

FIRE BEHAVIOR MODELING—A DECISION TOOL¹

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ABSTRACT.—The usefulness of an analytical model as a fire management decision tool is determined by the correspondence of its descriptive capability to the specific decision context. Fire managers must determine the usefulness of fire models as a decision tool when applied to varied situations. Because the wildland fire phenomenon is complex, analytical fire spread models will have descriptive limitations. Some limitations in the widely used and accepted Rothermel fire spread model are discussed in terms of the model's assumptions and mathematical formulations, in the context of prescribed burning in southern California shrublands.

INTRODUCTION

Any decision, including a fire management decision, implies a choice from among a set of potential alternatives. The decision is based on a best or desired outcome, with the best or desired outcome determined by social priorities and values. A decision is based on information from various sources. Information may be intuitive from experiences or computations from a model. In a practical sense, information either describes the uncertainty of the outcome or reduces the amount of the decision uncertainty, or both. But, the information does not determine the desirability of the outcome; a decision must still be made. In the context of fire management, fire managers make decisions using information from fire behavior models.

A real (as opposed to ideal) model such as the Rothermel fire spread model (Rothermel 1972, Albini 1976) provides descriptive

information that may reduce but not eliminate or describe uncertainty. Model information, however, may not adequately reduce uncertainty of specific decisions for two reasons. One, the model may not adequately account for all processes of the phenomenon; and two, the model may not provide information that is relevant to the outcome. Thus, decision usefulness may depend on specific fire environments (the technical adequacy of the model to account for all processes of the phenomenon). And, usefulness of a model's information in decisionmaking (relevancy), may change depending on the decision being made.

This paper examines two aspects of fire behavior modeling:

1. The first aspect considers various technical limitations of the Rothermel fire spread model, a major component of the Fire Behavior Prediction System (Rothermel 1983). These limitations are particularly significant to prescribed burning in southern California, and are largely due to the fact that the objectives of the original experimentation concerned steady propagating fires in dead fuel beds. The processes involved in going from ignition to a propagating fire in live fuel beds, which are significant to southern California prescribed burning, were not incorporated in the original scope of experimentation.

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2. The second aspect considers the general relation between a descriptive model that provides fire behavior information and management decisions that govern model applicability. It deserves noting that the Rothermel based fire behavior prediction methods have generally remained unchanged over the past 14 years while policy and associated decision requirements have changed significantly.

TECHNICAL EXAMINATION

Background and Methods

The operational use of fire behavior models based on the Rothermel fire spread model, particularly in the context of prescribed burning, has major difficulties in southern California. This lack of success has various contributing factors, administrative as well as technical. However, the possibility of modeling inadequacies prompts a general examination of shrubland fuel and fire behavior characteristics in relation to the formulation of the Rothermel fire spread model. Field observations and laboratory demonstrations have provided clues to various aspects of the fire spread model which may explain its lack of success.

Observations and cursory sampling from southern California shrubland prescribed fires indicate that fire will carry through exclusively living vegetation. But, observations indicate that fire commonly does not spread below a threshold windspeed, and often spreads only in the heading direction. Also, attempts at using helitorch ignition methods often do not result in fire spread.

Observations were also made in the laboratory. Due to the uncontrolled and confounding nature of field observations, fire spread was also studied in the more controlled environment of the laboratory.

Burning fuels on a fire table at the USDA Forest Service's Forest Fire Laboratory in Riverside California, demonstrated several fire behavior characteristics significant to the use of the Rothermel fire spread model (Rothermel 1972, Albini 1976) for prescribed burning in southern California (data and video record are available at the Forest Fire Laboratory):

1. Fine (< 6 mm) live chamise shrub (*Adenostoma fasciculatum*) fuel beds (20-45 cm deep), ignited from a line source of burning alcohol, resulted in a steady, propagating flame zone. The sampled average moisture content (foliage and stems) was 50%-70% (oven dry weight basis), with no wind and no slope.

