Predicting Fire Behavior in U.S. Mediterranean Ecosystems[1]

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Abstract: Quantification and methods of prediction of wildland fire behavior are discussed briefly and factors of particular relevance to the prediction of fire behavior in Mediterranean ecosystems are reviewed. A computer-based system which uses relevant fuel information and current weather data to predict fire behavior is in operation in southern California. Some of the difficulties encountered in attempts to isolate model and data deficiencies are described.

Recurrent wildland fires are common to those areas of the world that enjoy Mediterranean climate (McCutchan 1977). Because these areas are relatively populous, they present a particular challenge to the wildland manager who would use fire as a tool in ecosystem management or who seeks to minimize the undesirable consequences of wildland fires. The challenge of fire management in Mediterranean ecosystems is made more stringent by the flammability of the native vegetation and the frequent occurrence of long periods of severe burning conditions (Philpot 1977). These factors combine to intensify the need for and value of the ability to predict the behavior of wildland fires. Timeliness of such predictions is of paramount importance; indeed, the character of a system designed to satisfy the needs for fire behavior prediction and fire control dispatching assistance in southern California was dictated by the time constraints under which it must perform (Van Gelder 1978).

Quantifying Fire Behavior

Wildland fire behavior can be described quantitatively by measures of the rate of fire growth, its energy release, the distance over which it can be expected to spawn new fires (to "spot") remote from its present site, and the likelihood that it will consume or propagate in the crowns of the overstory forest if it burns in such. Free-burning fires tend to maintain geometrical similarity under constant fuel and burning conditions,[3] so projections of perimeter and area can be based on the forward rate of spread. The energy released per unit area burned is proportional to the quantity of fuel per unit area (fuel loading). The product of spread rate and the energy release per unit area gives the fireline intensity--or Byram's intensity--as the energy release per unit time per unit length of fire edge (Byram 1959). Another measure of intensity is the heat release per unit burning area per unit time, called "reaction intensity" by Rothermel (1972). The potential spotting distance is probably proportional to flame height (Albini 1979, 1981a) and thus to fireline intensity[4] (Nelson 1980; Albini 1981b). In this paper we shall not address the burning of tree crowns.

These considerations suggest that fire behavior can be described using three quantities: forward rate of spread, fuel loading (or heat release per unit area), and reaction intensity. Fireline intensity is the product of spread rate and heat release per unit area, and is roughly proportional to flame height and potential spotting distance. Flame length is roughly proportional to the square root of the fireline intensity (Byram 1959; Nelson 1980; Albini 1981b). Reaction intensity can be used to gauge the vigor of burning for prescribed fire planning.

Methods of Predicting Fire Behavior

Fire behavior can be predicted by any of three methods, each with unique merits and shortcomings:

1. One may draw upon personal experience in similar situations. This method is always instantly available and is the first and last resort of every experienced field firefighter. But although experience is the best teacher, it is also the slowest and most expensive. And the transfer of this capability from one individual to another is both difficult and error-prone. While firsthand experience is actively to be sought and experienced judgment ever to be respected, this means of prediction cannot be the sole resource for today's fire manager because it is a perishable and poorly shared commodity.

2. Experience may be captured for use by others through inferential (or statistical) models. Fire

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[3]Personal communication from Hal E. Anderson, Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Missoula, Mont., January 1981.

[4]Nelson gives a formula for flame height under wind influence that can be interpreted as proportional to fireline intensity or its square root.

behavior in similar situations can then be calculated by the inexperienced through observation of indicator variables such as windspeed, temperature, humidity, fuel type, etc. This technique is in principle cheap and simple to apply, and it represents a compact means of sharing experience. The unique deficiency of this approach stems from the great number of variables that influence fire behavior and the fact that chance observations must form a large part of the data set. This is so because extrapolation beyond the range of the data base supporting an inferential model is not valid and may lead to large errors. So, if severe fire behavior is to be predicted, it must be measured and correlated to its causative variables, in whatever combinations opportunity provides. The fact that one may not control any substantial number of these variables makes it unlikely that such models of broad applicability will ever come to be. Where such models exist and span important ranges of fire behavior, they should be exploited. But at present the realm of our combined experience, as captured in quantitative form, does not offer us the option of assembling the models needed to span the wide range of fire behavior experienced in Mediterranean ecosystems.

