Reformulation of Rothermel's wildland fire behaviour model for heterogeneous fuelbeds[1]

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Abstract: The Fuel Characteristic Classification System (FCCS) includes equations that calculate energy release and one-dimensional spread rate in quasi-steady state fires in heterogeneous but spatially-uniform wildland fuelbeds, using a reformulation of the widely used Rothermel fire spread model. This reformulation provides an automated means to predict fire behavior under any environmental conditions in any natural, modified, or simulated wildland fuelbed. The formulation may be used to compare potential fire behavior between fuelbeds that differ in time, space, or as a result of management, and provides a means to classify and map fuelbeds based on their expected surface fire behavior under any set of defined environmental conditions (i.e., effective wind speed and fuel moisture content). Model reformulation preserves the basic mathematical framework of the Rothermel fire spread model, reinterprets data from two of the original basic equations in his model, and offers a new conceptual formulation that allows the direct use of inventoried fuel properties instead of stylized fuel models. Alternative methods for calculating the effect of wind speed and fuel moisture, based on more recent literature, are also provided. This reformulation provides a framework for the incremental improvement in quantifying fire behaviour parameters in complex fuelbeds and for modeling fire spread.

Résumé : Le système de classification des caractéristiques des combustibles (SCCC) comprend des équations qui permettent de calculer le dégagement d'énergie et le taux de propagation unidimensionnel pour des feux à l'état de quasi équilibre dans des couches de combustibles, hétérogènes mais uniformes dans l'espace en milieu naturel, grâce à une reformulation du modèle de propagation du feu de Rothermel qui est largement utilisé. Cette reformulation fournit un moyen automatisé de prédire le comportement du feu dans n'importe quelles conditions environnementales et dans n'importe quelles couches de combustibles en milieu naturel, qu'elles soient naturelles, modifiées ou simulées. Cette formulation peut être utilisée pour comparer le comportement potentiel du feu entre des couches de combustibles qui diffèrent dans le temps, dans l'espace ou à cause de l'aménagement; elle fournit un moyen de classer et de cartographier les couches de combustibles sur la base de leur comportement attendue dans le cas d'un feu de surface dans n'importe quels ensembles de conditions environnementales (c.-à-d. : vitesse effective du vent et contenu en humidité des combustibles). La reformulation du modèle conserve la structure mathématique fondamentale du modèle de propagation du feu de Rothermel, réinterprète les données à partir de deux des équations de base originales dans son modèle et offre une nouvelle formulation conceptuelle qui permet l'utilisation directe des propriétés inventoriées des combustibles au lieu de modèles simplifiés des combustibles. D'autres méthodes basées sur la littérature plus récente et permettant de calculer l'effet de la vitesse du vent et de l'humidité des combustibles sont également fournies. Cette reformulation offre un cadre pour améliorer encore davantage la quantification des paramètres de comportement du feu dans les couches de combustibles complexes et pour modéliser la propagation du feu.

[Traduit par la Rédaction]

Introduction

The reformulation of the Rothermel (1972) fire spread model presented here allows the direct use of inventoried or synthesized fuelbed properties instead of stylized fuel models as inputs to a surface fire behaviour model, and provides a means of classifying and comparing fuelbeds based on fire behaviour predictions under a defined set of environmental conditions. The Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007) builds and catalogues fuelbed descriptions based on physical properties derived from direct or indirect observation, inventory, expert knowledge, or inference. These fuelbeds may exist in nature or could logically result from changes in existing fuelbeds through

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management, disturbance, or the passage of time. Fuelbeds can be classified or compared with others according to any of their native qualitative (e.g., dominant species) or quantitative (e.g., fuel load) properties, or by outcomes such as predicted fire behaviour (e.g., flame length). The fire behaviour formulation in this paper enables one set of many fuelbed classification possibilities based on measures of surface fire intensity or spread rate.

Rothermel's (1972) fire spread model is the foundation for many applications that support fire management in the United States. His spread rate equations are integral to the fire behavior prediction system (Burgan and Rothermel 1984; Andrews 1986; Burgan 1987; Andrews and Chase 1989) used in the United States. Spread and energy release components in the National fire danger rating system are also taken from Rothermel (1972) as modified by Albini (1976). Numerous fire management applications currently in use in the United States — FARSITE (Finney 1998, 1999), BehavePlus (Andrews and Bevins 2003; Andrews et al. 2003), NEXUS (Scott 1999), FlamMap (Stratton 2004), FFE-FVS (Reinhardt and Crookston 2003), FETM (Schaaf et al. 2004; Weise 2006), NFMAS, the National Fire Management Analysis System for economic planning (Lundgren et al. 1995), and RERAP, the Rare Event Risk Assessment Process (Wiitala and Carlton 1994), as well as other related investigations on fire effects and crown fire prediction — have as a common basis the Rothermel surface fire behaviour calculations.

Other models have been implemented as fire behaviour prediction systems and used as the basis for fire danger rating. The Canadian fire behaviour prediction (FBP) system (Forestry Canada Fire Danger Group 1992; Lee et al. 2002; Taylor et al. 1997), McArthur fire danger meters (Noble et al. 1980; Cheney et al. 1990), and Western Australia forest fire behaviour tables (Sneeuwjagt and Peet 1985) are other systems in widespread use that serve as decision support systems for fire management. These are primarily empirical systems based on a large number of field experiments and observations of wildland fires over a range of fuel characteristics and wind speed and moisture conditions. We did not address those systems in this paper to allow us to concentrate on applications of Rothermel's model in the United States.

The Rothermel (1972) fire spread model best represents fires that have stabilized into a quasi-steady-state, free-spreading process in homogeneous and spatially uniform surface fuels. Heterogeneous fuelbeds consisting of a mixture of fuel size-classes and live and dead categories are mathematically formulated into virtual homogeneous arrays to conform to experimental observations used to evaluate the basic spread equations. Input parameters representing common fuelbeds are catalogued into stylized fuel models that have been adjusted to produce reasonable outputs (in the experienced judgment of the fuel model builder) when combined with a range of environmental conditions of wind speed, slope, and fuel moisture (Andrews and Queen 2001). The most important of these subjective adjustments is the assignment of artifical fuelbed depths, loadings, and surface-to-volume ratios for <0.64 cm diameter fuels.

We validate our reformulation by predicting fire behaviour at benchmark environmental conditions for a wide range of fuelbed characteristics from an independent data set, then compare those predictions with predicted fire behavior for similar fuel types using BehavePlus (Andrews et al. 2005), a computerized application of Rothermel (1972) that relies on stylized fuel models (Anderson 1982) as input. We accept the combination of BehavePlus and 13 fuel models to provide the range of fire behaviours that best represent reality in the expert judgment of their developers. In this paper, we are interested only in whether or not we provide output that is similar in range to BehavePlus with some added value and without the subjective use of aids for selecting fuel models as inputs.

Approach

Rothermel (1972) presented his model in sections consisting of

(1) a conceptual mathematical framework;
(2) equations for rate of spread under no-wind, no-slope conditions;
(3) multiplication factors for the effect of wind speed and slope;
(4) formulation of a fire behaviour model for heterogeneous fuelbeds; and
(5) application to the field, using stylized fuel models as inputs.

In this paper, we follow this format to (*i*) offer no changes in the Rothermel (1972) basic framework other than to rearrange terms, (*ii*) propose a significant re-evaluation of the heat sink terms in the no-wind spread equation, including the effects of dead and live fuel moisture, (*iii*) discuss alternatives to the original coefficients for wind speed effects, (*iv*) provide a new formulation of a fire behaviour model for heterogeneous fuelbeds, and thereby, (*v*) enable application to the field using direct input of realistic fuelbed information such as that used in FCCS.

Conceptual framework

Rothermel's (1972) mathematical framework simulates fire spread as a quasi-steady-state series of ignitions in spatially uniform fuelbeds. Rate of spread in the Rothermel (1972) model is the ratio of propagating heat flux to the energy required to dry and preheat unburned fuels until they ignite. The framework defines the heat source as reaction intensity, I_R, the expression of fuel load, fuel particle size, fuel chemistry, fuel arrangement, and fuel moisture. I_R is not affected by wind speed or slope. Propagating flux combines the effect of forward radiation, convection (including flame contact), and piloted ignition. It is the product of I_R and the propagating flux ratio, ξ, the latter term representing the proportion of reaction intensity that is transferred to the unburned fuels. Propagating flux is evaluated first for the no-wind, no-slope condition, and then modified by a multiplication factor for wind speed and slope. Fireline intensity ($kJ \cdot m^{-1} \cdot s^{-1}$), as proposed by Byram (1959), is calculated from the product of reaction intensity ($kJ \cdot m^{-2} \cdot s^{-1}$), reaction time (min), and rate of spread ($m \cdot min^{-1}$); flame length (m) is calculated as a function of fireline intensity.

In this paper, we accept Rothermel's (1972) framework without modification other than to rearrange terms to segregate intrinsic fuelbed characteristics from environmental conditions. We acknowledge that there are other options available from more recent investigations, but we wish to establish a benchmark that relates to current fire management applications in the United States. Although our reformulation will not improve the inherent limitations, we use this as a first step to add value while providing consistency in current applications of the Rothermel model. We will use this as starting point in the future for investigating frameworks that depart from this established framework.

Spread equations

Rothermel's spread rate equation, modified to reflect changes by Albini (1976) and the metric conversions by Wilson (1980), is

$$R = (I_R \xi / \rho_b \varepsilon Q_{ig})(1 + \varphi_W + \varphi_S) \qquad [1]$$

where R is the rate of spread (m·min^{-1}), I_R is the reaction intensity (kJ·m^{-2}·s^{-1}), ξ is the propagating flux ratio, the proportion of I_R transferred to unburned fuels (dimensionless), ρ_b is the oven-dry bulk density (kg·m^{-3}), ε is the effective heating number, the proportion of fuel that is heated (dimensionless) before ignition occurs, Q_{ig} is the heat of preignition, a function of fuel moisture content, specific heat, and assumed temperature at ignition (kJ·kg^{-1}), and $(1 + \varphi_W + \varphi_S)$ is the multiplication factor for slope and wind speed (dimensionless).

The heat-source term in Rothermel's (1972) framework is I_R. A key variable in I_R (eq. 2) is the reaction velocity, $\Gamma = \eta_\delta / \tau_R$ (min^{-1}), a dynamic variable that indicates the proportion of fuel consumed (η_δ) in the reaction zone residence time (τ_R, min). I_R is a function of the potential reaction velocity, Γ', which is the reaction velocity that would exist if the fuel were free of moisture and mineral content.

$$I_R = \Gamma' w_n h \eta_s \eta_M \qquad [2]$$

where Γ' is the potential reaction velocity (min^{-1}), w_n is the net fuel load (kg·m^{-2}), h is the fuel low heat content (kJ·kg^{-1}), η_M is the moisture damping coefficient (dimensionless), and η_s is the mineral damping coefficient (dimensionless).