2. Increasing the bed depth while proportionally decreasing fuel bed density resulted in steady flame propagation. Fuel beds were composed of living fuel, under conditions of constant moisture content, with no wind and no slope.
3. Introducing a 1-m/sec wind at the top of the fuel bed resulted in steady fire spread in living fuel beds at constant moisture content and no slope.

Fire Model

The fundamental equation of the Rothermel fire spread model (Rothermel 1972), which concurs with earlier analyses by Anderson (1969) and Frandsen (1971), is as follows:

$$I_p = RQ \quad (1)$$

I_p = total propagating heat flux, (kJ/min)/m²;

R = forward rate of fire spread, m/min;

Q = heat required for ignition, kJ/m³.

From equation 1, after many experimental laboratory fires and ingenuity, came the following equations (2, 3, and 4) that resulted in the final form of the fire spread model (equation 5):

$$(I_p)_0 / I_R = \xi \quad (2)$$

$(I_p)_0$ = no-wind, no-slope propagating heat flux, (kJ/min)/m²;

I_R = rate of heat release per unit area, reaction intensity (kJ/min)/m²;

ξ = propagating flux ratio.

Rearranging terms and substituting equation 2 into equation 1 (I_p becomes the special case $(I_p)_0$) results in the rate of spread equation for a no-wind, no-slope condition.

$$R_0 = I_R \xi / Q \quad (3)$$

R_0 = no-wind, no-slope rate of spread, m/min.

Through laboratory experiments, the total propagating flux (I_p , considering wind and slope) was related to the no-wind, no-slope propagating flux $((I_p)_0)$.

$$I_p = (I_p)_0 (1 + \phi_w + \phi_s) \quad (4)$$

ϕ_w = wind factor

ϕ_s = slope factor.

Using equations 1, 3 and 4, the rate of spread equation (wind and slope considered) becomes:

$$R = I_R \xi (1 + \phi_w + \phi_s) / Q \quad (5)$$

LIVING FUELS.—Examination of how living fuels are considered in the fire spread model requires a look at the expression for the reaction intensity (I_R) (Albini 1976), which is currently used in the fire spread model:

$$I_R = \Gamma' [(w_N h \eta_m \eta_s)_d + (w_N h \eta_m \eta_s)_l] \quad (6)$$

Γ' = optimum reaction velocity, min^{-1} ;

w_N = net fuel loading (without moisture and minerals), kg/m^2 ;

h = fuel heat of combustion, kJ/kg ;

η_m = moisture damping coefficient;

η_s = mineral damping coefficient;

d denotes dead fuel category;

l denotes live fuel category.

The formulation of the live moisture damping coefficient requires the presence of dead fuel for a live fuel contribution to the calculation. The live moisture damping coefficient calculation follows the assumption that the energy required for burning the living fuels comes from the dead fuels. The live moisture of extinction represents the theoretical upper live moisture content limit for the live fuel contribution to the energy release. For live fuel moisture contents above the moisture of extinction, the live fuel is not considered a contributor to the flaming zone energy release. The variables involved are shown through the following functional dependence:

$$(\eta_m)_l = F[(M_C)_l, (M_X)_l]$$

and,

$$(M_X)_l = G[(w_N, \sigma, M_C, M_X)_d, (w_N, \sigma)_l]$$

M_C = fuel particle moisture content (oven dry weight basis);

M_X = fuel moisture of extinction;

σ = fuel particle surface area-to-volume ratio, cm^{-1} ;

d denotes dead fuel category;

l denotes live fuel category.

The mathematical behavior of $(\eta_m)_l$ is symbolically represented for a modeled fuel bed as the dead fuel component goes to zero ($\rightarrow 0.0$).

