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Chapter 21

Fire Danger and Fire Behavior Modeling Systems in Australia, Europe, and North America

*Francis M. Fujioka**, *A. Malcolm Gill, Domingos X. Viegas and B. Mike Wotton*

Abstract

Wildland fire occurrence and behavior are complex phenomena involving essentially fuel (vegetation), topography, and weather. Fire managers around the world use a variety of systems to track and predict fire danger and fire behavior, at spatial scales that span from local to global extents, and temporal scales ranging from minutes to seasons. The fire management application determines the makeup of the planning tool, which usually incorporates one or more computer models. Advanced computing technology has spawned a new generation of fire planning tools to predict fire occurrence and fire behavior. We reviewed fire danger and fire behavior modeling systems from Australia, Europe, and North America, including operational tools that have been in use for decades, and newer models that profoundly enhance the spatial and temporal resolution of the resultant predictions. Linkages between these models and air quality models could very likely improve the mapping and prediction of air pollution due to wildland fires.

21.1. Introduction

Wildland fire challenges management, wherever it occurs. The dimensions of the fire problem largely reflect the characteristics of the fire environment: the vegetation (fuel), topography, and weather/climate for any given place and time period. Significant differences in any of these factors may occur when comparing the fire environment from one place

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*Corresponding author: E-mail: ffujioka@fs.fed.us

to another. The complexities of wildland fire management spawned a specialized fire science that has produced a variety of systems globally to assess fire danger even before a fire starts and to predict fire behavior once it occurs. This chapter describes the products of fire danger and fire behavior research in Australia, Europe, and North America.

21.1.1. History of fire research: A U.S. perspective

From its inception in 1905, the USDA Forest Service acquired the responsibility of protecting the nation's forests and the public from the damaging effects of wildfire. By fire historian Stephen Pyne's account, fire research was nonexistent at the beginning of the 20th century. Thus, Forest Service professionals schooled in forestry science generated and applied the knowledge needed to meet the agency's fire protection mandate (Pyne, 1982). In the early years of fire research, the dominant theme was the economics of fire protection, which would provide the basis for a fire management policy. Show and Kotok (1929) described the need for a fire danger index in 1929 as a means of determining the difference in fire control required in major vegetation cover types. They had earlier underscored the importance of weather on fire activity by statistically relating relative humidity and wind to fire size and number of fires (Show & Kotok, 1925). But it was Gisborne who set the stage for a methodical diagnosis of the weather impact on fire danger.

Gisborne (1928) identified three factors that constitute fire danger:

1. The present number of fires burning, or the probability that fires will be started.
2. The present rate of spread (ROS) of fire, or the probability that fires will spread.
3. The loss occurring from existing fires, or the probability that fires will result in loss.

Through the research and leadership that Gisborne provided from Priest River, Idaho, the fire danger meter emerged in 1930, a precursor of the modern fire danger rating system. The meter assigned a fire danger level on the basis of ignition factors, visibility (visibility reductions increase fire danger because they visually obscure new fires from detection), fuel moisture, and wind speed (Hardy & Hardy, 2007). Pyne (1982) described the fire danger meter as "a philosopher's stone for forest administrators ... a quantitative measurement by which to compare fire seasons and to contrast fire problems among different regions." Much of fire research subsequently would focus on refinements to the fire danger meter and the development of similar meters for the nation's other forests.

Despite the administrative successes that its fire research program achieved for the Forest Service, a subdued minority in the agency lamented the lack of fundamental knowledge of fire behavior, which could only be gained by approaching it as a research problem in physics, chemistry, meteorology, and biology. Wallace Fons, a mechanical engineer with the California Experiment Station, along with John Curry, paved the way for fundamental fire physics research starting in the late 1930s. In 1946, Fons published a mathematical model to predict rate of fire spread (Fons, 1946), which would inspire the development of the Rothermel (1972) fire spread model more than two decades later and provide the basis for the modern U.S. National Fire Danger Rating System and the Fire Area Simulator (FARSITE) fire behavior prediction system.

Inasmuch as wildland fire is not uniquely a U.S. problem, research and development activities in fire danger rating and fire behavior prediction are not limited to the United States. The next section is a description of fire danger rating and fire behavior prediction systems from Australia, North America, and Europe. While rating fire danger and predicting fire behavior are very similar functions, they occupy different domains on a spatial/temporal scale. Fire danger rating assessments cover large areas, typically on the order of 10^3 ha (10^4 acres), over a period of days. They quantify the potential fire activity under a given scenario of fuels, weather, and topography. On the other hand, the coverage of fire behavior forecasts is typically an order of magnitude or more smaller in area, and for present purposes, not more than 48 h.

21.2. Operational fire occurrence and behavior systems in Australia

In Australia, there is an unbroken tradition of studying fire behavior in the field in order to develop empirical models for predicting the behavior of unplanned (wild) or prescribed fires. Fire behavior models are designed, in the first instance, to predict the ROS of fires burning with the wind.

Using the fire weather component of fire models, fire danger—defined as the "chance[s] of a fire starting, its ROS, intensity and difficulty of suppression" (McArthur, 1967)—can be determined and public warnings issued. When used in this way, models are applied to regional areas on a daily basis throughout the fire season whether there is a fire or not.

For fires prescribed for various purposes, burning safely and effectively is the motivation for the development of fire behavior guidelines. In Australia, prescribed burning is the deliberate application of fire to a defined area in order to obtain an explicit result under safe working conditions. Prescribed fires may be ignited during a relatively narrow window of weather conditions to reduce fuels and thereby potential fire intensity, to increase the chance of fire control to enable better protection of life and property, or to achieve desired ecological outcomes.

21.2.1. A geographical sketch

Australia is approximately 7.7 million km^2 in area divided into states and territories. It straddles the Tropic of Capricorn, where much of it lies within the tropics. Eucalypt forests and woodlands spread across the north in a wide belt that continues down the east coast; across the south are further discontinuous occurrences including those in the island state of Tasmania. A vast arid zone, vegetated with hummock grasslands and *Acacia* shrublands, occupies a large part of the center and central west of the continent. A modest mountain range, by world standards, parallels the east coast. Climates include wet tropical in the northeast, wet-dry monsoonal across the north, arid tropical and arid temperate in the arid zone, moist-temperate in the southeast, Mediterranean in the southwest and part of the south, and subalpine-alpine embedded in moist-temperate parts of the southeast.

Major cities are found in the temperate zone in coastal locations. Pastoralism is common in the north and center, while cropping and farming are common in the southeast and southwest. Conservation lands occupy about 10% of the continent (B. Cummings, personal communication).