Rothermel includes only the damping effect of moisture (η_M) and mineral content (η_s) in reducing Γ' to Γ. The effect of the size of homogeneous fuel elements, identified by their characteristic surface-to-volume ratio ($\bar{\sigma}$, cm^{-1}), on reaction efficiency determines maximum reaction velocity ($\Gamma'_{\max}$); this is reduced to potential reaction velocity by accounting for the inefficient arrangement of fuel elements within the fuelbed. At this point we expand eq. 2 by introducing a new term, $\eta_{\beta'} = \Gamma'/\Gamma'_{\max\bar{\sigma}}$, to make the damping effect of inefficient packing, $\eta_{\beta'}$, explicit.

$$I_R = \eta_{\beta'} \Gamma'_{\max\bar{\sigma}} w_n h \eta_s \eta_M \qquad [3]$$

where $\Gamma'_{\max\bar{\sigma}}$ is the maximum reaction velocity for fuels of size $\bar{\sigma}$ at optimum packing ratio (min^{-1}), $\bar{\sigma}$ is the characteristic surface area-to-volume ratio (cm^{-1}), $\eta_{\beta'}$ is the reaction efficiency effect of the packing ratio (dimensionless), β' is the relative packing ratio, the ratio of packing ratio (ρ_p/ρ_b) to optimum packing ratio (dimensionless), and ρ_p is the oven-dry fuel particle density (kg·m^{-3}).

We combined and rearranged eqs. 1 and 3 into a rate-of-spread equation made up of five factors representing (1) the propagating flux ratio, (2) the potential reaction intensity at optimum packing ratio and oven-dry conditions, (3) the reaction efficiency and heat sink as affected by fuel size and arrangement, (4) the the intensity-damping and heat-sink role of moisture, and (5) the spread-rate multiplication by wind speed and slope conditions.

$$R = \xi(\Gamma'_{\max\bar{\sigma}} w_n \eta_s h)(\eta_{\beta'}/\rho_b \varepsilon)(\eta_M/Q_{ig})(1 + \varphi_W + \varphi_s) \qquad [4]$$

This is the order in which we examined and modified the terms of the equation.

No-wind, no-slope, moisture-free fire spread equations

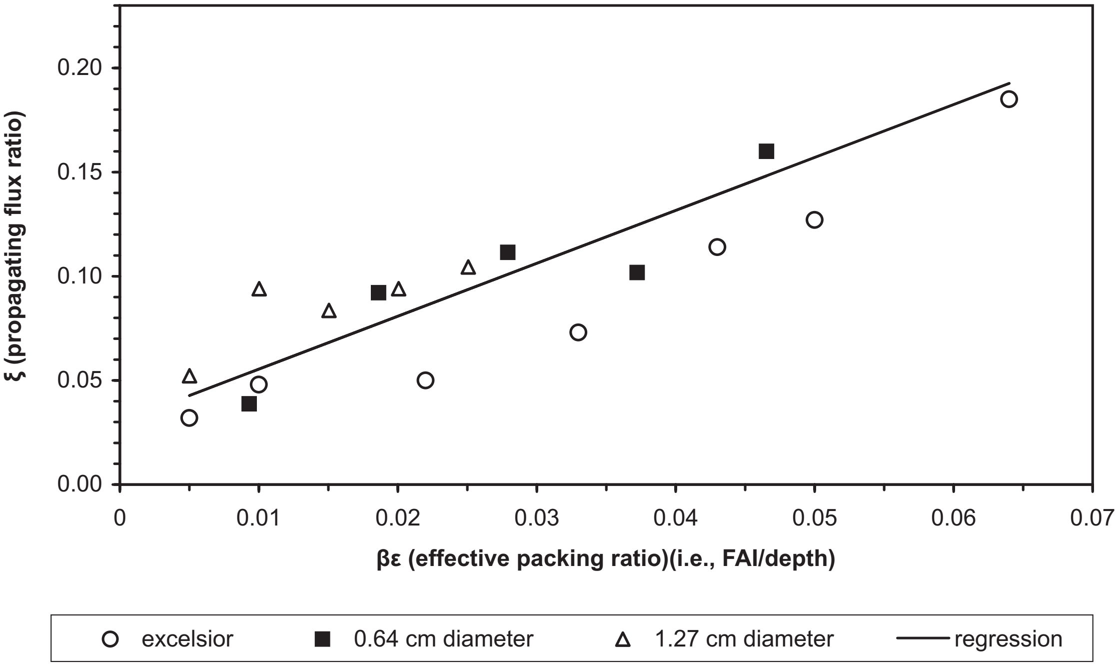
The first three factors in eq. 4 represent the potential rate of spread for the no-wind, no-slope, moisture-free condition, based only on the physical characteristics of the fuelbed. Evaluations, comparisons, and classifications of multiple fuelbeds can be made on the basis of these potentials by considering only their physical characteristics. The final two terms can be added to evaluate and classify fuelbeds based on predicted fire behaviour under realistic environmental conditions. In this section we reexamine the data used to evaluate terms of the equations in Rothermel's (1972) model, without adding any new experimental data or observations. We offer an alternative fit to the data used in one of those equations that significantly increases the heat-sink term for thermally thin fuel elements. Otherwise, our modifications are only cosmetic. In the future, we intend to modify other portions of the original equations using independent data.

Propagating flux ratio (ξ)

One limitation of the Rothermel (1972) framework is that no attempt is made to parse out the several pathways of heat transfer from the spreading flame to the unburned fuel ahead of the flame. Convection, radiation, flame contact (a form of convection), and ignition-point transfer are all contained in a single heat-transfer efficiency term (ξ). Nor is heat transfer within the fuelbed volume partitioned from what occurs through the space external to the fuelbed. Hence, the conceptual basis for the parameter is weak, which creates a limiting factor in the accuracy of the Rothermel (1972) spread model, as well in as our reformulation. Rethinking the concept of propagating flux ratio and engineering into it a more systematic evaluation of the roles of radiation, convection, flame contact, and ignition-point transfer to fire spread will be an important step in developing improved spread models in the future. This limitation is acknowledged by Andrews and Queen (2001), noting an improved approach advanced by Catchpole et al. (2002) that could be incorporated into future models.

The value of ξ reported by Rothermel (1972) varies from about 0.03 to 0.20, an empirical observation that does not adjust for the relative importance of heat-transfer mechanisms under different fuelbed configurations or environmental conditions. We have done nothing to improve the estimate of ξ other than to simplify its calculation without compromising its accuracy by regressing the parameter on the product of the effective heating number and the packing ratio β, which we call the *effective packing ratio*, β_ε.

Fig. 1. Recalculation of Rothermel's (1972) propagating flux ratio (ξ) by regression of his data on effective packing ratio (β_ε).



$$[5] \qquad \xi = 0.03 + 2.5\beta_\varepsilon$$

This new fit of this curve combines three sets of data (Fig. 1) rather than using Rothermel's (1972) individual curve fits for each size-class.

Potential reaction intensity at optimum packing ratio and oven-dry conditions $(\Gamma'_{\mathrm{max}\sigma} w_{\mathrm{n}} \eta_{\mathrm{s}} h)$

In the calculation of potential reaction intensity, we suggest no departures from Rothermel (1972) other than rearranging the terms to yield a factor that expresses reaction intensity at 0% moisture conditions and at an optimum packing ratio (i.e., air-to-fuel ratio) that provides the most efficient combustion environment (as measured by heat release rate). All of the terms are as defined by eq. 3. Users of FCCS have the option of employing defaults for mineral content and heating value or applying specific values for each fuelbed component.

Reaction efficiency and heat-sink density $(\eta_{\beta'}/\rho_{\mathrm{b}}\varepsilon_{\mathrm{FRANDSEN}})$ revised to $(\eta_{\Delta'}/\rho_{\mathrm{b}}\varepsilon_{\mathrm{FCCS}})$

The denominator of this factor represents the density of the heat sink, expressed as mass per unit of fuelbed volume that must be preheated and dried prior to ignition. Rothermel (1972) also defined the denominator as "the amount of fuel involved in the ignition process is the effective bulk density (ρ_{be})". A key term in the heat sink calculation is the estimate of the effective heating number, as described by Frandsen (1973). This term represents the proportion of a fuel element that must be preheated and dried for ignition. His exponential fit of measured ε in the experiments involving 0.64 and 1.27 cm cribs is shown in eq. 6.

$$[6] \qquad \varepsilon_{\mathrm{FRANDSEN}} = \exp(-4.53/\sigma)$$

It was not possible for Frandsen to measure the effective heating number in experiments using excelsior, so the fit was limited to the two points representing crib data.

Any number of curves could be used to fit two data points, therefore, the choice of curve form depends on one's perception of the physical reality that is being modeled by the curve. Frandsen's implicit assumption was that $\varepsilon = 1$ only when σ is infinitely large, that is, when the characteristic fuel element thickness is 0. That assumption is consistent with Anderson's (1969) characterization of flaming as a surface process and with Rothermel's (1972) formulation for heterogeneous fuels by surface-area weighting of fuel classes and categories to obtain a characteristic surface-to-volume ratio.

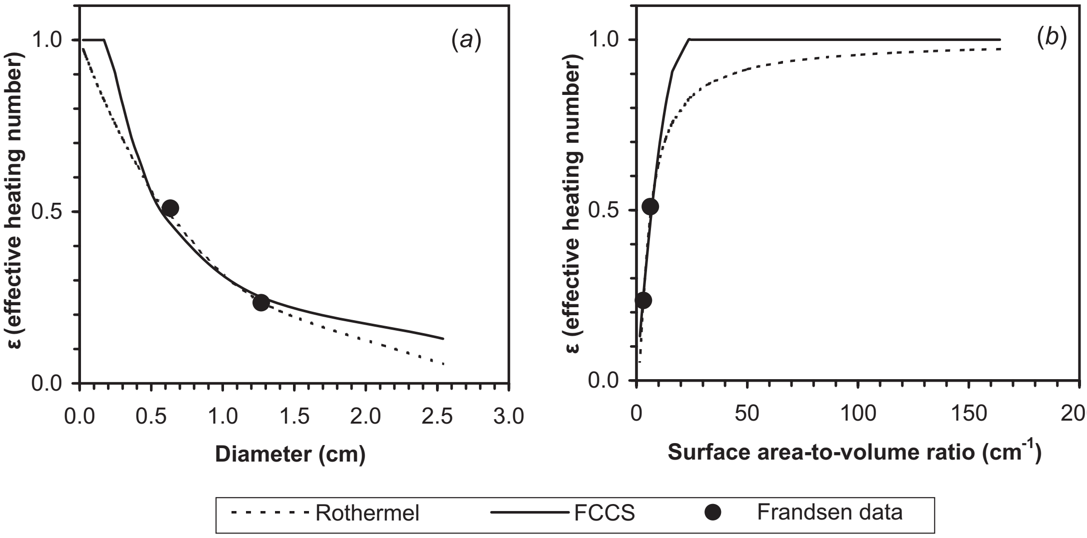
An alternative assumption is that there is some nonzero finite ignition thickness or particle radius (hereafter ς_{I}) below which the entire fuel element is heated before ignition, and therefore yields an ε value of 1. Wilson (1990) discussed this concept, crediting his discussions with Frandsen, and estimated the heated surface thickness of *thermally thick* fuel elements to be 0.11 cm, corresponding to a cylindrical fuel element with that radius. Fuel elements of smaller radius are defined as *thermally thin*. In fire management jargon, such fuel elements may also be called "flash fuel", but only if arranged so that the availability of oxygen to support combustion is not limiting.