3. A third alternative for predicting fire behavior is the assembly and use of a mathematical model that rests mainly on well-established laws of physics. Several such models have been proposed. While none of them are sufficiently general to handle the entire spectrum of wildland fire behavior, Rothermel's semi-empirical model (1972) has been mechanized (Albini 1976) and widely applied. It describes the behavior of fires in a variety of wildland surface fuels with gratifying consistency (Andrews 1980). The strength of this approach lies in the flexibility and growth capability and especially in the opportunity it affords to make use of controlled test data to improve important empirical components of the model (Wilson 1981). Such virtues, however, are of little value to the practical user if he must make lengthy computations. The complexity of the model renders it inscrutable and thus suspect; its demand for input data makes it tedious to apply; some data are unfamiliar but the model is sensitive to them, leaving the user unsure of the validity of the results.

Automating Fire Behavior Prediction

If the user of fire behavior predictions need not supply input data yet is supplied with prompt results, the difficulties just described can be largely circumvented and the mathematical model used as an aid to strategic and tactical fire control decisionmaking. Automation of calculations and maintenance of a machine-readable data base are needed to achieve this. Automated fire behavior prediction as part of the southern California FIRESCOPE system will be described in general terms below.

We shall show the sensitivity of fire behavior predictions to some fuel and environmental inputs in order to outline the minimal requirements that the automated data base must meet. We shall restrict attention to fuel communities typical of Mediterranean climate wildlands. We shall describe how the FIRESCOPE fire behavior data base is derived and maintained. Examples of system performance will be given and we shall describe efforts to test the reliability of the fire behavior predictions that are now possible.

FACTORS AFFECTING FIRE BEHAVIOR

Factors that affect the behavior of a wildland fire can be classified broadly as either environmental or fuel properties. Fuel properties can be described as intrinsic (i.e., the physical properties of the fuel matter) or extrinsic (i.e., the amount, arrangement, and physical condition of the fuel). While the model is indeed sensitive to intrinsic fuel properties and seasonal variation of them is likely (Philpot 1969), the range over which these properties vary is small enough that they may be considered to be constant for present purposes. So the principal variable factors affecting fire behavior in Mediterranean ecosystem wildlands are environmental and extrinsic fuel properties.

Extrinsic Fuel Properties

Fuel quantity is described in terms of dry weight per unit plantform area, or fuel. loading. For annual grasses and perennial shrubs, fuel loading is in approximate proportion to the height of the vegetation for any particular site. So fuel loading may vary seasonally and with stand age, but the compactness (or "packing ratio") of the fuelbed often may be considered to be a characteristic of the fuel species (or mix of species) and the number of plants per unit area. The relative behavior of wildland fires in such fuel complexes, as affected solely by fuel loadings, is shown in figure 1.

Rate of spread, reaction intensity, and flame length are proportional to fuel loading (for constant packing ratio), while fireline intensity varies quadratically with loading, all other things being invariant. This sensitivity is typical of the standing fuel complexes with which we are concerned here, but is not universally true for wildland fuels. Forest litter and harvest debris, for example, exhibit such strong dependence of packing ratio upon loading that the generalization of figure 1 does not apply to them. And forest understory growth, desert shrub stands, and bunch grasses lack the uniformity necessary to apply this simple rule even approximately.

