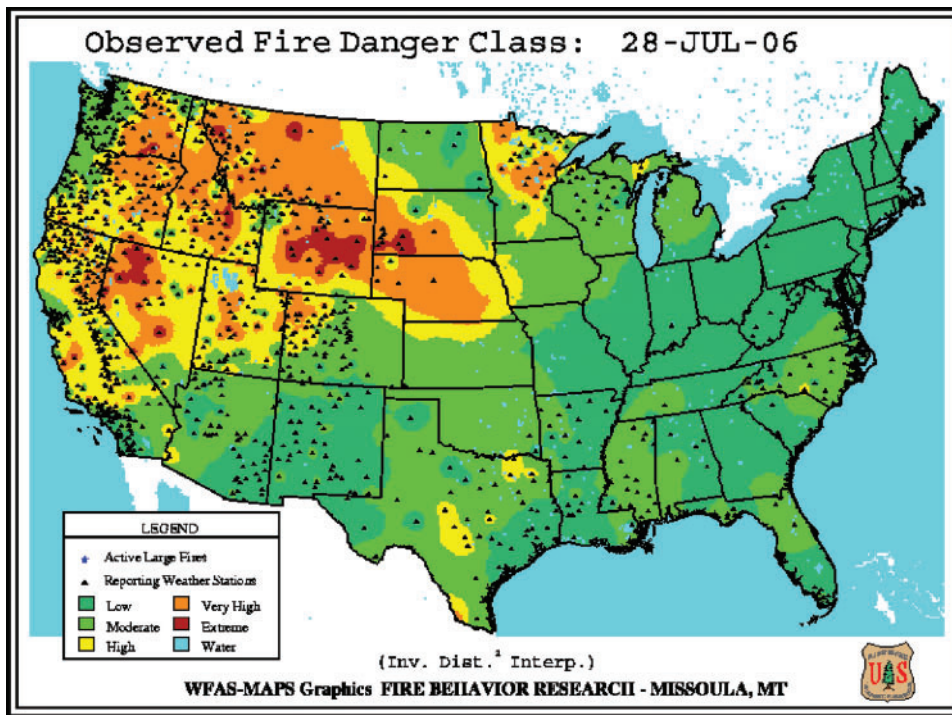


Fig. 11. Map of observed fire danger class for 28 July 2006, interpolated and displayed by WFAS for the conterminous USA.

Forest Service 2003). WIMS is a comprehensive system for managing weather and fire-danger information. WIMS accesses the National Interagency Fire Management Integrated Database (NIFMID) – a relational database that contains historical fire weather and fire record information – and enables access to a variety of weather information services. WIMS provides data management, manipulation, and display tools, and includes an interactive communications environment. Users can query and extract NFDRS information from WIMS in a variety of forms. Hourly and daily observation data, forecasts, and indices are archived and available online for a period of six weeks, after which only the weather observations are retained (by exporting the data to NIFMID).

WFAS – Wildland Fire Assessment System

The availability of satellite imagery and derived fuel and vegetation map products coupled with recent developments in geostatistics and spatial analyses have provided the opportunity to move fire-danger rating from point-based estimates to multi-spatial and multi-temporal applications. The Wildland Fire Assessment System (WFAS), first introduced in 1987 (Burgan *et al.* 1987), has become the principal delivery system for multi-spatial and multi-temporal observations and forecasts of fire-danger, fire potential, drought indices, and vegetation condition for the conterminous USA. WFAS provides access to map products of surface weather observations, satellite-derived measures of vegetation condition, standard fire-danger-rating computations, forecasts, and spatial interpolations in a single format both accessible and relevant to many fire management applications (Fig. 11). The web-based fire management resource is available to any user (www.wfas.net, accessed March 2007).

New science and innovations

The original organisation of what has become the modern NFDRS provided a framework that could not only incorporate new knowledge and methodologies as they became available, but would ultimately lead to a ‘purely analytical’ system (Deeming *et al.* 1972). This vision, if achieved, suggests that subjective elements and assumptions required by the system would be wholly eliminated. In his ‘Reflections on the development, application, and future of the National Fire-Danger-Rating System’, Deeming (1983) noted technical deficiencies of the system, including those of observed input data (weather and fuel models) and of derived inputs (dead fuel moisture, live fuel moisture, drought, and mid-flame windspeed).

Weather observations

Since 1983, significant progress has been made regarding both the density and the quality of the fire weather observations used to support NFDRS. WIMS receives weather observations from 1661 satellite-telemetered remote weather stations, 89 radio/cellular remote stations, and 279 manual stations – all are distributed throughout the USA (USDA Forest Service 2003). These fire weather observation stations provide the point-based weather inputs used by NFDRS to compute fire-danger components and indexes. The 2005 revisions to the NWCG weather station standards call for a ten-year transition from the current network of mixed-station configurations to a network comprised entirely of satellite-based, hourly reporting stations, and includes solar radiation observations (National Wildfire Coordinating Group 2005). The solar radiation data are a key input to new modelling of fine dead fuel moisture, discussed further in the next section.