A value of $\varsigma_{\mathrm{I}} = 0.085$ cm (~1/32 in.) provides the best agreement with Frandsen's two crib data points, therefore, we used that value to represent both the heating thickness of a "shell" for thermally thick fuel elements and the radius of the largest flash fuel, and multiplied by ρ_{b} to calculate the heat sink density. In other words, where *d* is the diameter of a fuel cylinder (cm):

$$[7] \qquad \varepsilon_{\mathrm{FRANDSEN}} = \varepsilon_{\mathrm{FCCS}} = [d^2 - (d - \varsigma_I)]^2/d^2$$

only when $\varsigma_{\mathrm{I}} = 0.085$ cm.

Fig. 2. Comparison of the effective heating number, ε, derived by Frandsen (1973) with that calculated by the Fuel Characteristic Classification System (FCCS), assuming that a shell of reaction thickness ς_I = 0.085 cm (or the particle radius, if <0.085 cm) is heated. (*a*) Comparison between effective heating number and diameter; (*b*) comparison between effective heating number and surface area-to-volume ratio. Highlighted data points refer to Frandsen's (1973) 0.64 and 1.27 cm crib data.



The change from the ς_I = 0 cm used to calculate $\varepsilon_{\mathrm{FRANDSEN}}$ to the ς_I = 0.085 cm used to calculate $\varepsilon_{\mathrm{FCCS}}$ is significant because it increases the calculated heat sink (the estimated energy required to heat flash fuels prior to ignition). The two approaches are illustrated in Fig. 2.

Anderson (1969) found that fire intensity was strongly influenced by fuelbed porosity, expressed as the ratio of fuelbed void volume to fuel particle volume, and identified an optimum value that resulted in the highest mass loss rate in experimental fires. Rothermel (1972) introduced the similar concept of a packing ratio β, the proportion of fuelbed volume occupied by solid fuel elements. He also concluded that there is some optimum volume of air entrained in the fuelbed that produces the highest possible reaction velocity. If there is excess air or shortage of air entrained, then there is less efficient combustion. He experimentally established an optimum packing ratio (β_{op}) as a function of fuel particle size, and defined relative packing ratio (β') as a ratio of β to β_{op}. $\eta_{\beta'}$was evaluated experimentally by Rothermel as a function of β' such that

$$[8]\qquad \eta_{\beta'} = \Gamma'/\Gamma'_{\max} = \beta'\exp(1-\beta')^{A}$$

where A is an empirical function of σ ranging from ~0.2 to 1.0 that reduces the sensitivity of $\eta_{\beta'}$ to β' for large values of σ.

Rothermel's calculation of β_{op} reflects the assumptions used in calculating $\varepsilon_{\mathrm{FRANDSEN}}$ in that β_{op} approaches 0 at very small fuel diameters. We reexamined Rothermel's (1972) data and determined that the ratio of incorporated air to the volume of heated fuel at ignition for Frandsen's validation data at β_{op} was about 45:1. In other words, at the two data points where he identifies optimum packing, the air incorporated in the fuelbed has 45 times the volume of the reactive shell around the fuel sticks, assuming ς_I = 0.085 cm. Because thermally thin fuels are completely heated at ignition ($\varepsilon_{\mathrm{FCCS}} = 1$), they should all have the same value for β_{op} such that

$$[9]\qquad \beta_{\mathrm{op}}\varepsilon_{\mathrm{FCCS}} = \beta_{\mathrm{op}}(\text{flash fuels}) = 1/45 = 0.022$$

The Rothermel (1972) and FCCS approaches to estimating β_{op} are compared in Fig. 3.

Another way to visualize the idea of packing ratio is to accept that a fuelbed containing any solid fuel volume has an optimum depth, and the ratio of that optimum depth (δ_{op}) to the measured depth (δ) provides a relative depth (Δ') equivalent to β' and an equivalent measure of efficiency ($\eta_{\Delta'} = \Gamma'/\Gamma'_{\max}$). Whether one is more comfortable visualizing optimum depth or optimum packing is a matter of preference. We used the depth-based notation to distinguish between how FCCS calculates optimum depth from how Rothermel (1972) calculates optimum packing.

We offer that the optimum depth of a fuelbed is 45 times the reactive volume of fuels plus the particle volume of fuels per unit area.

$$[10]\qquad \delta_{\mathrm{op}} = 45(w_{\mathrm{n}}\varepsilon_{\mathrm{FCCS}}/\rho_{\mathrm{p}}) + (w_{\mathrm{n}}/\rho_{\mathrm{p}})$$

Each unit mass loading (1 kg·m^{-2}) of flash fuels and of the reactive shell on larger fuels, assuming a particle density of 513 kg·m^{-3}, would require a fuelbed depth of 8.8 cm (in English units, each lb·ft^{-2} would require a 1.4 ft depth) to be optimal. Figure 4 compares the optimum depth for unit loadings over a range of fuel diameters based on FCCS versus the Rothermel (1972) calculation. Note that stylized fuel models used to drive applications of Rothermel's model have a characteristic surface area-to-volume ratio ranging from 38 to 126 cm^{-1}, all within the same range, although the two methods of establishing optimum fuelbed depth are considerably different. Fire behaviour prediction system (FBPS) fuel model 1 (grass), for example, has a $\bar{\sigma} = 115$ cm^{-1}, so that Rothermel's (1972) formulation would assign an optimum fuelbed depth more than 5 times that of the FCCS calculation for the same fuel load.

$\eta_{\Delta'}$, reflecting the damping effect of nonoptimal fuelbed depth in any layer or stratum, is represented in our revision as

Fig. 3. Comparison of optimum packing ratios between Rothermel's (1972) formulation and two alternative Fuel Characteristic Classification System (FCCS) formulations. Only the ignition thickness of 0.085 cm was used. The important differences are in the flash fuels (diameter $\leq 2\varsigma_I$) and in large fuels (diameter > 10 cm).

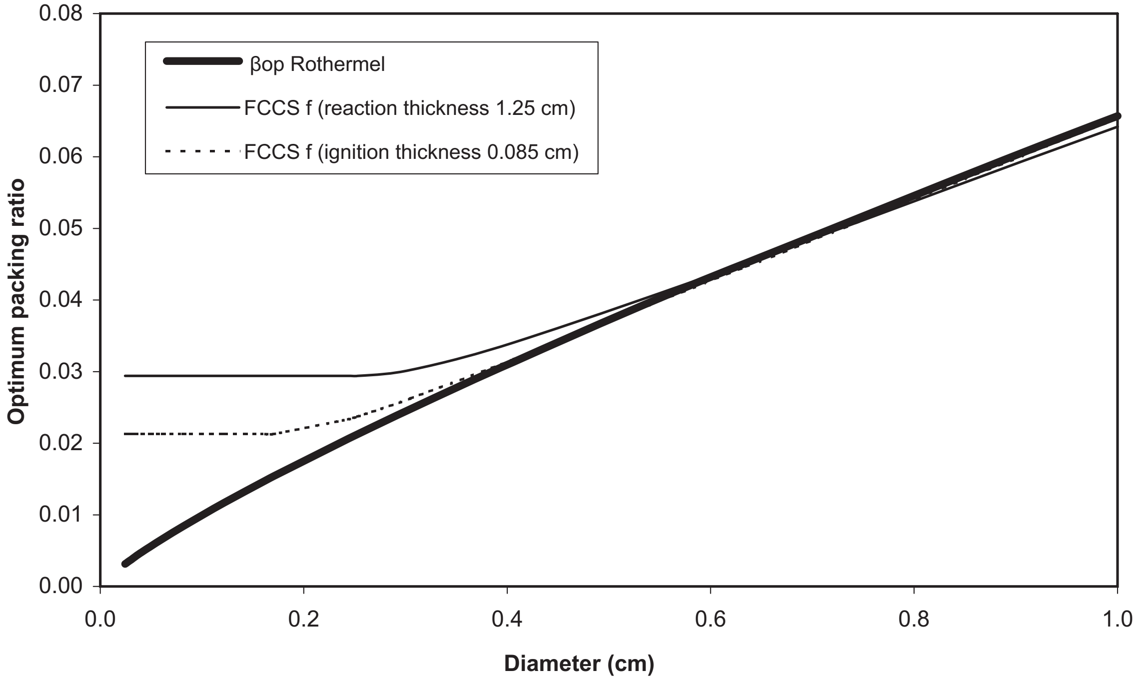
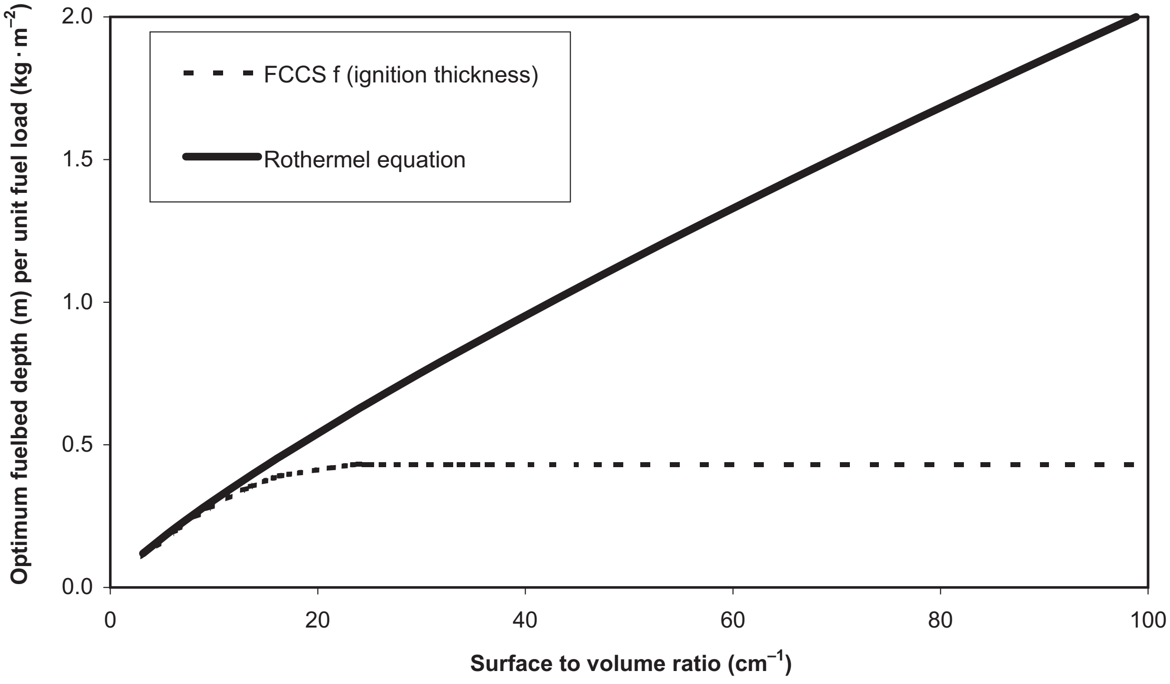