The Mediterranean climate exempts wildland vegetation from hailstorms, snowpack, and ice buildup, so dead foliage and small stems may persist on standing shrubs for many years and dead grasses or forbs may not lodge for several seasons. So the relative abundance of live and dead fuel components

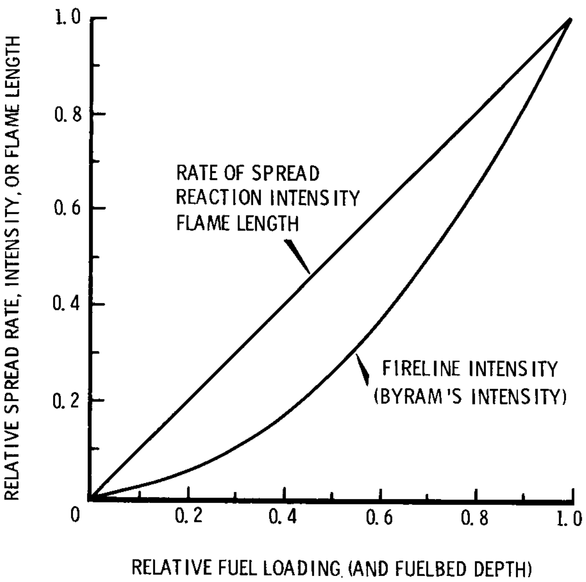

Figure 1--The effect of fuel loading on behavior of fire (fuelbed depth is assumed to be proportional to fuel loading).

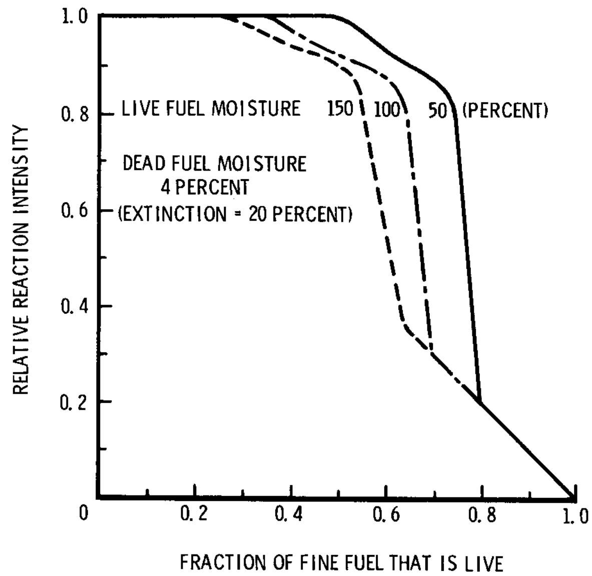

Figure 3--The effect of live-dead proportions on reaction intensity of fire.

may vary with stand age and season (Rothermel and Philpot 1973). Any given region in a Mediterranean climate zone may include sites with greatly different live-dead fuel loading proportions.

Sensitivity of predicted fire behavior to fraction of fine fuel loading that is live is shown in figures 2 and 3. The hypothetical fuel complex used to derive these curves consisted of particles identical in every respect except that the dead particles were kept at 4 percent moisture content and the live particles at 50, 100, or 150 percent. The surface/volume ratio of the particles was assumed to be 2000 ft^{-1} (66 cm^{-1}). It was further assumed that the "moisture of extinction" (Rothermel 1972) of the dead fuel was constant at 20 percent. That is, if the dead fuel moisture were raised to 20 percent it would not support a spreading fire. This parameter is thought to be a property of the fuelbed as an entity, not an intrinsic property of the fuel material.

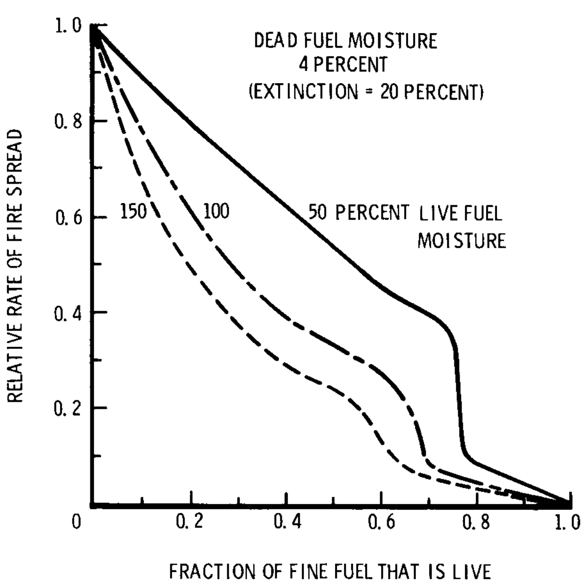

Figure 2--The effect of live-dead proportions on rate of spread of fire.