The vast majority of the country is fire-prone. Most of the area burnt each year is in the northern tropical savanna (Russell-Smith et al., 2002).

21.2.2. Fire danger rating

Fire danger rating across the country is determined largely or entirely on the basis of McArthur's models for grasslands (McArthur, 1966) and eucalypt forests (McArthur, 1967). Ratings consist of categories of the Forest Fire Danger Index (FFDI), a 100-point scale consisting of the following inputs: screen air temperature (T), screen relative humidity (RH), and wind speed in the open at 10 m height (V), plus a Drought Index—a measure of moisture in a hypothetical soil profile holding a maximum 200 mm water (initially based on the work of Keetch & Byram, 1968 in the United States)—and a Drought Factor—a variable with values from 1 to 10 determined by the amount of recent rainfall and days since the last rainfall event. For the Grassland Fire Danger Index (GFDI) inputs are grassland curing (proportion of dead grass), relative humidity, air temperature, fuel weight (in later versions), and wind speed as for the FFDI. The equations for these systems are to be found in Noble et al. (1980).

On the basis of the forecast fire danger, fire warnings are issued to the public by the Bureau of Meteorology, a federal government organization. On the basis of fire weather warnings, land management agencies, usually state- or territory-based, may then issue Total Fire Bans—no lighting of fires in the open. Local land managers, public and private, are expected to heed the warnings and assess their local fuels and terrain in order to decide what their response should be in terms of preparedness for fire occurrence and firefighting.

21.2.3. Fire behavior models and guides

Fire behavior research in Australia arose from the need to predict the behavior of unplanned fires during firefighting operations or to preemptively modify fuels using prescribed fires. Observations of unplanned fires were made and experiments conducted so that quantitative guidelines could be created to assist fire practitioners (McCaw et al., 2003). Fire behavior models and field guides predicted the ROS of the perimeter where it is most directly affected by the wind—the "head" of the fire. Results were often reported in ways related to their practical use rather than as rigorous scientific models in scientific journals. Beck (1995), in presenting a set of equations for the fire behavior guidelines known as the *Forest Fire Behavior Tables for Western Australia* (Sneeuwjagt & Peet, 1985) remarked that, "Despite its operational success, the incompleteness of published data behind the WA [Western Australian] fire behavior prediction system detracts from its scientific credibility."

Fire behavior guides from the Commonwealth Scientific Industrial and Research Organization. (CSIRO) (1997), include influential variables such as slope and grazing history (related to height of treated pasture), not used in the original research (Cheney et al., 1993), to allow them to be more generally applicable. McArthur's (1966) GFDI was linked directly with the predicted ROS of the head fire, but for forests (McArthur, 1967), ROS of the head fire was considered to be proportional to FFDI multiplied by the fuel load of litter less than 6 mm in diameter found on the forest floor (Noble et al., 1980).

McArthur's forest fire work in eastern Australia was expanded geographically to south-western Australia in a collaboration with Peet, who developed a set of tables suited to local conditions (McCaw et al., 2003). Various modifications to these pioneering efforts in Australia have taken place for various reasons, including conversion to metric units, and can be seen in the five versions of the *Forest Fire Danger Meter* (Noble et al., 1980) and a series of revised editions of the *Forest Fire Behavior Tables for Western Australia* (McCaw et al., 2003; Sneeuwjagt & Peet, 1985).

Predicting spot fire development close to or distant from a fire front remains a problem. McArthur's (1967) model for distance of spotting was based on ROS and fuel load (Noble et al., 1980) and includes the effects of different bark type on different species of eucalypt trees. The comprehensive experiments of forest fire behavior in south-western Australia over the last decade (*Project Vesta*; McCaw et al., 2003) are expected to soon provide better understanding of the effects of fuel in different parts of the fuel array, not just the litter layer, on rates of spread and spotting behavior (Gould et al., 2004).

As with forest fire-behavior models there have been five versions of the McArthur Grassland Meter (Noble et al., 1980), mostly manifested as circular slide rules. While McArthur's (1966) model was for annual and perennial pastures of unspecified composition, Condon (1979) saw the need to identify the behaviors of fires burning in stands of particular grass species in more-open semi-arid western New South Wales (NSW) grasslands; modifications were made on the basis of experiences of bushfire-brigade captains in the widespread fires in western NSW in 1974–1975. In the revised model, grass height was added as well as the effects of the main fuel species. The *Western Australian Bush Fires Board* also modified the meter using grass height, density, and texture in an undated meter.

While the McArthur (1966) model and its successors were for grasslands with continuous cover, the vast arid lands of Australia contain grasslands formed by discrete clumps of hummock grasses. A spread model for the latter type was first developed by Griffin and Allan (1984), while the latest hummock grassland model has been developed by Burrows et al. (2006); this breaks new ground for Australian models in first predicting the likelihood of spread, then predicting the ROS, assuming spread is possible.

A consensus shrub-fire model using data from Australia and New Zealand uses wind speed and vegetation height as its only variables

(Catchpole et al., 1999). While the predictions of ROS were "rather more variable than is desirable for an operational tool," the model fitted available data "reasonably well" (Catchpole et al., 1999).

21.3. Operational fire danger/behavior systems in Canada

The Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al., 1989) is used across Canada each day of the fire season for a range of fire management decisions from prevention planning to fire occurrence prediction and evaluating fire behavior potential. The system has also been adopted by or adapted to a number of countries around the world (e.g., New Zealand, Mexico, Indonesia, Malaysia, and Portugal). The CFFDRS contains two major subsystems: the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System. The FWI System (Van Wagner, 1987) provides a means of evaluating the severity of fire weather conditions in a common standardized forest type, including numerical ratings of fuel moisture in important fuel layers and several relative indices of fire behavior. The FBP System (Forestry Canada Fire Danger Group, 1992) relies on outputs from the FWI System and other site-specific information (such as topography and time of year) and provides quantitative assessments of fire behavior in a number of major fuel types across Canada.

The CFFDRS also contains two other components that have not been formally developed or implemented nationally; these are the Accessory Fuel Moisture (AFM) System and the Fire Occurrence Prediction (FOP) System. The AFM System contains additional fuel moisture models to add temporal resolution to existing models or to model moisture in specific fuel layers (e.g., Lawson et al., 1996a; Van Wagner, 1987; Wotton et al., 2005); it also converts moisture code values to stand-specific moisture (e.g., Lawson & Dalrymple, 1996b; Wotton & Beverly, 2005). The FOP System is an important component of the CFFDRS, as it represents the fire risk component of fire danger rating assessment. However, it is not implemented throughout Canada. Several regional fire occurrence prediction models developed by numerous researchers are available in Canada, but fire managers typically rely on their experience in processing fuel moisture codes (from the FWI System) and ignition risks from lightning or potential human activity to determine expected fire occurrence.