Fig. 4. Comparison of optimum fuelbed depth (δ_{op}) between Rothermel's (1972) formulation and two alternative Fuel Characteristic Classification System (FCCS) formulations. Only the ignition thickness of 0.085 cm was coded. Particle density (ρ_p) is 14.5 kg·m^{-3} (32 lb·ft^{-3}). Important differences are in the flash fuels (diameter $\leq 2\varsigma_I$) or when $\sigma \geq 24$ cm^{-1} (714 ft^{-1}). The original 13 fire behaviour fuel models have 34 cm^{-1} (1050 ft^{-1}) $\leq \bar{\sigma} \leq 115$ cm^{-1} (3500 ft^{-1}).



$$[11] \qquad \eta_{\Delta'} = [\Delta' \exp(1 - \Delta')]^A$$

the same function used by Rothermel to calculate reaction efficiency based on, but distinguished from the different method that FCCS uses to characterize ε_{FCCS} and δ_{op}. The possible range of values for Γ'_{max} is reduced by the FCCS methodology, which constricts the range of fuel element thickness under consideration to $<2\varsigma_I$, thus limiting Γ'_{max} to a range of 12 to 16 min^{-1} based on Rothermel's evaluation of Γ'_{max} as a function of fuel diameter.

Reaction thickness (ς_R) represents the depth of thick fuel elements that are liberating pyrolized gases within the reaction zone, and is therefore part of the heat source. In contrast, the ignition thickness is that portion heated at the time of ignition and therefore involved in the heat sink only up to the time of ignition. Rothermel (1972), Frandsen (1973), and Wilson (1990) apparently all assumed that the thickness of the reactive shell (ς_R) was equal to the ignition thickness (ς_I). That may be true, and we have implicitly accepted that assumption in the calculation of δ_{op}. Otherwise, one could conclude that the air-to-fuel ratio would shrink to 33:1 if, for example, ς_R = 1.5 cm and ς_I = 0.128 cm. It is reasonable to expect that a slightly greater shell thickness is involved in the reaction zone than in the ignition zone (that is, $\varsigma_R > \varsigma_I$). The numerical effect of the difference on heat sink is negligible, except in rare cases, and is not discussed further here. Independent laboratory testing is ongoing to refine this estimate, which will be important in future formulations.

Moisture damping coefficient and heat of ignition (η_M/Q_{ig})

We rearranged the terms (equation 4) in Rothermel's (1972) spread rate framework to allow separation of the effects of intrinsic physical fuel characteristics from the more variable and less well understood (and less manageable) environmental conditions of moisture, wind speed, and slope. Given the lack of scientific consensus on the behaviour of fires affected by fuel moisture, this framework allows the flexibility to incorporate future improvement or consensus.

Rothermel (1972) postulated a moisture damping coefficient η_M, as a ratio of the reaction intensity at any moisture content (M_f), $I_R(M_f)$, to the reaction intensity in an oven-dry condition, $I_R(M_f = 0)$, which acts to reduce reaction velocity below its potential value. The value of η_M for a range of moisture contents in dead-fuel cribs was determined experimentally in the laboratory by fitting a polynomial

$$[12] \qquad \eta_M = 1 - 2.59\frac{M_f}{M_x} + 5.11\left(\frac{M_f}{M_x}\right)^2 - 3.52\left(\frac{M_f}{M_x}\right)^3$$

where M_x is the moisture content of extinction at which the fire will not spread. The value of M_x was assumed without experimental determination to be ~0.30 by Rothermel, but applications of the model since that time have treated it as a variable determined by fuel type ranging from 0.12 to 0.40 (Scott and Burgan 2005) to adjust model outputs.

The heat of ignition (Q_{ig}, kJ·kg^{-1}) is the heat required per unit mass to evaporate moisture, increase fuel temperature, and liberate pyrolysis gases before ignition occurs. When multiplied by heat-sink density, $Q_{ig}\rho_b\varepsilon$ (kg·m^{-3}), the result is heat sink per unit volume. Heat of preignition was included implicitly in the development of η_M, so is counted both as affecting heat source and heat sink.

The above empirical work on moisture damping was done with dead fuels. Rothermel (1972) incorporated a purely theoretical heat-balance formulation by Fosberg and Schroeder (1971) for predicting the moisture of extinction of living fuels based on the ratio of living-to-dead fuels and the moisture content of fine dead fuels. No experimental evidence was gathered. Their purpose was to include herbaceous fuels in the National fire danger rating system. An assumption that dead fuels have an $M_{x.1} = 0.25$ is explicit in their calculation of the excess heat that is available to raise living fuels to ignition temperature, as is the assumption that moisture is liberated from live fuels with the same amount of energy as if they were dead. Theirs is a useful graphical solution based on this assumption and is equivalent to calculating a heat-sink term for living and dead fuels separately.

Currently our reformulation incorporates the polynomial moisture-damping equations of Rothermel (1972) for both dead and live fuels, without great confidence that they represent the best current science. We arbitrarily set the moisture contents of extinction as 0.25, 1.2, and 1.8, respectively, for dead fuel (including litter), live nonwoody fuel, and live shrubs. This approach is equivalent to weighting the moisture damping of the fuelbed components by the volume of fuel preheated to ignition (rather than by fuel surface area) in each fuelbed component. This allows us to compare model results and provides users with a model version that behaves similarly to applications of Rothermel's (1972) model. In the future, we encourage the substitution of other options for modeling moisture damping.

Options to account for moisture damping coefficient and heat of ignition (η_M/Q_{ig})

Wilson (1990) revised the experimental method used by Rothermel (1972) and revised the moisture-damping coefficient as a ratio of the rate of spread with and without moisture. As summarized by Weise and Biging (1997), the effect is to parse out the heat of ignition Q_{ig}, into the sum of the heat of pyrolysis (Q_f) and the heat of vaporization ($Q_M M_f$) to derive $Q_{ig} = Q_f + Q_M M_f$, a function of fuel moisture content (kJ·kg^{-1}). Wilson (1990) also accounted explicitly for the enthalpic moisture load and removed the effect of Q_{ig} from the sink term by assuming that fuel in the reaction zone was already dry. The most significant change was to divorce moisture damping from fire extinction. His simplified equation, $\eta_{M.WILSON} = \exp(-M_f/M_c)$, introduced a new variable of characteristic moisture content M_c that, in Wilson's opinion, varies with both the size and physiology of different fuels. Wilson did not offer a predictive equation per se, but published his data knowing that others could "satisfy pragmatic needs for such a predictive equation by model builders of fire predictive systems." Catchpole et al. (1998) endorsed Wilson's logic in observing an exponential decay of spread rate with increasing fuel moisture and greater moisture damping in sticks rather than in thermally thin needles and excelsior.

Rothermel's (1972) observation that "the exact effect of moisture has not been adequately explained in terms of reaction kinetics'' is still true over 30 years later. There is no well-accepted or fundamentally based model for moisture damping of reaction intensity or rate of spread, although many empirical observations exist. Much less information is available for fuelbeds that include shrubs and nonwoody live fuels. We hope that future developers can modify the treatment when new knowledge about the energy required to liberate moisture from fuel elements with different physiologies becomes available.

Wind speed and slope multiplication coefficients $(1 + \varphi_{\mathrm{W}} + \varphi_{\mathrm{S}})$

Coefficients that account for the combined effects of wind speed and slope act as a multiplier on the basic no-wind spread equations presented by Rothermel (1972). Reaction intensity is not considered affected by wind speed or slope in his framework. The form and evaluation of all of these coefficients have been called into question by other investigators (e.g., Wilson 1990; Weise and Biging 1997; Catchpole et al. 2002). Rothermel's wind speed multiplication factor (φ_{w}) is empirically derived from laboratory observations in excelsior and 0.635 cm diameter sticks and is combined with field data in grass fires obtained from McArthur (1968*a*, 1968*b*). The factor φ_{w} is a complex and somewhat controversial function of fuel size (represented by $\bar{\sigma}$), β', and midflame wind speed (U) such that

$$[13] \qquad \varphi_{\mathrm{W}} = CU^B/(\beta')^E$$

where C, B, and E are functions of $\bar{\sigma}$.

There is some disagreement over the exponent B, which is an exponent on the wind speed. The coefficient B exceeds the value of 2 when $\bar{\sigma}$ exceeds 107 cm^{-1}, meaning that fire spread rate increases with the square of the increase in wind speed for fine fuels such as grass. Rothermel's value of B = 1 (i.e., linear) when $\bar{\sigma} = 6.3$ cm^{-1} and with less than the square root (i.e., $B < 0.5$) of the increase in wind speed for 0.64 cm diameter stick fuelbeds. This extreme dependence on characteristic fuel size has not been validated by other researchers, most of whom have observed a linear or only slightly exponential response in spread to wind speed in fine fuelbeds (e.g., grass, litter, or excelsior) (Nelson and Adkins 1986; McCaw 1997; Catchpole et al. 1998). A fire behaviour prediction system in Australia uses a value of B = 1.1 (McCaw 1997). There is no perfect agreement among investigators, but the range of B that fits their observations seems to fall between 1.0 and 1.2. Pagni and Peterson (1973) report a value of B = 0.8 in pine-needle fuelbeds. FCCS uses a default value of B = 1.2, but allows a user to input other values to conform to other model systems.