Figure 2 shows that rate of spread (and so fireline intensity) decreases with increasing live fuel fraction, with a sharp decline at some large live fuel fraction. The model predicts that, at this critical live-dead loading ratio, the live fuel no longer contributes to the release of energy in the fire front. This feature is exhibited much more strikingly in figure 3, which shows the variation of reaction intensity with live fuel fraction. Although this transition point prediction is probably the most weakly-supported relationship in the fire behavior model, it fortuitously gives results that are in good agreement with field experience in southern California chaparral.[5]

[5]"There are several factors which affect fire behavior that can be evaluated prior to the burn date. The most important of these is the proportion of fuel that is dead.... If less than 20 percent of the brushfield is dead fuel, burning efforts are nearly always futile. If about one third of the fuel is dead, and other factors are favorable, we should have a good burn. If half or more is dead, conservatism in the use of other burning variables is necessary, or another Marble Cone wildfire situation would exist." - Lisle R. Green, Chaparral Research and Development Program (Riverside Fire Laboratory), Chaps Newsletter, December 1980, p. 1.

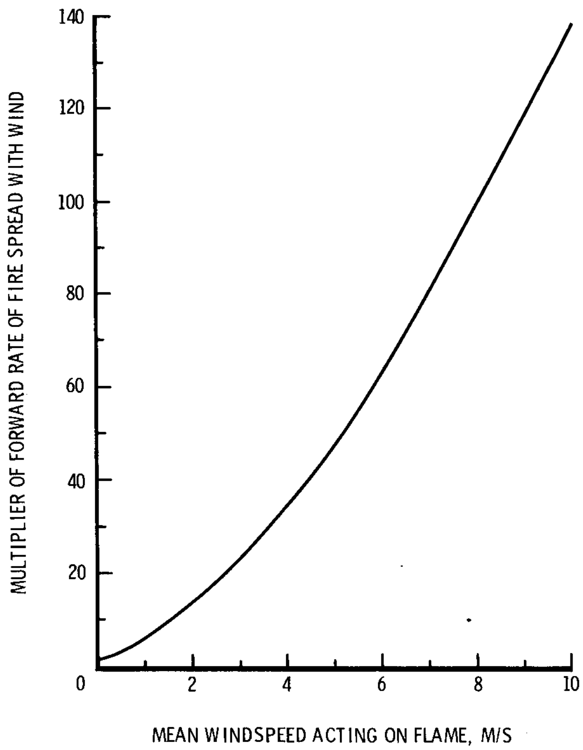

Figure 4--The effect of wind on rate of spread.

Environmental Factors

Wind, terrain slope, and fuel moisture content are the environmental variables that must be specified to the fire behavior model. Terrain slope must be archived to a spatial resolution consistent with the anticipated use of the model, but can be considered for present purposes to be a site-dependent constant. Windspeed, wind direction, and fuel moisture are subject to great temporal variability. These volatile and important factors impose stringent demands on the process for maintenance of a timely data base for fire behavior prediction.

Mediterranean climate zones are prone to occasional winds of great force during their long, dry burning seasons, as well as nearly daily land and sea breezes (McCutchan 1977). The great sensitivity to windspeed of spread rate--and hence fireline intensity--is illustrated in figure 4. Rate of spread increases by more than 2 orders of magnitude as the windspeed acting on the flame goes from zero to 10 m/s. It is apparent that a modest error in windspeed can give rise to a serious misprediction of fire behavior.