In the current system, spatial interpretations of NFDRS outputs are produced by interpolating the point-based outputs across the USA (Burgan *et al.* 1987). A potential alternative to interpolation of point-based outputs is to directly compute spatial 'surfaces' (or grids) of the input data, which provides the capability to generate outputs at any point across the gridded surface for the USA. One approach is the Surface Observation Gridding System (SOGS), whereby point data are automatically retrieved, the point-source weather data are transformed (interpolated) into spatially continuous surfaces using geostatistical techniques, and the results are displayed at multiple scales (Jolly *et al.* 2004). This approach facilitates interpolation of system inputs, rather than outputs. Current and future research in fire danger will continue to both explore the potential for, and to apply, high-resolution grids. Examples of current innovations include 15-day forecasts of fire danger (<http://cefa.dri.edu/data/NatIERC/natlErc.html>, accessed March 2007), high-resolution fire-danger maps (www.wfas.net/content/view/26/41, accessed March 2007), and hourly fire danger (<http://cefa.dri.edu/data/NatIERC/natlErc.html>, accessed March 2007).

Derived inputs

Fine dead fuel moisture

The fine dead fuel moisture input to the NFDRS is determined either by direct measurement (using the moisture sticks), or by a mathematical model incorporated into the system. The modelling alternative is more common and it requires inputs acquired through user's daily observations of the 'state-of-the-weather'. These subjective observations are clearly sensitive to the observer's perceptions and habits, the frequency and regularity of observations, and they can be deliberately skewed towards achieving a desired outcome. All of this exacerbates attainment of a 'purely analytical' system. Development of a more mechanistic model for predicting fine dead fuel moisture that functions independently of observer input is clearly desirable.

An example effort directed at accomplishment of that objective is the recent work by Nelson (2000), in which he has shown considerable success at modelling fine dead fuel moisture using only the inputs acquired directly from automated fire weather observations. The model is radiation driven, and utilises hourly weather data. In contrast to requiring observer inputs, the availability, frequency, accuracy, and reliability of these automated data are attributes perfectly suited to an analytical approach. Input requirements for the model are modest, requiring only air temperature, relative humidity, solar radiation flux, and rainfall amount. Currently, 83% (1376 stations) of the Remote Automated Weather Station (RAWS) network stations have solar radiation sensors, and an implementation strategy for transition to the Nelson model (Nelson 2000) is currently in development.

Live vegetation (fuel) moisture

In certain regions of the USA, the live vegetation dominates the fire danger. The live vegetation moisture models in the NFDRS require users to determine and input a 'greenness factor' for their fire-danger-rating area. These periodic, subjective inputs are intended to reflect trends in green-up and subsequent

curing, and are used by the NFDRS to estimate live vegetation moisture content. Like the dead woody fuel inputs discussed previously, these observations of vegetation condition by users are highly susceptible to the interpretation and motivation of the observer. As Deeming has stated, 'poor management can cause poor performance' (Deeming 1983).

In the mid-1990s, several experimental products developed to estimate vegetation condition were derived from satellite data. The Normalised Difference Vegetation Index (NDVI) is computed from satellite data, and is used to measure and monitor plant growth and cover (Goward *et al.* 1991). By using the NDVI as base data, a suite of experimental 'greenness' products have been explored as estimators for NFDRS (Burgan *et al.* 1991, 1996; Burgan and Hartford 1993). Although none of these products have been formally incorporated in the NFDRS, they continue to be processed and delivered to users through web-based applications such as WFAS (www.wfas.net, accessed March 2007).

Ecologists and vegetation modellers share with fire managers the desire to predict trends in green-up, growth, and curing of live vegetation. One such modelling effort (Jolly *et al.* 2005) has resulted in a phenological model of a vegetation index called Growing Season Index (GSI). The GSI foliar phenology model is based on three readily available meteorological variables: low temperatures, evaporative demand, and photoperiod. When verified using observed vegetation moisture data, the GSI corresponds extremely well with live fuel moisture observations. This is another example of a relatively 'pure' analytical model with potential for application to fire-danger rating.

Conclusions

We have discussed the evolution, in both principles and practices, of fire-danger rating for the USA. While much has changed since 1916, much of the initial work by Gisborne and others in the 1920s and 1930s has retained its relevance to today's needs. Since its implementation in 1972, the National Fire-Danger-Rating System has successfully incorporated new knowledge and technologies, mostly without compromise to the objectives for a consistent, national system. New innovations and improved science continue to move the NFDRS closer to the developer's original vision of a 'purely analytical' system.

Implementation of new knowledge and approaches must ultimately require more revolution and less evolution, however, and this is as much a cultural challenge as a technical challenge. Rather than integrating these innovations into the existing system, we anticipate the need to provide a fully dimensioned, physics-based fire-behaviour processor around which a new system can then be built. Recent conversations among a national, interdisciplinary and interagency caucus of core fire scientists could soon lead to the design and development of such a system. However, its implementation will require commitment, advocacy, and collaboration on behalf of the extensive user community, much as that enjoyed in the early years of fire-danger-rating development.

Certainly, future scientists and developers of knowledge and delivery systems may wonder what Harry Gisborne meant when he admonished us to 'wind the watch'; that is, we must both maintain the system and foster continuous improvements.

Our watches are now digital, some containing integrated GPS technology and receivers tuned to the atomic clock. Today, the 'best watch in the world' needs no winding, we're now burdened with the responsibility to bring forward the lessons from the old timekeepers while at the same time we acknowledge and aggressively pursue science and technology discoveries for the future.

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