We compare outputs with the applications of Rothermel (1972) based on a default wind speed of 1.79 m·s^{-1} (4 mi.·h^{-1}) to avoid controversy over the effect of $\bar{\sigma}$, because there is mathematical agreement, regardless of $\bar{\sigma}$, that CU^B is always near a value of 9.4 ($CU^B = \phi_{\mathrm{w}}\ \beta'^E \approx 9.4$) at that windspeed when $\beta' \approx 1$. One may observe this agreement in Rothermel's (1972) application (see figure 20 in his work) or by verifying that the influence of C and B cancel each other out at that wind speed for all values of σ. It is also true that $CU^B = \phi_{\mathrm{w}} \approx 9.4$ when $\beta' = 1$. We hope to explore alternative wind-effect approaches in the future, but for this work we have used

$$[14] \qquad \left(1 + \varphi_{\mathrm{W(FCCS)}}\right) = C_U(1 + \beta'^{-E})(U/U_{BMU})^B = 9.4(1 + \Delta'^{-0.52})(U/1.79)^B$$

where $(1 + \varphi_{\mathrm{W(FCCS)}})$ is the wind speed multiplication factor (dimensionless), C_U is the wind speed multiplication constant (C_U = 9.4 at U_{BMU} = 1.79 m·s^{-1}), β' is the relative packing ratio (dimensionless), E is the effect of β' on wind speed multiplication, U_{BMU} is the benchmark wind speed, 1.79 m·s^{-1} (4 mi.·h^{-1}), $\Delta'^{-0.52}$ is the effect of relative fuelbed depth ($\Delta' = \delta_{\mathrm{op}}/\delta$) on wind speed multiplication, and B is the variable exponent expressing the σ effect of multiplication.

Rothermel (1972) found the slope factor to be proportional to the square of the slope and weakly dependent on β.

$$[15] \qquad \varphi_{\mathrm{S}} = 5.3(\tan \mathrm{slope})^2\beta^{-0.3}$$

Rothermel's experiments used excelsior fuels only, therefore in this case, β_{ε} and β are the same. Our reformulation does not yet have the capability to input slope. The user may apply eq. 14 to the no-slope case or combine the effects of slope and wind speed into an "effective wind speed" as described by Viegas (2004) or Margerit and Séro-Guillaume (2002). Weise and Biging (1997) discuss the interaction of wind speed and slope in a qualitative comparison of several fire spread models and point out the strengths and weaknesses of each approach. For now, they favor the approaches taken by Albini (1976) and by Pagni and Peterson (1973) over that taken by Rothermel (1972).

Flame length

Flame length (FL, m) was derived as the product of reaction intensity, residence time, and rate of spread as in Byram (1959) and Albini (1976).

$$[16] \qquad \mathrm{FL} = 0.045(I_{\mathrm{R}}R\tau_{\mathrm{FL}})^{0.46}$$

where 0.045 is the observed constant of proportionality (min·kJ^{-2}) and τ_{FL} is the flame residence time (min).

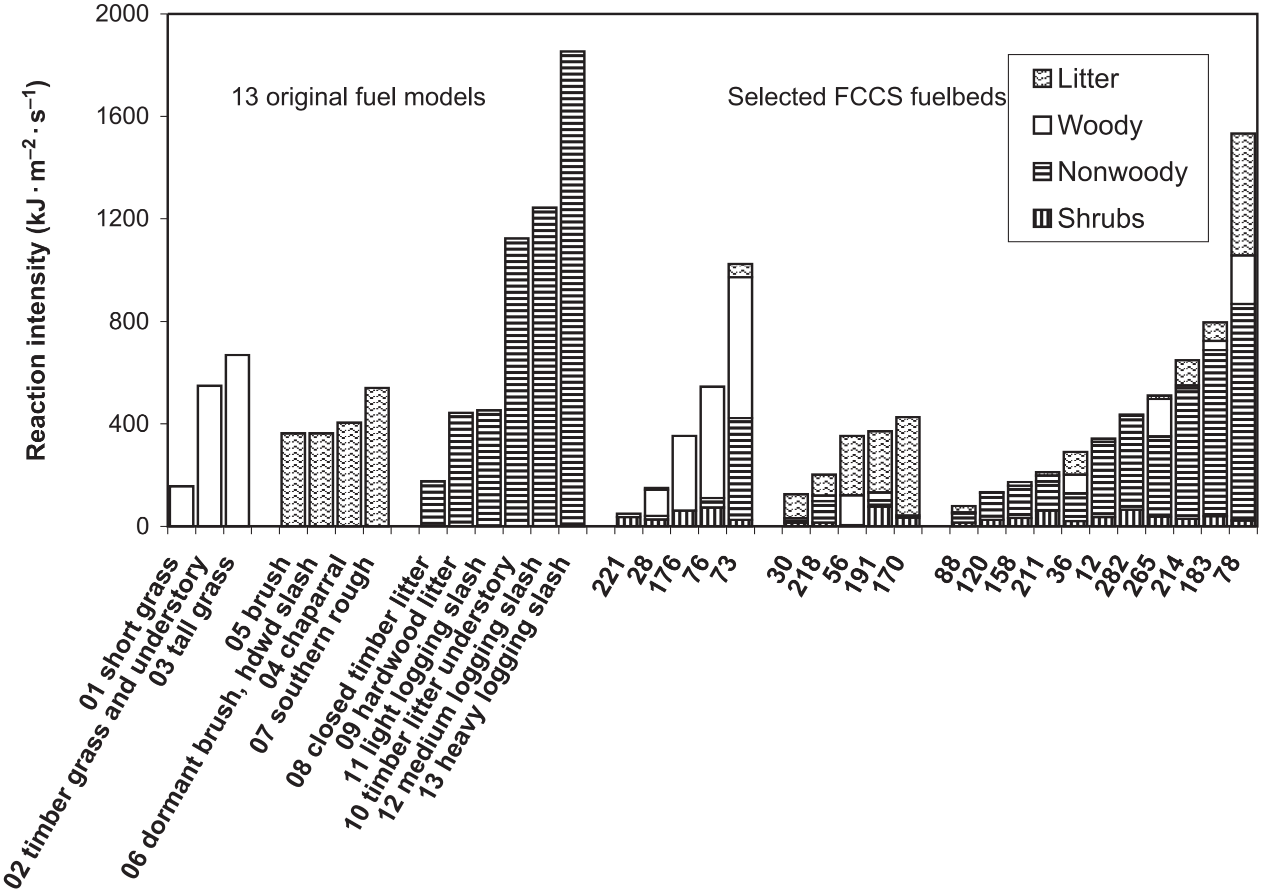
Recent investigations (e.g., Weise 1996) have questioned its predictive accuracy, but we employ it temporarily for consistency with current applications of Rothermel (1972).

Formulation of a spread model

Having evaluated coefficients for reaction intensity and spread rate in homogeneous fuel arrays, Rothermel (1972) formulated a spread model for heterogeneous fuel arrays of *n* discrete fuel size-classes (e.g., 2.5–7.6 cm diameter) and *m* fuel categories (e.g., live versus dead fuels). The formulation provided weights of the influence of dissimilar fuel elements based on their surface area to create a virtual uniform and homogenous fuelbed that can be described by a single set of inputs to the spread equations. The formulation is purely conceptual and is not validated by experimental or synthetic data. Many investigators have since compared predictions with observed fire behaviour with mixed success. Our immediate purpose is to include a model reformulation in the FCCS with the capability to predict surface fire behaviour similar to that of applications of Rothermel, but the formulation may later find other applications independent of FCCS. In the future, we will amend the formulation by including other spread equations to compare predictions with independent observations of fire behaviour.

Here, we present an alternative formulation for multicomponent fuelbeds that weights the influence of the fuel mass involved, rather than fuel surface area, in the first stage of flaming combustion of each fuelbed component. More importantly, we do not homogenize the bulk properties of each component into a single virtual fuelbed. We evaluate the role of each component separately, and then combine the energy sources and sinks. In future work, we will extend

Fig. 5. Predicted reaction intensity for 13 original fuel models in three groups (grass, shrub, and timber litter – slash) using BehavePlus (Andrews et al. 2005) compared with predicted reaction intensity using our reformulation of Rothermel's (1972) model for a random selection from all 216 Fuel Characteristic Classification System (FCCS) fuelbeds (Riccardi et al. 2007) stratified according to the fuelbed strata contributing most to reaction intensity. FCCS fuelbed 12, red fir – mountain hemlock – lodgepole pine – white pine forest; fuelbed 28, ponderosa pine savanna; fuelbed 30, turbinella oak – mountain mahogany shrubland; fuelbed 36, live oak – blue oak woodland; fuelbed 56, sagebrush shrubland; fuelbed 73, koa – pukiawe forest; fuelbed 76, slash pine – molasses grass forest; fuelbed 78, Florida hopbush – Mauna Loa beggarticks shrubland; fuelbed 88, black spruce – sphagnum moss forest; fuelbed 120, oak – pine – mountain laurel forest; fuelbed 158, loblolly pine – shortleaf pine – mixed hardwoods forest; fuelbed 170, pond pine – little gallberry – fetterbush shrubland; fuelbed 176, smooth cordgrass – black needlerush grassland; fuelbed 183, loblolly pine – shortleaf pine forest; fuelbed 191, longleaf pine – slash pine – gallberry forest; fuelbed 211, interior ponderosa pine forest; fuelbed 214, grand sequoia – white fir – sugar pine forest; fuelbed 218, Gambel oak – sagebrush shrubland; fuelbed 221, wheatgrass – ryegrass grassland; fuelbed 265, balsam fir – white spruce – mixed hardwood forest; and fuelbed 282, loblolly pine forest.



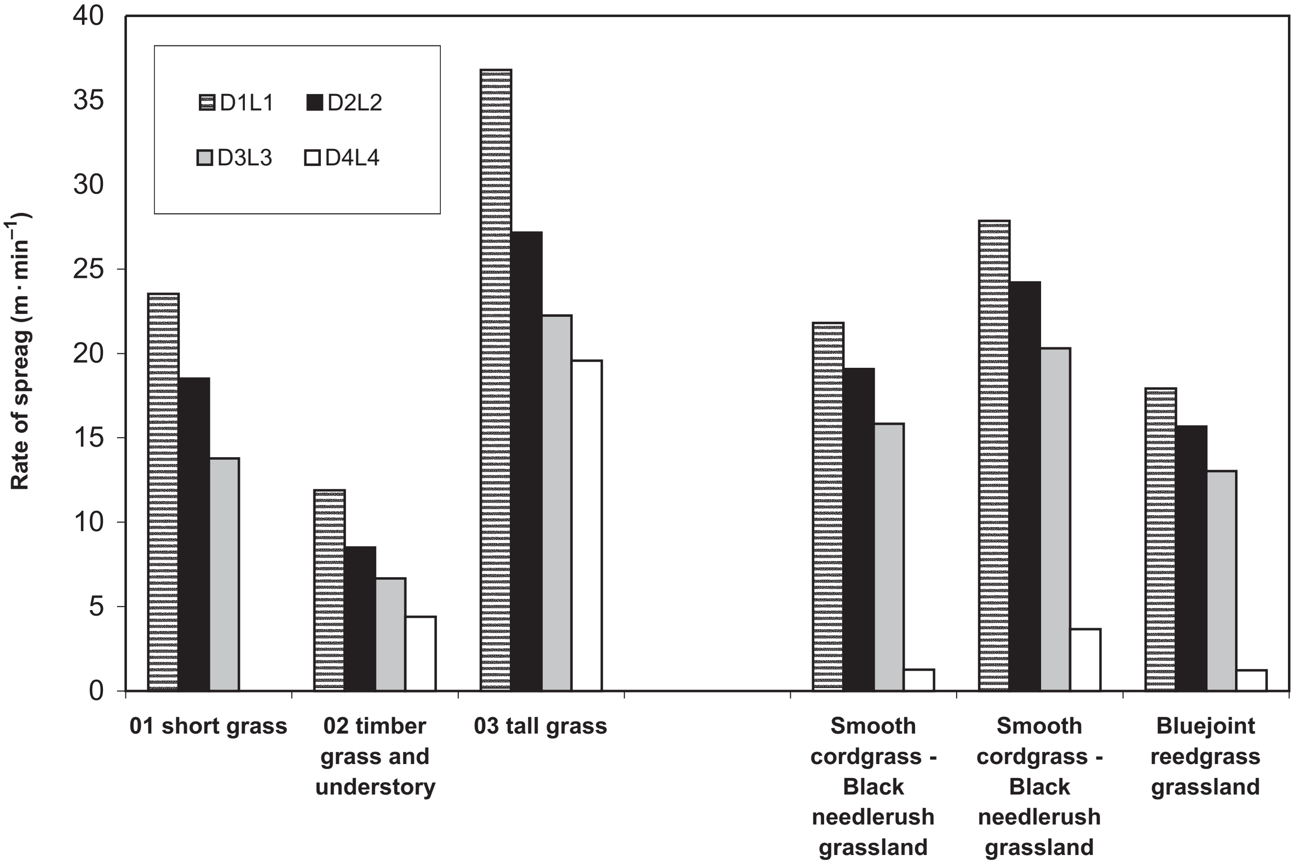
this reformulation to include measures of variability to represent spatially nonuniform and discontinuous fuelbeds.