To construct figure 4, a fuelbed of particles with surface/volume ratio of 2000 ft^{-1} (66 cm^{-1}) was assumed, with an "optimum" packing ratio that maximizes the wind-insensitive reaction intensity. This is not a "conservative" assumption, because southern California chaparral fuels often exhibit packing ratios (Rothermel and Philpot 1973) which increase their windspeed sensitivity beyond that displayed in figure 4. For a packing ratio equal to half the "optimum" value, the spread rate ratio of figure 4 would increase by about 30 percent.

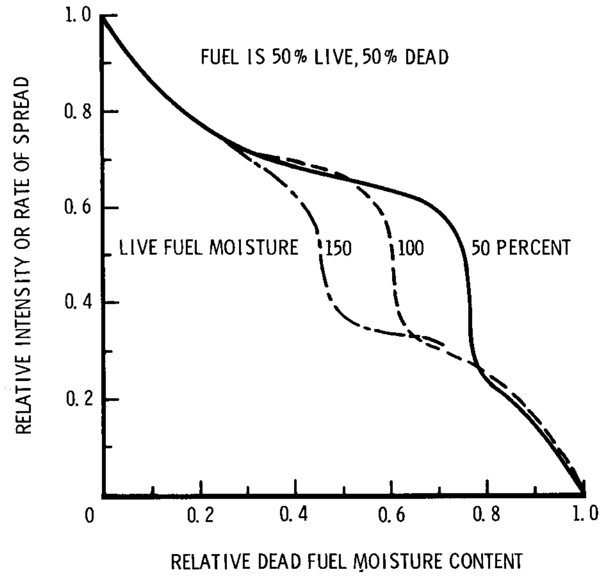

Figure 5--The effect of fuel moisture content on rate of spread and fire intensity.

The long, dry summer season of Mediterranean climates favors drought-resistant shrub species that exhibit live foliar moisture contents in the neighborhood of 50 percent toward the end of the dry season. But the flush of new foliar growth in early spring can raise the mean live foliar moisture to 150 percent or more. This is in stark contrast to the relatively slight seasonal variation of live foliar moisture common to understory vegetation of more moist temperate climates (Hough and Albini 1978) and conifer foliage in even cold climates (Philpot and Mutch 1971; Van Wagner 1977). In addition to this seasonal variation expected in live fuel moisture, fine dead fuel can exhibit large and rapid changes in moisture content, in response to the wide swings in humidity that occur (usually twice daily) in coastal areas.

Sensitivity of spread rate and reaction intensity to fuel moisture are nearly identical, as shown in figure 5 for a hypothetical fuelbed made up of equal parts live and dead particles of 2000 ft^{-1} (66 cm^{-1}) surface/volume ratio. Dead fuel moisture content is represented in figure 5 by its value relative to the "moisture of extinction" mentioned earlier. The precipitous drop in intensity corresponds, as before, to the loss of a heat release contribution by the live fuel components.

The factors discussed above represent the most important data variables that must be maintained if prompt prediction of fire behavior is to be attempted for fuel communities typical of Mediterranean climate wildlands. Each factor imposes a different spatial and temporal resolution requirement on the data gathering and maintenance elements of the FIRESCOPE system, as it must on any similar system.

THE FIRESCOPE SYSTEM

Ultimately, the FIRESCOPE predictive fire behavior modeling system will incorporate 3 levels of sophistication. The simplest model is called southern California FIREMOD and is used by dispatchers and fire managers to predict first-hour, free-burning fire behavior characteristics (i.e., rate of spread, fireline intensity, and potential size in acres) based upon inputs such as fuel type (mixed brush, chamise, or grass), fuel age, fine fuel moisture, slope, and windspeed. A second level of suppression-oriented operational modeling couples fire behavior characteristics with fire suppression information and results in a "probability of successful containment and control" prediction given a designated suppression resource dispatch to a fire site. Each of these two levels assume elliptical fire shapes to provide estimates of area burned within specific time intervals. The most sophisticated level of modeling is for large "campaign" fires and will provide expected fire perimeter locations over a long fire period, taking into account suppression actions and using information such as airborne infrared data to update or reinitialize the computation process.