The models within the CFFDRS are based on a common approach or philosophy. Basic physical reasoning and understanding of the physical processes governing fire spread or fuel moisture exchange are used to develop models, which are then calibrated with field-based observations (from both experimental and wildfire observations). This approach ensures that the model outputs capture the true physical range of the phenomena being modeled, which has to a large extent been responsible for the successful adoption of the system across Canada and in other countries. Implementation can be problematic when adapting the system beyond its original design (Taylor & Alexander, 2006).

21.3.1. The FWI System

The current fire danger system in Canada has its roots in an extensive program of meteorological observations and field sampling of moisture and ignition sustainability research that began in the early part of the 20th century. From experimental sites across the country, fire hazard and fire danger tables were developed for numerous regions in Canada. In the late 1960s, the need for common indices led to the development of a universal system, which was released nationally in 1970 (Muraro, 1968; Van Wagner, 1974).

21.3.1.1. Inputs

The FWI System relates weather information to fuel moisture and fire danger indices for a standard forest type (mature jack pine, *Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta*). The system relies on daily measurements (taken at 1200 local standard time (LST)) of air temperature and relative humidity (measured at 1.4 m above the ground in a radiation shielded screen), 10 m open wind speed, and 24-hour accumulated precipitation, as well as the estimated fuel moistures in three fuel layers from the previous day.

21.3.1.2. Outputs

The system has three codes to track moisture in different levels of the forest floor and three fire behavior indices that are relative ratings of fire behavior potential. All of the moisture codes in the FWI System are based on an exponential model of moisture exchange. The moisture content values are converted to a code value so that increasing dryness of the fuel increases the value of the code itself. The user therefore readily associates a high code value with high fire danger.

Moisture in the surface litter layer of the standard pine stand is tracked by the Fine Fuel Moisture Code (FFMC). This surface litter layer is considered a 1.2 cm thick layer of pine litter, sitting atop a thick, generally wet, organic layer, with a fuel load of 0.25 $\mathrm{kg\,m^{-2}}$. The response time of this layer varies with ambient weather but is about half a day when air temperature is 25 °C, RH is 30%, and wind speed is $10\,\mathrm{km\,h^{-1}}$. Moisture in the upper portions of the organic layer—a layer approximately 7 cm deep with a biomass load of $5\,\mathrm{kg\,m^{-2}}$—is modeled by the Duff Moisture Code (DMC). The response time of this layer varies with temperature and RH, and is about 10 days in mid-summer, when temperature and RH average 25 °C and 30%, respectively. Moisture in the deep organic layer is modeled by the Drought Code (DC), which is similar to other drought models such as the Keetch-Byram Drought Index (Keetch & Byram, 1968) and the Palmer Drought Index (Palmer, 1988). The DC accounts for the long-term effect of drying on fuels and has a response time of approximately 50 days in mid-summer.

Although these moisture codes nominally represent moisture content in the standard jack/lodgepole pine stand, they can also track changes in the moisture content of other stand types (Wotton & Beverly, 2005). Figure 21.1 shows the relationship between the calculated FFMC and actual litter moisture sampled in several stands of pine and several stands of aspen as part of the Canadian Forest Service's small-scale test fire program (Paul, 1969; Simard, 1970). While the absolute relationship between FFMC and actual litter moisture is different for pine and aspen litter, changes in moisture content in both stands can be tracked by changes in the FFMC.

Potential fuel consumption on the landscape is characterized by the Build-up Index (BUI), which in its simplest form, is a harmonic mean of the DMC and DC. Relative ROS is indicated by the Initial Spread Index (ISI), a nonlinear function of FFMC and wind speed. BUI and ISI are combined following Byram's concept of fireline intensity (Byram, 1959) to form the FWI, which represents the relative intensity of a potential fire on the landscape. It is important to remember that these three fire behavior indices are relative indicators that have been scaled based on observed fire behavior to provide a meaningful range of output values. The FBP System converts these relative indices to stand-specific, physically recognizable, and interpretable predictions of fire behavior.

21.3.2. FBP System

The FBP System produces predictions of fire behavior in 16 major fuel types in Canada (including both conifer and deciduous types) and accounts for influences of factors such as topography and foliar moisture content. In its secondary outputs the system employs a simple elliptical model of fire growth to estimate flank and backfire rates of spread and fire shape. A model of acceleration predicts fire spread from either a single point or an ignition line. The models that makeup the FBP System