For $(w_N)_l > 0.0$, and $(w_N)_d \rightarrow 0.0$,

$$(M_X)_l \rightarrow 0.0, \text{ resulting in}$$

$$(\eta_m)_l \text{ and } (\eta_m)_d \rightarrow 0.0, \text{ then,}$$

$$R \rightarrow 0.0.$$

The above representation illustrates that as the dead fuel component is removed from the fuel bed, leaving only the live fuel, the modeled rate of spread goes to zero. According to the fire spread model, exclusively live fuel beds do not carry fire, which is not consistent with experience.

MOISTURE OF EXTINCTION.—Currently in the fire spread model, the condition for extinction is described only by a specific moisture content. The calculation of both the living and dead moisture damping coefficients $(\eta_m)_d$ and $(\eta_m)_l$ from equation 6] is dependent on a specific moisture of extinction $[(M_X)_d]$:

$$(\eta_m)_d = H[(M_C)_d, (M_X)_d];$$

and as the ratio,

$$(M_C)_d / (M_X)_d \rightarrow 1.0, \text{ resulting in}$$

$$(\eta_m)_d \rightarrow 0.0, \text{ then,}$$

$$R \rightarrow 0.0.$$

A specific moisture content exclusively describes the extinction condition. However, our recent field observations and laboratory experiments in shrub fuels suggest that general fuel bed conditions, such as fuel bed geometry as well as fuel moisture content, contribute to fire extinction. The contribution of fuel bed conditions other than moisture content to fire extinction is suggested by Albini (1980) and is experimentally demonstrated by Wilson (1982).

Wilson (1982, 1985) reexamined in the laboratory the Rothermel model formulations concerning fuel geometry and moisture content with no wind and no slope. He found that conditions near the extinction point of burning were not just a function of the moisture content, but also of the total fuel particle surface area.

The preliminary experiments performed at the Forest Fire Laboratory (Riverside) using fuel beds deeper than those of Wilson (1982) and with living fuels suggest additional considerations. Experimental fires have been made to propagate by increasing the fuel bed depth, while keeping the loading constant. This changes the fuel bed geometry but holds the total fuel particle surface area constant. However, the effect of fuel bed geometry, other than the total surface area, needs further investigation before conclusions can be made.

Identifying near extinction conditions is more complicated for prescribed burning. Ignition techniques can quickly establish multiple flaming zones that produce a nonsteady fire situation that enhances fire spread. However, this situation is totally out of the scope of the fire spread model. Wind and slope also affect the ability for flame propagation

to occur and are particularly significant to the prescribed burning situation.

WIND AND SLOPE.—The fire spread model assumes that wind and slope enhance the heat transfer of a fire capable of spreading under a no-wind, no-slope situation. Substituting equation 3 into equation 5 results in the following form of the fire spread equation:

$$R_{w, s} = R_0 (1 + \phi_w + \phi_s) \quad (7)$$

$R_{w, s}$ = rate of spread influenced by wind and slope, m/min.

The wind and slope factors are defined as follows:

$$\phi_w = (R_w/R_0) - 1.0 \quad (8)$$

$$\phi_s = (R_s/R_0) - 1.0 \quad (9)$$

In equation 7, wind and slope only enhance existing fire spread because the wind and slope factors are dependent on a nonzero rate of spread (R_0). The effect of wind and slope to enable propagation is not considered by the model; however, fire spread requiring a minimum wind is commonly observed in shrubland prescribed burning and reported for independent tree crown fires (Van Wagner 1976). In laboratory experiments at the Forest Fire Laboratory (Riverside), living fuel beds incapable of fire propagation without wind result in steady flame spread with wind.

PRESCRIBED FIRE.—Prescribed fire fundamentally differs from wildfire, not in the context of desired outcomes or planning and control, but in a technical modeling context. The behavior of an initiating fire from the time of ignition to a steady burning situation is nonsteady. And, due to multiple ignitions, a prescribed fire can burn under largely nonsteady burning conditions.