In the ultimate system, these models will operate from a common computerized data base having terrain and fuel characteristics (age and type) stored and retrievable through an appropriate coordinate system. Inputs with seasonal and/or diurnal variations would be calculated as needed, using information supplied from a remote automated weather station network. Completion of the ultimate FIRESCOPE system is not expected for several years since considerable effort is still required to establish the data bases, integrate the models, and evaluate the system operationally.

Prototype Evaluation

During the past several fire seasons, prototype models of the first 2 levels were made available and evaluated in southern California. Evaluation of the prototypes included examination of the input-output data formats, assessment of data requirements, and estimates of the utility of the predictions. The prototype structure, though limited in fidelity, provided some indication of the problems which would require solution prior to implementation of the final operational system. Unfortunately, field evaluation of the prototypes was not as simple or clean as imagined earlier by the system developers.

Field use of FIREMOD began with establishment of an Operations Coordination Center (OCC) in Riverside, Calif., for use by southern California fire agencies involved in the FIRESCOPE program. When a fire would occur within the jurisdiction of a given agency, the dispatch office of that agency would call in the necessary input information to the OCC which in turn would access the computer and calculate a fire behavior prediction for the requesting agency. Followup was limited to subsequent discussions between the OCC and the fire agencies that commented on the utility of the predicted fire behavior information in relation to what actually occurred in the field. With the initial prototype FIREMOD, discussions with the field indicated that the predicted fire behavior was accurate enough to be useful about 50 percent of the time.

A more controlled evaluation was conducted with the midlevel system. An experimental model, called the Experimental Initial Attack Evaluation Program, was developed by the Mission Research Corporation (Sanderlin and Sunderson 1976), and modified into a midlevel prototype by the USDA Forest Service. This was later renamed the Initial Attack Assessment (IAA) Program. During the 1978 fire season the San Bernardino National Forest, USDA Forest Service, and the San Bernardino Ranger Unit, State of California, Department of Forestry, participated with the FIRESCOPE Program Office, Riverside, Calif., in an operational evaluation of the IAA. The procedure involved identifying fuel type, fuel age, and slope from maps available in the agency dispatch office using coordinates or landmark identification from the person reporting the incident to locate the fire site. Weather data, including windspeed, wind direction, temperature, and relative humidity, was that available from the weather station closest to the incident. These input data were available to the dispatcher, with verification of the fuel and slope characteristics possible only after arrival of the first firefighting resources.

Evaluation Results

Results from the early operational evaluation of the prototype models was disappointing because of many major differences between the predicted fire behavior and that observed at the fire site. A consistent and disturbing occurrence was the great difference in fire behavior predicted by FIREMOD and IAA. At this juncture, it appeared that a thorough reassessment of the prototype models, and how they were being used, was needed. Initial effort involved an orderly debugging of the computer programs followed by many runs of each model using "made-up" fire data to isolate inconsistencies and differences in the logic of the prototype models. After completion of these steps, some minor differences in output values remained because the formats of input field-level data and later conversions to common internal parameters varied between the models.

The simpler of the models, FIREMOD, was converted to account for the fact that in Mediterranean-type ecosystems under 10 years of age, the fuel usually consists of a grass/brush mixture (Rothermel and Philpot 1973). A simplifying assumption was made that for mixed fuel up to 2 years of age, a grass model would be used. For fuel ages from 3 to 10 years, linear combinations of the rates of spread, intensities, and flame lengths computed via the 2 different fuel models are used to represent the grass/brush mixture.

After adjustment of FIREMOD, fire incident data were rerun and comparisons of the model output with behavior values reported from the fires are shown in table 1. Reasons for the variations in most cases were traced to (a) lack of knowledge of the actual fuel carrying the fire (i.e., in some cases,

Table 1--Some comparisons of acres burned predictions vs. actual fire size.