The most significant difference between spread rate formulations in the FCCS and those by Rothermel (1972) is that in FCCS, heat sink is not considered to be well represented by a single homogeneous fuelbed. In other words, the shrub, nonwoody, woody, and especially, the litter–lichen–moss strata, do not exhibit a single representative value for area coverage (θ), δ (or ρ_b), ρ_p, ς_i (or $\bar{\sigma}$), or M_f. We consider it is more likely that each fuelbed component acts separately as a heat sink according to its own properties and arrangement. The reformulation need not be limited to the four fuelbed components currently used, but these are the only components we consider useful at present. Finally, in the rate of spread equation, we allow that fuelbed components do not uniformly cover the entire fuelbed area or that the total cover of each component is equal to 100%, and have replaced the heat sink with the sum of individual heat sinks as follows

$$[17] \quad R_{\mathrm{FCCS}} = \frac{I_R \xi (1 + \varphi_W + \varphi_S)}{\sum_{i=1}^{4} (\theta \rho_b \varepsilon_{\mathrm{FCCS}} Q_{\mathrm{ig}})} \quad \text{or}$$

$$R_{\mathrm{FCCS}} = \frac{I_R \xi (1 + \varphi_{\mathrm{W.FCCS}})}{(\mathrm{FAI} \varsigma_{\mathrm{I}} \rho_{\mathrm{p}} Q_{\mathrm{ig}} / \delta)_{\mathrm{woody}} + (\theta \rho_{\mathrm{b}} Q_{\mathrm{ig}})_{\mathrm{nonwoody}} + (\theta \rho_{\mathrm{b}} Q_{\mathrm{ig}})_{\mathrm{shrub}} + (\theta \eta_{\Delta'} \rho_{\mathrm{b}} Q_{\mathrm{ig}})_{\mathrm{LLM}}}$$

Fig. 6. Predicted rates of spread at a midflame wind speed 1.79 m·s^{-1} for three original fuel models in the grass using BehavePlus (Andrews et al. 2005) compared with predicted rates of spread using our reformulation of Rothermel's (1972) model for three of 216 Fuel Characteristic Classification System (FCCS) fuelbeds (Riccardi et al. 2007) with a spread rated most similar to fuel model 1 (short grass). Comparison was made at four "moisture scenarios" of dead fuel moisture, herbaceous (nonwoody), and live (shrub) fuel moisture contents as shown in the figure legend.

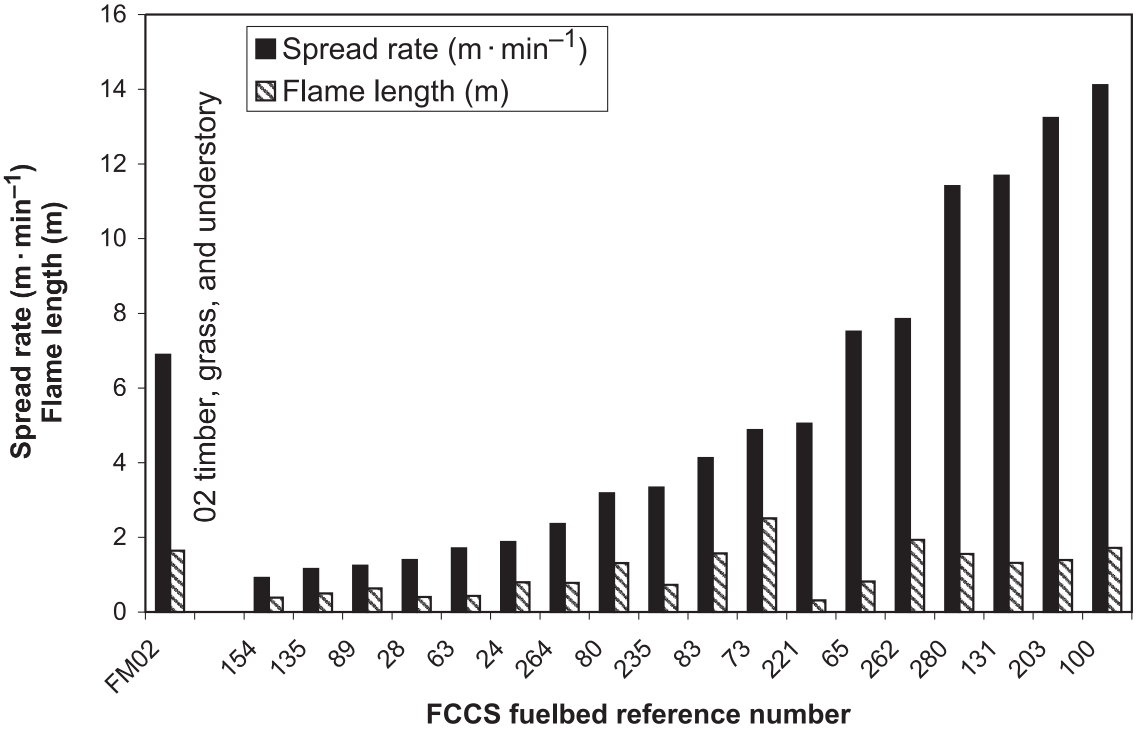


where R_{FCCS} is the rate of spread using the FCCS reformulation of Rothermel's (1972) application (m·min^{-1}), FAI is the fuel area index of dead woody fuels (the fuel surface area per unit of ground surface area; m^{2}·m^{-2}); the subscript *i* represents the individual fuelbed component, θ_i is the proportion of ground surface area occupied by the fuelbed component (m^{2}·m^{-2}), Δ' is the ratio of fuel stratum depth relative to the optimum depth for absorbing propagating energy flux; assumed to be equal to β' for densely compacted strata (i.e., $\beta' > 1$), particularly for the litter–lichen–moss stratum, LLM is the litter–lichen–moss component, and $\eta_{\Delta'\text{LLM}} = \eta_{\beta'\text{LLM}}$ is the absorption efficiency of the litter–lichen–moss (LLM) stratum, assumed to be equal to reaction efficiency.

Several assumptions or conclusions that are implicit in eq. 17 deserve explanation. First, we assume that only the woody fuelbed stratum contains thermally thick elements, that is, fuel elements that are larger in radius than the ignition thickness. Fuel elements in the other strata are assumed to be thermally thin, so that the entire element is heated to ignition temperature. Second, the mass of the heated volume of thick fuel elements is roughly equal to their surface area density (FAI) times the ignition thickness, ς_{i}, times the fuel particle density, ρ_{p}. FAI is analogous to the (two-sided) leaf area index commonly used in ecological descriptions. These are the strata for which $\varepsilon_{\text{FCCS}} = 1$, so ε disappears from those terms. Third, the LLM component is sufficiently densely packed that it forms an inefficient energy-absorbing stratum. This means that only the fraction of the LLM stratum nearest the surface absorbs energy before the stratum is ignited, and (in absence of better evidence) that fraction is equal to the mass fraction of LLM involved (i.e., combusted) in the reaction zone, $\eta_{\Delta'\text{LLM}} = \eta_{\beta'\text{LLM}}$. We estimated $\eta_{\Delta'\text{LLM}}$, as a function, $\eta_{\Delta'} = \Delta'_{\text{LLM}} \exp(1 - \Delta'_{\text{LLM}})$, of the ratio of optimum litter depth to reactive litter depth, where optimum litter depth would provide an air–fuel ratio of 45:1 within the LLM stratum. R.D. Ottmar (personal communication 2005) used field data from 25 years of consumption experiments to develop a table of reactive LLM depths and reactive LLM fuel loads for a range of litter, moss, and lichen morphologies for the FCCS calculator. Finally, not all strata (notably the shrub and nonwoody strata) are likely to cover the entire ground surface area, so their heat sink is assumed to be linearly proportion to their areal coverage, θ_i.

Surface fuelbed depth, δ_{surface}, for the purpose of calculating reaction efficiency, is calculated as the mean depths of measured woody, nonwoody, and shrub strata, and weighted by their cover, θ_i, and reactive fuelbed volume $\Upsilon_{\text{R}.i}$. FCCS uses Δ' rather than β' as a starting point for estimating reaction efficiency. The two parameters would be numerically equal if we had not altered the calculation of ε.

Fig. 7. Sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 2 (timber, grass, and understory) at fuel moisture scenario D2L2 (6%–1/2% dead fuel and litter, 30% nonwoody fuel moisture, and 60% shrub fuel moisture), midflame wind speed of 1.79 m·s^{-1}. FCCS fuelbed 24, Pacific ponderosa pine – Douglas-fir forest; fuelbed 28, interior ponderosa pine – limber pine forest; fuelbed 63, showy sedge – alpine black sage grassland; fuelbed 65, purple tussockgrass – California oatgrass grassland; fuelbed 73, koa – pukiawe forest; fuelbed 80, fountain grass grassland; fuelbed 83, molasses grass grassland; fuelbed 89, black spruce – sheathed sedge cottonsedge woodland; fuelbed 100, altai fescue grassland; fuelbed 131, bluestem – Indian grass – switchgrass grassland; fuelbed 135, eastern redcedar – oak – bluestem savanna; fuelbed 154, bur oak savanna; fuelbed 203, sawgrass – Muhlenbergia grassland; fuelbed 221, wheatgrass – ryegrass grassland; fuelbed 235, Idaho fescue – bluebunch wheatgrass grassland; fuelbed 262, molasses grass grassland; fuelbed 264, post oak – blackjack oak forest; and fuelbed 280, bluestem – Gulf cordgrass grassland.