Equation 1 represents an equilibrium condition between the propagating heat flux and the amount of heat required for a specific rate of spread. The fire spread model is predicated on the existence of a spreading fire, and only considers the steady fire spread situation. Given ignition, the minimum conditions for fire spread are not described; they are assumed to exist. Although it is important to know if fire will spread for a prescribed burn, predicting the capability for fire spread is outside the scope of the Rothermel fire spread model.

DECISION CONTEXT

There are limitations to the use of any model as a decision tool, the fire behavior model included. First and foremost it must be recalled that a model does not produce a decision. A model produces reduced or analyzed data that functions as another source of information of potential utility for a decision.

The decision remains the purview of the decisionmaker; the model only supplies more information. To consider a model as producing a decision is to preempt the responsibility of the decisionmaker with a single analytical tool that is, at best, a simplified representation of the decision situation.

Model Verification and Applicability

The preceding technical discussion of the Rothermel fire spread model is generally in the context of verification. That is, the comparison of modeled estimates to observed reality—a "truth" test. Simply, a verification produces a description of the information accuracy and a probabilistic description of the information uncertainty. Importantly, however, a verification is exclusive of any decision requirements. Without understanding the decision requirements, useful application of model information cannot be determined.

The operational usefulness or applicability of a model is not guaranteed by simply the best match of a model prediction to an observation. Application of model information is determined by its ability to meet the requirements of the decision context. Applicable model information only needs to meet the decision requirements, not exceed. In this context, improved model accuracy and precision does not improve the decision. Also, formerly applicable information may not be applicable for a changed decision context.

Fire Behavior Decisions

The Rothermel fire spread model and associated models are part of the Fire Behavior Prediction System, which is an operational decision tool. The prediction system produces information (e.g., spread rates, intensities, etc.) that affects a particular set of decisions (such as, holding forces required and line location). The degree of precision and accuracy required of this model-produced information is defined by the decisions. As decision needs change (e.g., as the activity changes from wildfires to prescribed fires) or as the fire environment changes (e.g., from forest litter to living shrubland fuels), the fire model's applicability may also change.

The contexts of wildfire and prescribed burning illustrate two relatively different sets of information requirements. A decisionmaker in a wildfire context already knows that an ignition will occur with subsequent fire spread, because it is defined by the situation. Therefore, the decisionmaker needs a prediction of continued fire behavior, given the set of existing conditions, including the observed fire behavior.

A decisionmaker in a prescribed fire context is faced with considerably different prediction needs. Given the ignition, will the fire spread?

Will the fire characteristics be sufficient to achieve resource management goals? Will the fire be manageable with the control forces at hand? The prescribed burning context demands different information.

Often users try to apply a model beyond what it was originally designed to do. Users should recognize the necessity to analyze their information needs because the model designer cannot envision all potential applications. If conditions change from those under which the prototype model was developed, the applicability of the model is likely to change. An example of such a change in conditions is in using the Rothermel fire spread model for prescribed fire predictions in southern California shrublands—an application not envisioned by the model designer.

LITERATURE CITED

- ALBINI, F. A. 1976. Computer-based models of wildland fire behavior: a user's manual. USDA For. Serv. INT (nonserial). 68 p.
- ALBINI, F. A. 1980. Thermochemical properties of flame gases from fine wildland fuels. USDA For. Serv. Res. Pap. INT-243. 42 p.
- ANDERSON, H. E. 1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69. 20 p.
- FRANDSEN, W. H. 1971. Fire spread through porous fuels from the conservation of energy. Combustion and Flame 16:9-16.
- ROTHERMEL, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115. 40 p.
- ROTHERMEL, R. C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143. 161 p.
- VAN WAGNER, C. E. 1976. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23-34.
- WILSON, R. A. JR. 1982. A reexamination of fire spread in free-burning porous fuel beds. USDA For. Serv. Res. Pap. INT-289. 28 p.
- WILSON, R. A. JR. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combustion Sci. and Tech. 44:179-193.