Fire data	Fire date (1978)	Actual size (acres)	Predicted size[1] (acres)
		(1 acre = 0.4 Ha)	
Fuel: brush	9/21	2	4
Slope: 0-5 pct.	9/27	12	7
Age: 5-10 yr.	10/1	1	1
	10/13	7	30
Fuel: brush	9/23	220	100
Slope: 10-30 pct.	10/3	3	3
Age: 5-10 yr.	10/11	10	33
	10/12	90	400
	10/22	5	150
Fuel: grass	8/14	1	1
Slope: 0-5 pct.	8/22	1	4
Age: annual	8/23	4	32
	9/14	12	3
	9/28	5	1
	10/3	4	7.5
	10/24	2	2

[1]Calculated at time of control. Assumes a free-burning fire until time of control.

the fuel was identified as brush, but later discussions revealed the actual fire was carried by grass understory); (b) weather data were taken from stations distant from the fire area; and (c) topographical variations (e.g., the general area has a 30 to 40 percent slope while the actual fire was burning in a rather small local flat area), etc., (d) suppression actions not modeled; (e) natural barriers inhibiting fire growth.

It became obvious that further evaluation to establish the accuracy of the models through field evaluation would require more detailed knowledge of the actual fire conditions than was normally available in the dispatch offices of the evaluating units Our evaluation of IAA is being delayed until a more sophisticated data base and weather station reporting network is available. In the interim, the updated FIREMOD was used to assess fire potential in southern California during the 1980 fire season. Although written records of success ratio or accuracy were not kept, comments from users indicated that with accurate inputs (such as those transmitted to the OCC when first-in firefighting resources reached the fire) the model provided a reasonable assessment of fire potential 70 to 80 percent of the time.

Model Integrity vs. Input Data Accuracy

Attempts to evaluate the theoretical fire behavior models described above through operational or field-level experiment resulted in unclear definitions of the reasons for output inconsistencies. It is impossible, for the most part, to isolate the cause of output variations to either the accuracy or resolution of the input data, applicability of the model to the real world, or (in some cases) to errors which may have crept into the program during the implementation process. Even in the simplest model, FIREMOD, complex relationships between input data readily available to field personnel and internal model parameters exist (table 2). This makes it extremely difficult to evaluate which input variable is suspect when deviations are noted between predicted and actual fire behavior characteristics. Further "fine tuning" of models used in the FIRESCOPE system would require a controlled evaluation program using trained observers at actual fires throughout the fire season. Also needed is a validated, computerized fuels data base coupled to a weather reporting network that would provide on-site windspeed and fuel moisture (or temperature, relative humidity, and previous rainfall) to a higher degree of resolution than is currently available. The minimum resolution needed is presently unknown.

CONCLUSIONS

The input demands of the fire behavior model used in the FIRESCOPE system impose 3 time scales for data maintenance:

1. Stand age must be maintained for each shrub field site in the domain of the system in order to infer fuel quantity from growth models. Stand composition, condition, and other site-specific factors must also be verified periodically.

2. Seasonal trends must be tracked and perhaps deviations from a long-term norm should be accommodated.

Table 2--Inference of fire behavior input variables for southern California FIREMOD prediction program.

Input variable	How variable is determined
Fuel loading	Fuel type and stand age, keyed to map. (Height of stand is age-dependent also.)
Live/dead ratio	Inferred from stand age.
Fine dead fuel moisture content	Entered by operator (usually assumed to be fixed by current data from the nearest weather station).
Live fuel moisture content	Calendar date used in standard seasonal profile.
Windspeed	Nearest weather station last available reading.
Terrain slope	Keyed to map location of fire, read from topographic relief map.

3. Temperature and humidity (which determine dead fuel moisture) and windspeed and direction must be updated at least frequently enough to accommodate diurnal variation, and more frequently when significant changes are anticipated.