Reaction intensity

The FCCS predictive equation for reaction intensity is considerably different from Rothermel's (1972) equation

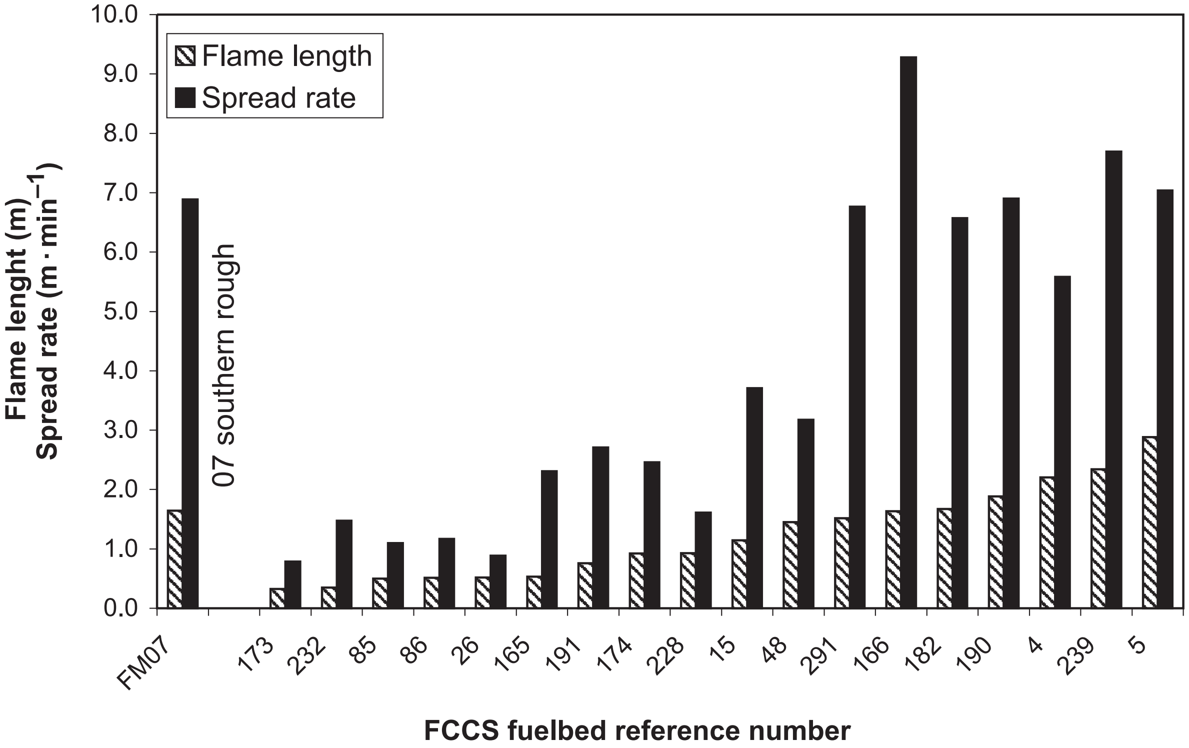
$$[18]\qquad I_{\mathrm{R.FCCS}} = \eta_{\Delta'\mathrm{surface}}\sum_{i=1}^{3}(\Gamma'_{\mathrm{max.FCCS}}\Upsilon_{\mathrm{R}}\rho_{\mathrm{p}}h\eta_{\mathrm{M.FCCS}}\eta_{\mathrm{s}})_i + (\eta_{\Delta'}\Gamma'_{\mathrm{max.FCCS}}\Upsilon_{\mathrm{R}}\rho_{\mathrm{p}}h\eta_{\mathrm{M.FCCS}}\eta_{\mathrm{s}})_{\mathrm{LLM}}$$

where FCCS is a subscript that denotes a variable calculated differently in FCCS than by Rothermel (1972), $\eta_{\Delta'\mathrm{s}}$ is the reaction efficiency (dampening effect of Δ') of the surface fuelbed layer (including woody, nonwoody, and shrub strata, dimensionless), Γ'_{max} is the maximum reaction velocity for the fuel category at optimum fuelbed depth (min^{-1}), $\Upsilon_{\mathrm{R}} = \Upsilon_i\varepsilon_{\mathrm{FCCS}.i}$ reaction volume of fuels involved in the reaction zone (volume per unit ground surface area of fuels that contribute energy forward to unburned fuels) (m^3·m^{-2}), $\eta_{\mathrm{s}} = 0.42$, consistent with 1% silica-free ash content, i is the subscript reference to a single fuelbed stratum in the surface fuelbed layer (shrub, nonwoody, or woody), surface is a subscript reference to the combined surface fuelbed layer (shrub, nonwoody, and woody categories), and $\eta_{\Delta'\mathrm{LLM}}$ is the reaction efficiency of the litter–lichen–moss stratum (dampening effect of Δ', dimensionless).

Reaction efficiency is calculated in FCCS collectively for components of the surface fuelbed layer (shrub, nonwoody, and woody), Γ'_{max}, Υ_{R}, ρ_{p}, h, η_{M}, and η_{s}, and separately for the LLM stratum, $\Upsilon_{\mathrm{R}i}$. Our rationale is that the reaction volumes of all three surface fuelbed strata will combust in one flame zone and therefore they must all share a single reaction efficiency, but that the combustion efficiency in the LLM stratum will be more starved for air and thus burn less efficiently. By separating the two, we provide a way to explicitly include litter characteristics and condition in the calculation of reaction intensity in eq. 18, essentially computing the reaction intensity contribution of the LLM stratum separately and adding it to the reaction intensity contribution of the surface fuelbed layer. We assert that this method is more physically correct and reproducible than the attempt to include litter in stylized fuel models by including it as a virtual 1 h fuel load through expert judgment. We anticipate that a better understanding of combustion of the LLM stratum will improve these calculations in the future.

While we can rationalize that the three surface-layer fuelbed strata combust with a single reaction efficiency, we cannot make the same argument for combining any of the other terms in the calculation of reaction intensity. Therefore, we depart from Rothermel's (1972) formulation by calculating and chain-multiplying $\bar{\sigma}$ separately for each of the three strata in the surface fuelbed layer, then adding them together. This effectively weights the importance of each var-

Fig. 8. A sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 7 (southern rough) at fuel moisture scenario D2L2 and at 1.79 m·s^{-1} midflame wind speed. FCCS fuelbed 4, Douglas-fir – *Ceaonthus* forest; fuelbed 5, Douglas-fir – white fir forest; fuelbed 15, Jeffrey pine – red fir – white fir – greenleaf manzanita – snowbrush forest; fuelbed 26, interior ponderosa pine – limber pine forest; fuelbed 48, Douglas-fir – tanoak – madrone – California bay forest; fuelbed 85, black spruce – lichen forest; fuelbed 86, black spruce – feathermoss forest; fuelbed 165, longleaf pine – three-awned grass – pitcher plant savanna; fuelbed 166, longleaf pine – three-awned grass – pitcher plant savanna; fuelbed 173, live oak – sea oats savanna; fuelbed 174, live oak – sabal palm forest; fuelbed 182, longleaf pine – slash pine – saw palmetto – gallberry forest; fuelbed 190, slash pine – longleaf pine – gallberry forest; fuelbed 191, longleaf pine – slash pine – gallberry forest; fuelbed 228, interior ponderosa pine – limber pine forest; fuelbed 232, mesquite savanna; fuelbed 239, Douglas-fir – sugar pine – tanoak forest; and fuelbed 291, longleaf pine – slash pine – saw palmetto forest.



iable by the reaction volume η_{Mi} of each category rather than by the surface area of each, such as is done when using a characteristic surface-to-volume ratio ($\bar{\sigma}$) for the entire layer. It also has the advantage of allowing the individual calculation of moisture damping coefficients for each component (η_{Mi}), even when that single stratum may be too wet to burn by itself. In other words, the combination of η_{Mi} and h can lead to a negative contribution of energy from an individual fuelbed stratum when compared with the energy required to drive moisture from that stratum. We believe this is a better option than computing a single moisture content of extinction for the entire fuelbed.

If we assume ρ_b = 514 kg·m^{-3}, then we can define δ_{op} in terms of fuel volume.[3] The FCCS calculator (Riccardi et al. 2007) estimates Υ_R as the sum of all flash fuel volumes,

$$[19]\qquad \Upsilon_R = \sum_{i=1}^{3} \Upsilon_{R.i} = \Upsilon_{woody}\varepsilon_{FCCS} + \Upsilon_{nonwoody} + \Upsilon_{shrub} \approx \text{FAI}_{woody}\varsigma_R + \Upsilon_{nonwoody} + \Upsilon_{shrub}$$

roughly equal to the volume of flash fuels plus the product of the surface area of thermally thick fuels, FAI$_{woody}$ loading (kg·m^{-2}), as in Fig. 4. δ_{op} (m) is approximated in FCCS as

$$[20]\qquad \delta_{op}(\text{cm}) = 3.35\text{FAI}_{woody} + 45(\Upsilon_{nonwoody} + \Upsilon_{shrub})$$

Application to the field

The capability to model surface fire behaviour with real-world fuelbed properties, without adjustment, is necessary to provide universally available, objective assessments or comparisons of fuelbeds. With this capability, FCCS provides users with a single set of fuel inputs to fire behaviour and fire effects models and eliminates the individual subjectivity of choosing and adjusting fuel models. Users may categorize fuelbeds based on expected fire behaviour under any set environmental conditions, as well as on inherent fuelbed properties. Comparisons may be made between any number of fuelbeds at any resolution useful to the user.