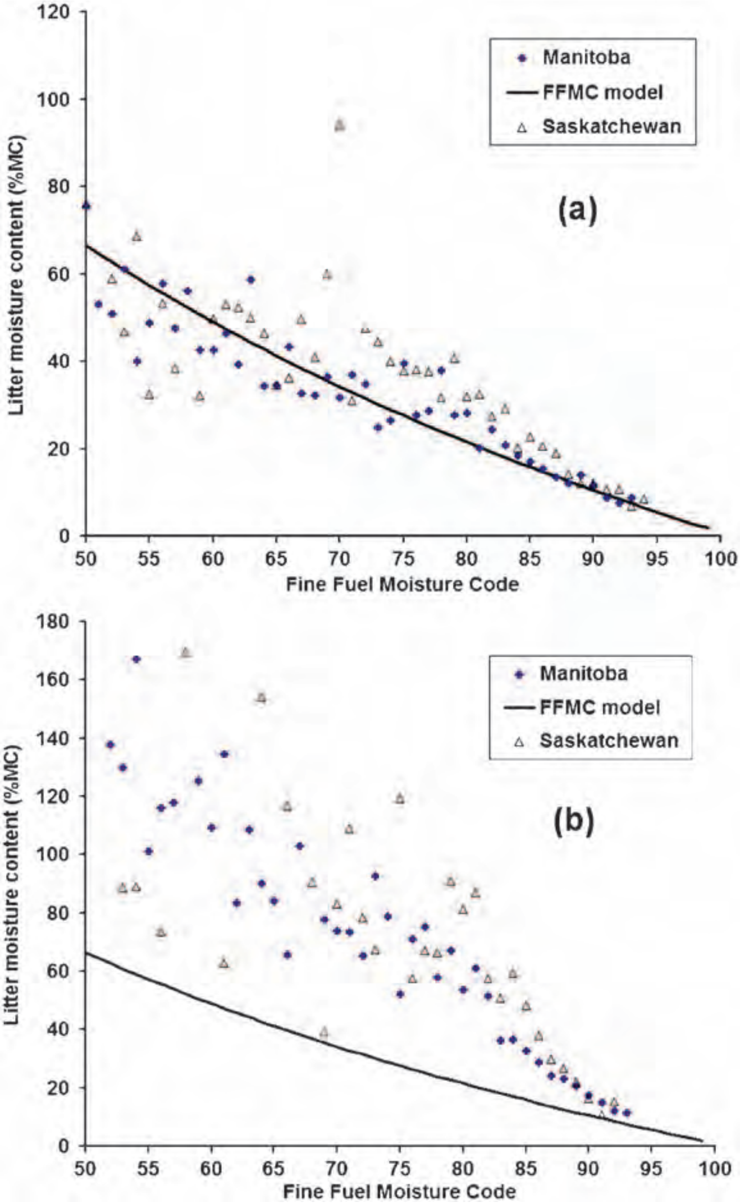

Figure 21.1. Fuel moisture and fine fuel moisture code (FFMC) relationship for (a) pine stands and (b) aspen stands in Canada.

are based on years of experimental burning under a range of weather conditions and forest types. These experiments attempted to capture the range of fire danger conditions encountered operationally; however, performing experiments under extreme conditions can be difficult, though not impossible (Stocks et al., 2004). Experimental fire data are also supplemented with well-documented wildfire observations.

21.3.2.1. Inputs

Predictions from the FBP System require information about the fuel type in which the fire is spreading (e.g., grass, slash, insect-killed mixedwood), the location of the fire (latitude and longitude), topographical information (slope and aspect), and time of year. The System also uses the codes and indices from the FWI System (specifically the FFMC, ISI, BUI) as well as wind speed and direction. When combined with slope and aspect, the wind data account for the slope/wind interaction using vector analysis. The FBP System does not currently allow the user to input fuel load for a stand specifically; it specifies a standard load for each of the FBP fuel types (with the exception of the grass fuel type).

21.3.2.2. Outputs

The three primary outputs of the FBP System are analogous to the three relative fire behavior indices of the FWI System. The system predicts surface fuel consumption (SFC) in a range of stand types using the BUI. SFC includes consumption of forest floor organic material, litter, and down and dead woody material. Crown fuel consumption (CFC) is estimated from a standard crown loading for each fuel type and an estimate of the crown fraction burned. Empirical relationships between head fire ROS and the ISI have been developed for each of the FBP fuel types. Figure 21.2 shows an example of the relationships between SFC and BUI and ROS and ISI for the mature jack/lodgepole pine model of the FBP System. Fireline intensity is calculated in the FBP System from the total fuel consumed (SFC and CFC) and ROS, using Byram's classic equation (Byram, 1959).

21.3.2.3. Applications

The CFFDRS is used operationally across Canada throughout the fire season for a lengthy list of fire management activities, such as prevention planning, setting alert levels, fire suppression planning, and evaluating fireline safety. Predicting fire occurrence is another important application in which fire managers couple experience with an understanding of the

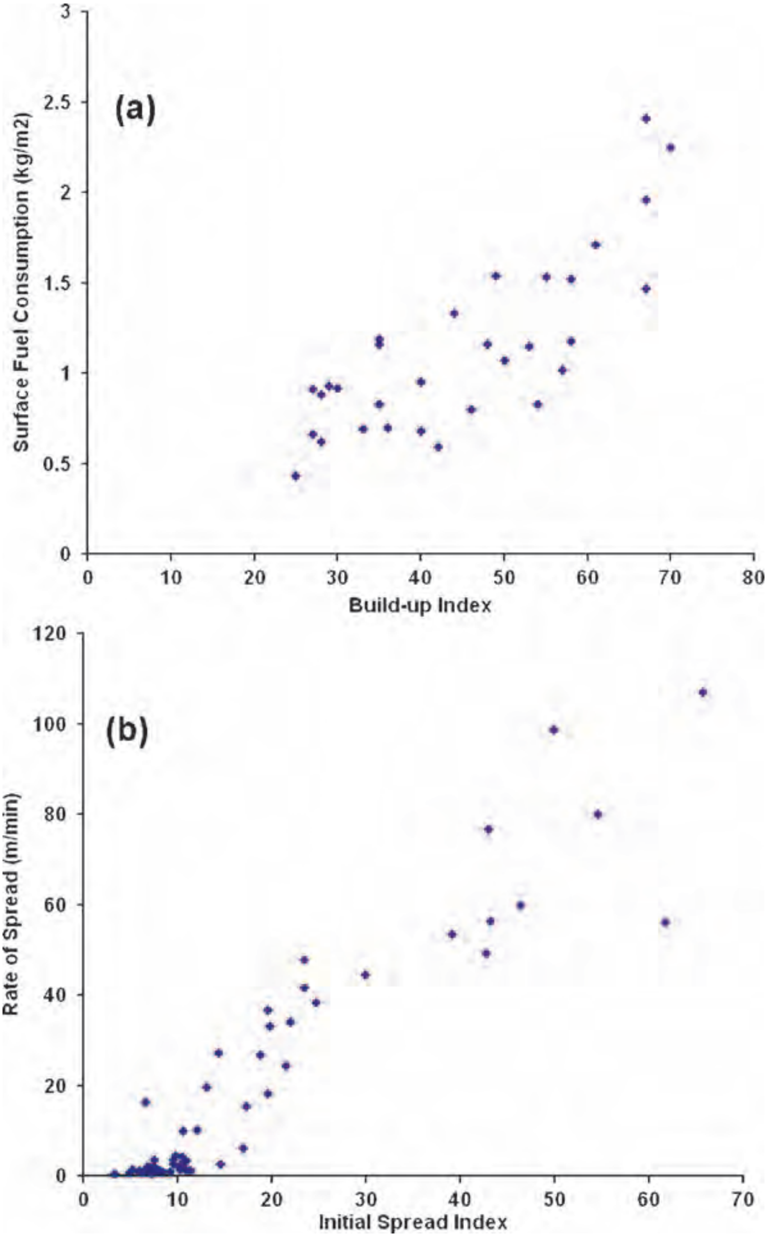

Figure 21.2. Example of the fire behavior prediction (FBP) System relationships for (a) surface fuel consumption versus build-up index and (b) rate of spread versus initial spread index for the mature jack pine fuel type (known in the FBP system as C-3) in Canada.