The spatial resolution required of the data base depends upon the uniformity of fuel type, stand age, and condition, the amount and regularity of terrain relief, and the operational needs which the fire behavior model output is expected to fill.

Testing the reliability or accuracy of fire behavior predictions is subject to great uncertainty, not the least of which is that associated with validating the data base and the inferences drawn therefrom. Specifically, our operational experience in southern California indicates that:

1. Accurate assessment of the southern California fire behavior models will require controlled on-site evaluation by trained observers during actual fires.

2. Actual operational use of the fire behavior models must await completion of an accurate stored computerized data base accessible to the dispatcher through input of fire location coordinates.

Weather information will require considerable improvement in resolution through use of a sophisticated weather station network and computerized wind models to interpolate conditions to fire site locations.

LITERATURE CITED

Albini, Frank A. Computer-based models of wildland fire behavior: a users' manual. Ogden, Utah: Intermt. For. and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1976. 68 p.

Albini, Frank A. Spot fire distance from burning trees--a predictive model. Ogden, Utah: Intermt. For. and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1979; Res. Paper INT-56, 73 p.

Albini, Frank A. Spot fire distance from isolated sources--extensions of a predictive model. Ogden, Utah: Intermt. For, and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1981a; Res. Note INT-309. 9 p.

Albini, Frank A. A model for the windblown flame from a line fire. Comb. and Flame (to be published). 1981b.

Andrews, Patricia L. Testing the fire behavior model. In: Robert E. Martin and others, eds. Proc. sixth conf. on fire and forest meteorology. Wash., D.C.: Soc. Am. For.; 1980; 70-77.

Byram, G. M. Combustion of forest fuels. In: Kenneth P. Davis, ed. Forest fire control and use. New York: McGraw-Hill Book Co.; 1959; p. 90.

Hough, W. A.; Albini, F. A. Predicting fire behavior in palmetto-gallberry fuel complexes. Asheville, North Carolina: Southeastern For. Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1978; Res. Paper SE-174. 44 p.

McCutchan, Morris H. Climatic features as a fire determinant. In: Proc. of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems. Wash., D.C.: Forest Serv., U.S. Dep. Agric. Gen. Tech. Rep. WO-3; 1977:1-11.

Nelson, Ralph M., Jr. Flame characteristics for fires in southern fuels. Asheville, North Carolina: Southeastern For. Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1980; Res. Paper SE-205, 14 p.

Philpot, C. W. Seasonal changes in heat content and ether extractive content of chamise. Ogden, Utah: Intermt. For, and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1969; Res. Paper INT-61. 10 p.

Philpot, C. W.; Mutch, R. W. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. Ogden, Utah: Intermt. For. and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1971; Res. Paper INT-102. 21 p.

Philpot, C. W. Vegetative features as determinants of fire frequency and intensity. In: Proc. of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems. Wash., D.C.: Forest Serv., U.S. Dep. Agric. Gen. Tech. Rep. WO-3; 1977:12-16.

Rothermel, Richard C. A mathematical model for predicting fire spread in wildland fuels. Ogden, Utah: Intermt. For. and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1972: Res. Paper INT-115. 40 p.

Rothermel, R. C.; Philpot, Charles W. Predicting changes in chaparral flammability. J. For. 11:640-643; 1973.

Sanderlin, J. C.; Sunderson, J. M. Users' guide, experimental and initial attack evaluation model. Santa Barbara, Calif.: Mission Research Corp. Rep. No. 7611-1-376; 1976.

Van Gelder, Randall J. FIREMANS--a fire management system simulation model for operational fire planning support. In: Proc. workshop/symposium on simulation techniques in forest operational planning and control. Wageningen, The Netherlands. 1978:188-194.

Van Wagner, C. E. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23-34; 1977.

Wilson, Ralph A. A reexamination of fire spread in free-burning porous fuel beds. Ogden, Utah: Intermt. For, and Range Exp. Stn., Forest Serv., U.S. Dep. Agric.: 1981 (to be published).