FWI System fuel moisture codes, to predict daily expected fire activity. Human- and lightning-caused fires are distinctly different and hence separate predictions are made for these ignition types. The FFMC has been found to be a good indicator of the receptivity of surface fuels to ignition and is used to determine expected human-caused fire occurrence. Figure 21.3a shows the relationship between human-caused fire occurrence and FFMC for two regions of the province of Ontario.

Of course, expected human activity in the forest must also be considered in any prediction. Numerous models that characterize the relationships between fuel moisture and human-caused fire occurrence have been developed for specific regions of Canada (e.g., Martell et al., 1989; Poulin-Costello, 1993; Wotton et al., 2003). Moisture in the upper organic layer is important for determining the probability of ignition from lightning strikes; lightning discharges tend to run down tree boles and ignite the surface fuels or organic material near the base of the tree. The DMC has become the standard indicator in Canada of landscape receptivity to ignition by lightning. Figure 21.3b shows the probability of lightning fire ignition as a function of DMC for historical fires and lightning from the forested area of Alberta. Detailed models of lightning fire occurrence have been developed for specific regions and include dependencies on the DMC and other factors (Anderson, 2002; Kourtz & Todd, 1992; Wotton & Martell, 2005).

It is important to remember that, while the FFMC and DMC seem to be robust relative indicators of fire occurrence, these relationships will vary from region to region. To provide quantitative predictions the users must understand the character of the relationship between these fuel moisture codes and fire occurrence in their fire management district.

In Canada fire growth across the landscape is modeled using the Prometheus fire growth model (Tymstra, 2002). Prometheus is very similar to the FARSITE system (Finney, 1998), relying on the elliptical wavelet fire propagation formulation (Anderson et al., 1982; Richards, 1990, 1995). In Prometheus, however, the FBP System forms the core fire behavior engine that drives fire growth. This model, which continues to be enhanced, is beginning to be used for fire growth scenario evaluation on large project fires in Canada.

21.4. Fire danger rating and fire behavior prediction in the USA

21.4.1. Fire danger rating

The current version of the U.S. National Fire Danger Rating System (Fig. 21.4; Schlobohm & Brain, 2002) expresses fire danger through four

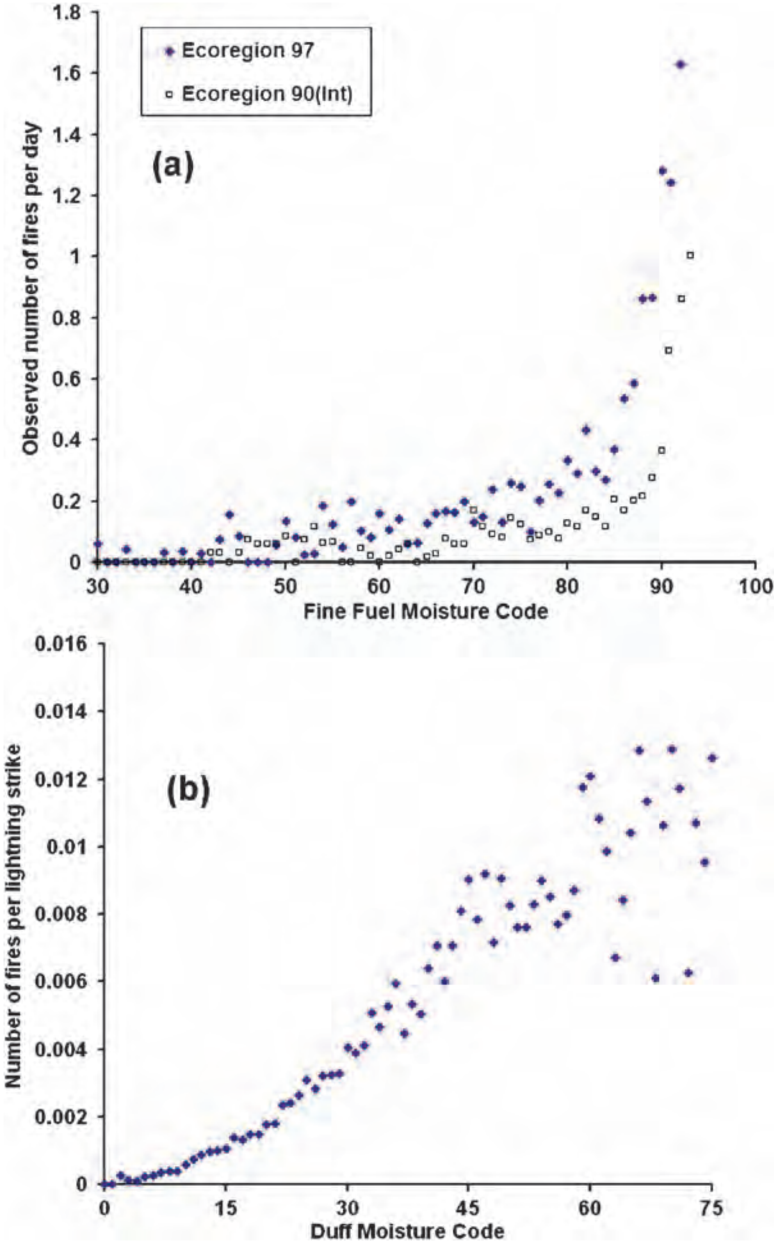

Figure 21.3. Examples of fire occurrence and moisture code relationships for (a) human-caused fires (1976–2004) for two ecoregions in Ontario and (b) lightning-caused fires in the forested area of Alberta (1984–2004).

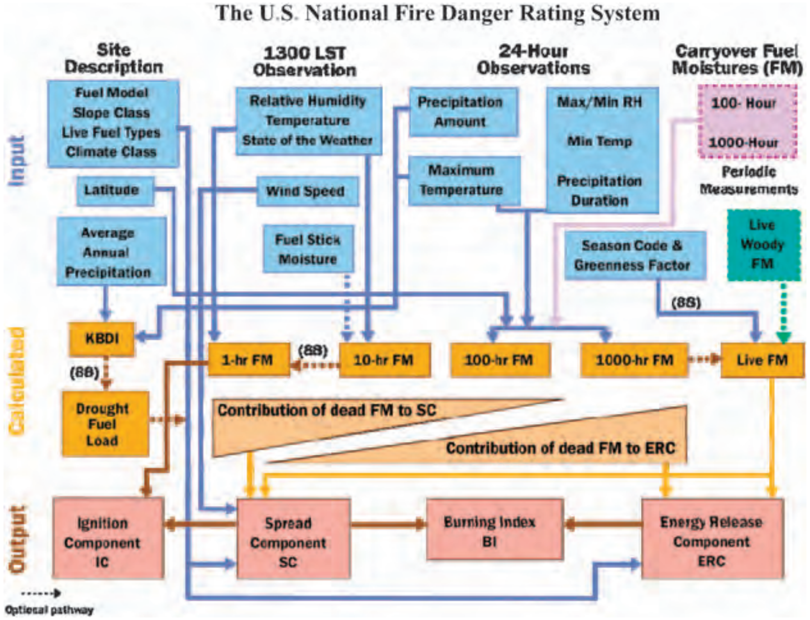

Figure 21.4. Structural diagram of the U.S. National Fire Danger Rating System (NFDRS).

indices, of which two—the ignition component (IC) and the spread component (SC)—match Gisborne's (1928) elements of fire danger. The IC is a number ranging from 0 to 100 that may be interpreted as the probability that a firebrand will start a fire with growth potential. Schroeder used empirical studies of ignitions in slash pine litter by Blackmarr (1972) to develop the original ignition probability algorithm of the 1972 system (Bradshaw et al., 1984). The dependency of IC on SC (Fig. 21.4) is a modification of the 1972 NFDRS IC that the 1978 NFDRS introduced, to limit the ignition probability to fires that achieve a reportable size.

The SC is the ROS from the Rothermel model, expressed as feet per minute (Rothermel, 1972). It is very sensitive to wind speed and the surface area-to-volume ratio of a fuel particle. Because fine fuels have large surface area-to-volume ratios, they yield relatively high values of SC compared to larger fuels. Topographic slope also influences SC. The slope factor in Rothermel's equation is a continuous variable, but is limited to five classes in the 1978 NFDRS.

The energy release component (ERC) represents the energy flux from the flaming front of the head fire. It is directly proportional to the heat release rate per unit area of the flaming front—the reaction intensity—and inversely proportional to the surface area-to-volume ratio. Hence, larger fuels have more influence on ERC than smaller fuels, in contrast to the SC. The sensitivity of the ERC to fuel moisture content of both dead and live fuels makes it the most useful of the four NFDRS indices in Fig. 21.4 for monitoring short-term drought effects on vegetation. The 1988 revision to the NFDRS integrated the Keetch-Byram Drought Index (KBDI; Keetch & Byram, 1968) as an intermediate variable that controlled dead fuel loading due to drought. Other 1988 changes modified the calculation of live fuel moisture and the 1-hour dead fuel moisture, as shown in Fig. 21.4 by the ‘‘(88)’’ annotation (Burgan, 1988).

The SC and ERC combine to give the Burning Index (BI), a number conceptually equal to 10 times the flame length. It is based on a relationship Byram (1959) derived between flame length on the one hand and spread rate and residence time of the flaming front on the other. The BI therefore has implications for the magnitude of the fire-control problem under the specified conditions, and of fire effects on vegetation. Note the similarity of the BI to the FWI in the CFFDRS.

The inputs to the NFDRS (Fig. 21.4) may be classified as weather and nonweather data, the latter comprising fuel and topographic characteristics that are assumed to be fixed over time. The weather variables, of course, change dynamically over time, but note that the NFDRS uses two types of weather data. One is an instantaneous description of weather (1300 LST observation), while the other is composed of summary statistics of weather over a 24-hour period: maxima and minima, and totals. In fact, the NFDRS integrates the weather variables over a period longer than 24 hours in the boxes represented by the Carryover Fuel Moistures and the KBDI.

The SC, ERC, and flame length describe fire behavior characteristics, but the NFDRS is not considered a fire behavior prediction system. The NFDRS provides a large area assessment of worst case conditions for a quasi-steady-state surface fire. On the other hand, FARSITE has been designed by Finney (1998) as a fire behavior prediction system.

21.4.2. Fire behavior prediction

Whereas the NFDRS output is a series of indices that characterize fire danger, FARSITE is a system capable of generating a sequence of fire perimeters representing the growth of a fire under given fuel, weather, and terrain conditions. Both systems employ the Rothermel fire spread model, which predicts the head fire ROS. FARSITE simulates fire growth in two dimensions with spread algorithms that augment the one-dimensional

Rothermel model. Finney implemented Richards' (1990) algorithm employing Huygens' principle of wave propagation (Anderson et al., 1982), which assumes that fire spreads locally in the shape of an ellipse. By computing the localized fire growth at multiple points of the given fire perimeter, FARSITE generates the growth increment from the curve that envelops the local ellipses tangentially. Fuels and terrain data at 30 m intervals satisfy the need for local fire environment, nonweather data.

FARSITE uses the same weather variables that the NFDRS requires, a necessity imposed by the Rothermel model. Unlike the NFDRS, however, FARSITE is not limited to describing the worst case fire scenario. It has to map the dynamic changes in fire behavior, particularly as the weather changes over the area of interest, temporally and spatially. When he introduced FARSITE, Finney (1998) utilized algorithms that calculated diurnal temperature and humidity variations from given maxima and minima of those variables (Beck & Trevitt, 1989; Rothermel et al., 1986), apparently to minimize the weather input requirements. Subsequently, weather models provided significantly higher spatial and temporal resolution, not to mention a comprehensive physics-based approach to generate the weather data that FARSITE needs. Finney modified FARSITE to take advantage of gridded weather data, when such data are available.

Fujioka (2002) evaluated the accuracy of FARSITE fire growth predictions with and without gridded weather inputs for a southern California fire that burned in 1996. Figure 21.5 is a FARSITE output showing the fuels (colored polygons), terrain, afternoon wind vectors, and predicted fire perimeters from this case study. A high-resolution weather model calculated hourly weather variables at a 2 km grid interval over the area. The study, which focused on the early, essentially free-burning stage of the fire, revealed complex simulation error patterns, which included both overprediction and underprediction. It exemplified the severe test that fire specialists face in predicting fire behavior in complex fire environments. Although it would be highly desirable to have weather data on the same 30 m grid interval as the fuels and terrain data, the lack of a suitable weather model and operational capability make it an unlikely prospect for the foreseeable future.

21.5. Operational fire systems in Europe

Forest fires in Europe as in many other parts of the world are the result of a complex interaction between natural processes and human-related activities, such that it is difficult to determine the relative

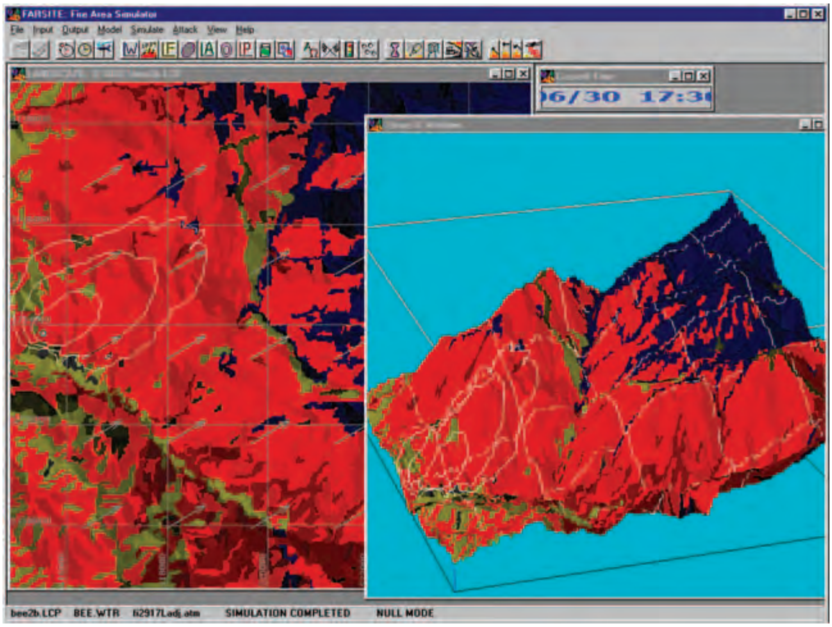

Figure 21.5. FARSITE simulation of the bee fire in the San Bernardino national forest, California, summer 1996.

importance of each. Despite the fact that forest fires are mainly caused by human activity, it is generally recognized that natural phenomena, namely meteorological conditions, play a very important role in the entire process. It is therefore very understandable that the analysis of meteorological factors and their influence on fire activity has always been a basic requirement in fire science and management.

In Western Europe forest fires have a greater incidence in its southern extent, namely in Portugal, Spain, France, Italy, Greece, and the other countries of the Mediterranean basin. Fires occur mainly during summer, but in some regions there are also winter fires. The countries of central and northern Europe have fire problems as well, but on a much smaller scale. Russia and the other countries of the former Soviet Union, with their vast territories, experience very large fires. In Europe there were several methods to assess fire danger associated with meteorology. Some of these methods were developed for a particular set of conditions, for example a particular region or a fire season, but others attempted a broader scope.

21.5.1. Historical overview

In Portugal a very simple method developed by Ångström in Sweden was used between 1970 and 1986. This method is based on a very simple ratio between air temperature and relative humidity. The daily value of the Ångström index was evaluated at mid-day and threshold values were established to determine three fire danger classes then in use. The index was noncumulative in the sense that it did not take into account the pronounced effect of a sequence of days with high values of Ångström index and no precipitation. In 1987 a method based on the Nesterov index was applied (Instituto Nacional de Meteorologia e Geofisica, 1988). This method had a cumulative component and used daily values of precipitation and wind velocity in addition to temperature and relative humidity. The modified Nesterov index performed quite well and was well accepted by operational institutions.

In Italy, Bovio et al., 1984, developed an original method, the IREPI, that estimated evapo-transpiration and was applied mainly in the Alpine Region of Italy to winter fires (from January to April). In France there were several methods applied by fire experts, and it was common practice to evaluate more than one index in each region and base operational decisions on trends deemed significant by the decision makers. The more common methods were developed by Meteo France (Drouet and Sol, 1990). In Spain, a method based on the McArthur system of Australia, described earlier in this chapter, was applied (Instituto Nacional para la Conservacion de la Naturaleza, 1988). This was a noncumulative index that used daily values of air temperature and relative humidity as well.

21.5.2. Comparative study

The variety of methods in use in southern Europe made overall assessment of the fire danger situation in each country or region very difficult. For this reason, the European Union (EU) sponsored a study comparing fire danger rating practices in 1992, which is briefly summarized here (for further details see Viegas et al., 1999).

The four methods that were used in Portugal, Spain, France, and Italy, as well as the methods of the CFFDRS (Van Wagner, 1987) were selected for the study. The U.S. National Fire Danger Rating System (Bradshaw et al., 1984) was also considered, but it was not retained because it included other factors besides meteorological ones that made implementation difficult. The regions, time periods, and relevant fire statistics of the study are given in Table 21.1.

Different parameters were considered to statistically test the relative efficiency of the various fire danger rating methods. In practically all cases

Table 21.1. Study areas and period of analysis considered in the comparative study of fire danger rating practices in southern Europe

Region of study	Fire season	Period of study	Area (km^2)	Number of fires		Burned area (ha)	
				Total	Daily av.	Total	Daily av.
Alps Haute Provence, France	Jan./Apr.	1981–1990	6925	191	0.18	1920	1.77
Bouches du Rhone	Jan./Apr.	1981–1990	5087	675	1.47	3434	50.94
Var, France	Jul./Sep.	1986–1990	5973	954	2.07	48,939	106.39
Eastern Pyrenées, France/Spain	Jul./Sep.	1986–1990	4116	292	0.63	7098	15.43
Veneto, Italy	Jan./Apr.	1988–1990	18,368	515	1.43	5244	14.53
Savona, Italy	Jan./Apr.	1987–1989	1544	284	0.79	2329	6.45
	Jun./Sep.	1987–1989		282	0.77	2017	5.51
Central Portugal	Jun./Sep.	1988–1992	17,216	29,080	23	159,373	261.3

it was found that the FWI performance was better than those of other methods, even for winter fires. As a consequence of this study a recommendation was made to the European Commission in 1997 to adopt the CFFDRS as a standard method to assess fire danger in EU countries. This proposal was immediately adopted by Portugal and France. Subsequently, the Joint Research Center of the EU developed a common Web-based service disseminating daily values of the CFFDRS components computed on a grid of 10 km × 10 km.

Similar studies have been carried out in other regions using other methods, with the result that the FWI performed better than the other methods almost always. As a consequence the CFFDRS has become a common language not only among scientists but also between practitioners dealing with fire danger assessment. Recent studies on the impact of climate change on forest fire activity also use the Canadian system as a standard tool to quantify the relative changes on fire activity predicted in the various future climate scenarios.

21.5.3. Calibration of FWI in Portugal

The application of the CFFDRS in each region requires a calibration because the measurements of each weather station do not represent the meteorological conditions in absolute terms in the region. Viegas et al. (2004) applied the Canadian system by performing a calibration of the FWI to estimate the threshold values for five fire danger classes in each of the 18 districts of the Portuguese territory, and by using meteorological and statistical data on fire occurrence between 1988 and 1996 (Table 21.2).

A good correlation between burned area in Portugal and the average value of the DC during the summer months was found after a nonlinear

Table 21.2. Threshold values of FWI defining fire danger classes for six districts of Portugal

District	Fire danger class				
	Low	Moderate	High	Very high	Extreme
V. do Castelo	<10	15	30	45	>45
Bragança	<23	30	45	55	>55
Guarda	<8	15	25	50	>50
Coimbra	<15	22	30	45	>45
Évora	<40	50	65	75	>75
Faro	<30	40	60	75	>75

transformation of the data (Fig. 21.6). Similarly, it was found that the live fuel moisture content of shrub vegetation during the summer is well correlated with a nonlinear transformation of the DC (Fig. 21.7).

The FFMC is a good estimator of the moisture content of dead leaves of pine and eucalyptus trees that are a very important part of fuel litter in Portugal (Fig. 21.8). The ISI is in principle correlated with the ROS of fire in a given fuel bed. Experimental results obtained in Central Portugal for *Erica* type shrubs confirm this assertion after applying a nonlinear transformation (Fig. 21.9).

21.6. Summary

Fire science, now about a century old, has contributed substantially to wildland fire management. Nevertheless, many knowledge gaps remain. Although there are many challenges in predicting unplanned fires, predicting the behavior of prescribed fires creates new challenges because the pattern of ignition becomes an added variable. Prescribed burning takes place under relatively mild conditions, and the degree of precision sought for this activity may be higher than in the case of unplanned fires (McArthur, 1962). The prescription is often designed to achieve a certain fuel reduction, such as over a certain proportion of ground at an intensity that allows fire control with available resources (e.g., Marsden-Smedley, 1993). Prescribed fire behavior guides have been developed for many situations including different vegetation types, standing timber crops of various types, and logging debris.

As wildland fire management is a global problem, its solution suggests the need for a global enterprise. Similarities between the operational systems in Australia, Europe, and North America reflect the benefit of shared knowledge and experience. The Canadian FWI has become a

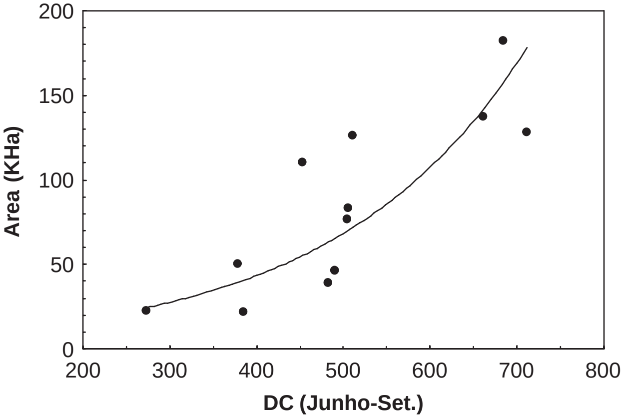

Figure 21.6. Total burned area as a function of the average value of the drought code (DC) in Portugal in the period 1987–2000.

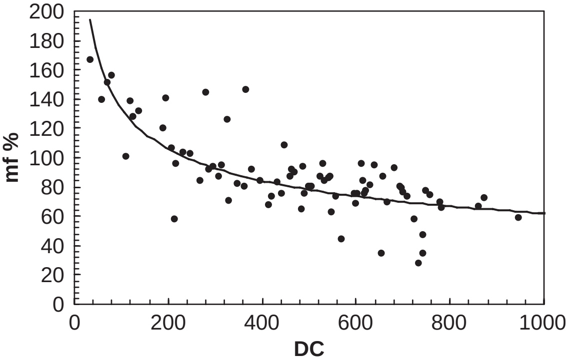

Figure 21.7. Live fuel moisture content of shrubs (*Calluna vulgaris*) as a function of drought code (DC) in Portugal during summer.

standard tool to estimate fire danger conditions correlated to meteorology in Europe. Provided that it is calibrated using local data, it can be applied to a large range of conditions, and its components can be used to assess various relevant properties of fire danger, namely the fuel moisture content and the overall severity of a fire season. Currently, new methods are being developed combining FWI with other sources of data, such as those derived from satellite sensors.

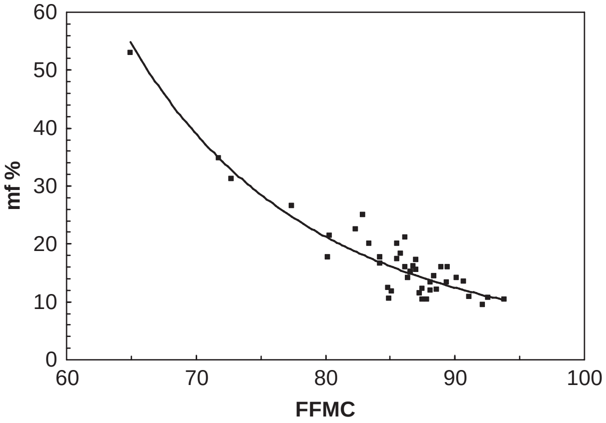

Figure 21.8. Dead fuel moisture content of tree leaves (*Eucalyptus globulus*) as a function of fine fuel moisture code (FFMC).

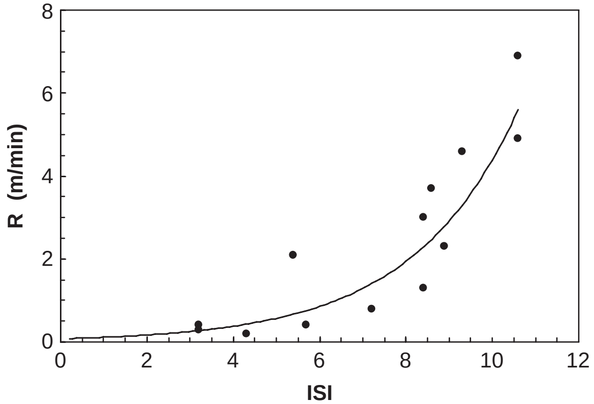

Figure 21.9. Rate of spread of a fire in shrub vegetation (*Erica arborea*) as a function of initial spread index (ISI).

Mounting concerns about wildland fire impacts on air quality and global climate also require further research. In this area, the linkage between fire behavior modeling and air quality modeling is yet to be explored. This research would result in a more dynamic and therefore more realistic description of the temporal and spatial variability of fire emissions and their effects on ecosystems and people.

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