The US fire management community has relied on stylized fuel models for more than 30 years to obtain reasonable predictions of surface fire spread and intensity for a few

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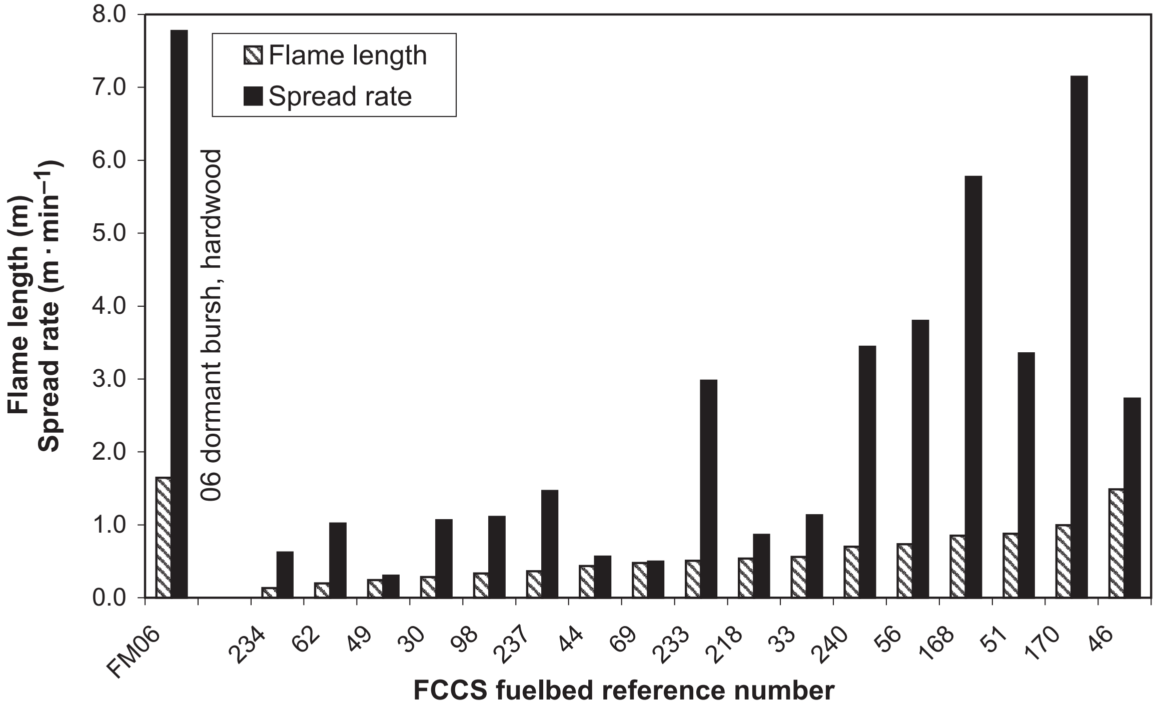
[3] We have caused some confusion here by assuming that the fuel particle density is 514 kg·m^{-3}, although FCCS uses a default particle density of 401 kg·m^{-3} in its other algorithms. We did this because we observed that Rothermel (1972) and Frandsen (1973) assumed the greater particle density in crib-burning experiments, so our argument that an optimum air–fuel ratio exists should use that same assumption.

Fig. 9. A sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 6 (dormant brush) at fuel moisture scenario D2L2 and at 1.79 m·s^{-1} midflame wind speed. FCCS fuelbed 30, turbinella oak – mountain mahogany shrubland; fuelbed 33, Gambel oak – sagebrush shrubland; fuelbed fuelbed 44, scrub oak – chaparral shrubland; fuelbed 46, chamise chaparral shrubland; fuelbed 49, creosote bush shrubland; fuelbed 51, Coast sage shrubland; fuelbed 56, sagebrush shrubland; fuelbed 62, *Vaccinium* – heather shrublands; fuelbed 69, western juniper – sagebrush – bitterbrush shrubland; fuelbed 98, marsh Labrador tea – lingonberry tundra shrubland; fuelbed 168, little gallberry – fetterbush shrubland; fuelbed 170, pond pine – little gallberry – fetterbush shrubland; fuelbed 218, Gambel oak – sagebrush shrubland; fuelbed 233, sagebrush shrubland; fuelbed 234, sagebrush shrubland; fuelbed 237, *Vaccinium* – heather shrublands; and fuelbed 240, saw palmetto – three-awned grass shrubland.



fuelbed characteristics by using applications of the Rothermel (1972) spread model. The fuel-model approach has served the community well over the years by providing a consistent means to predict the relative changes in fire behaviour that will occur if environmental conditions such as wind speed and fuel moisture vary. Although the algorithms that reflect those environmental drivers have come into question, their consistency has been valuable to experienced fire managers. However, using fuel models does not allow automated fire behaviour predictions without subjective adjustment of fuel characteristics, does not reflect the range of characteristics that occur in nature, and is not useful for predicting incremental changes in fire potential that occurs over time or as a consequence of management.

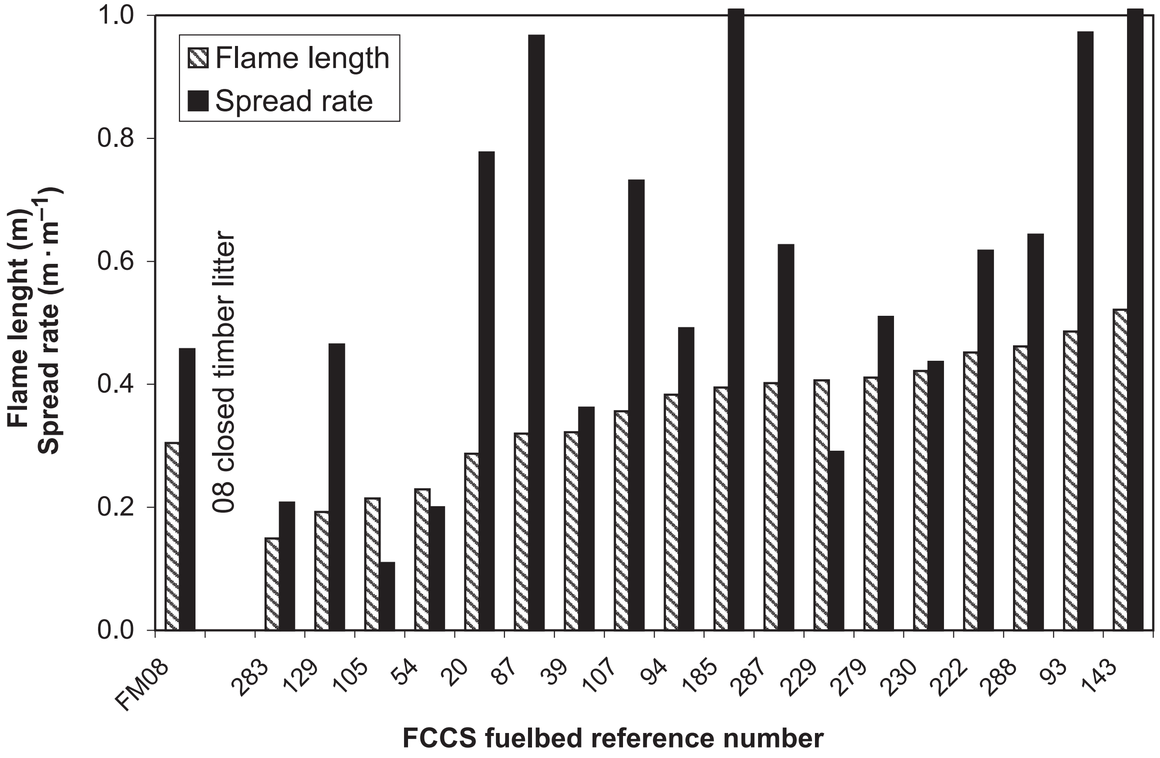
Validation and crosswalk to original 13 fuel models

We have made minor revisions to the basic spread equations advanced by Rothermel (1972) and reformulated the way the model is applied to heterogeneous fuelbeds. Our objective is to provide a formulation that uses inventoried fuelbed characteristics, not stylized or adjusted, which provide surface fire behaviour predictions similar in absolute and relative terms to values predicted by the original formulation. To this end, we predicted rates of spread and flame lengths, applying one benchmark wind speed (1.79 m·s^{-1}) and five of the moisture scenarios used in BehavePlus (Andrews et al. 2005) with the new formulation, using all of the 216 original fuelbeds in FCCS (Riccardi et al. 2007) as direct inputs. FCCS fuelbeds constitute an original, independent, and unadjusted data set collected from a variety of sources. We also used BehavePlus for each of the 13 original fuel models at the same environmental conditions.

First, we compared the range of reaction intensity predicted by BehavePlus for 13 fuel models with the reaction intensity predicted by our formulation for the 216 FCCS fuelbeds. For example, at moisture scenario D2L2, dead fuel moisture is effectively 6.25%, nonwoody (i.e., herbaceous) fuel moisture is 30%, and shrub (i.e., live) fuel moisture is 60%. Reaction intensities at these conditions (Fig. 5) range from 156 (fuel model No. 1) to 1853 kJ·m^{-2}·s^{-1} (fuel model No. 13). The 13 fuel models are grouped by the fuelbed component that is thought to be dominant in determining fire spread; that is, into three “grass”, four “shrub”, three “timber litter”, and three “slash” fuel models.

Our reformulation predicted reaction intensities for the 216 FCCS fuelbeds from 6 (fuelbed 236, tabosa–gramma grassland) to 1533 kJ·m^{-2}·s^{-1} (fuelbed 78, Florida hopbush – Mauna Loa beggarticks shrubland). A random sample of results for 21 FCCS fuelbeds is displayed in Fig. 5. We stratified the sample according to which of three fuelbed strata (nonwoody, shrub, or woody plus litter) contributed the most to reaction intensity, according to eq. 18. We will use the stratification of FCCS fuelbeds later to crosswalk each fuelbed to one of three groups of fuel mod-

Fig. 10. A sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 8 (closed timber litter) at fuel moisture scenario D2L2 and at 1.79 m·s^{-1} midflame wind speed. FCCS fuelbed 20, western juniper – mountain mahogany woodland; fuelbed 39, sugar pine – Douglas-fir – oak forest; fuelbed 54, Douglas-fir – white fir – interior ponderosa pine forest; fuelbed 87, black spruce – feathermoss; fuelbed 93, paper birch – trembling aspen forest; fuelbed 94, balsam poplar – trembling aspen forest; fuelbed 105, paper birch – trembling aspen – white spruce forest; fuelbed 107, pitch pine – scrub oak forest; fuelbed 129, green ash – American elm forest; fuelbed 143, trembling aspen – paper birch – white spruce – balsam fir forest; fuelbed 185, longleaf pine – turkey oak forest; fuelbed 222, interior ponderosa pine forest; fuelbed 229, ponderosa pine – juniper forest; fuelbed 230, pinyon – juniper forest; fuelbed 279, black spruce – northern white cedar – larch forest; fuelbed 283, willow oak – laural oak – water oak; fuelbed 287, eastern white pine – eastern hemlock forest; and fuelbed 288, bald-cypress – water tupelo forest.



els. We are satisfied that the range is reasonably similar to those expected for the 13 fuel models, considering that fuel models tend to represent the upper end of the distribution of expected reaction intensities.

Having stratified the 216 FCCS fuelbeds into three groups, we then compared our predicted rates of spread and flame lengths with each BehavePlus-generated prediction for the fuel models in the similar group. For example, Fig. 6 illustrates the predicted rates of spread at four moisture scenarios (all at a midflame wind speed of 1.79 m·s^{-1}) for the three grass fuel models and for the three FCCS fuelbeds having a rate of spread most similar to fuel model No. 1 at moisture scenario D2L2. FCCS will identify these three fuelbeds as a suggested "crosswalk" to fuel model No. 1 so that FCCS users can use either our surface fire behavior predictions or use applications of Rothermel's model.

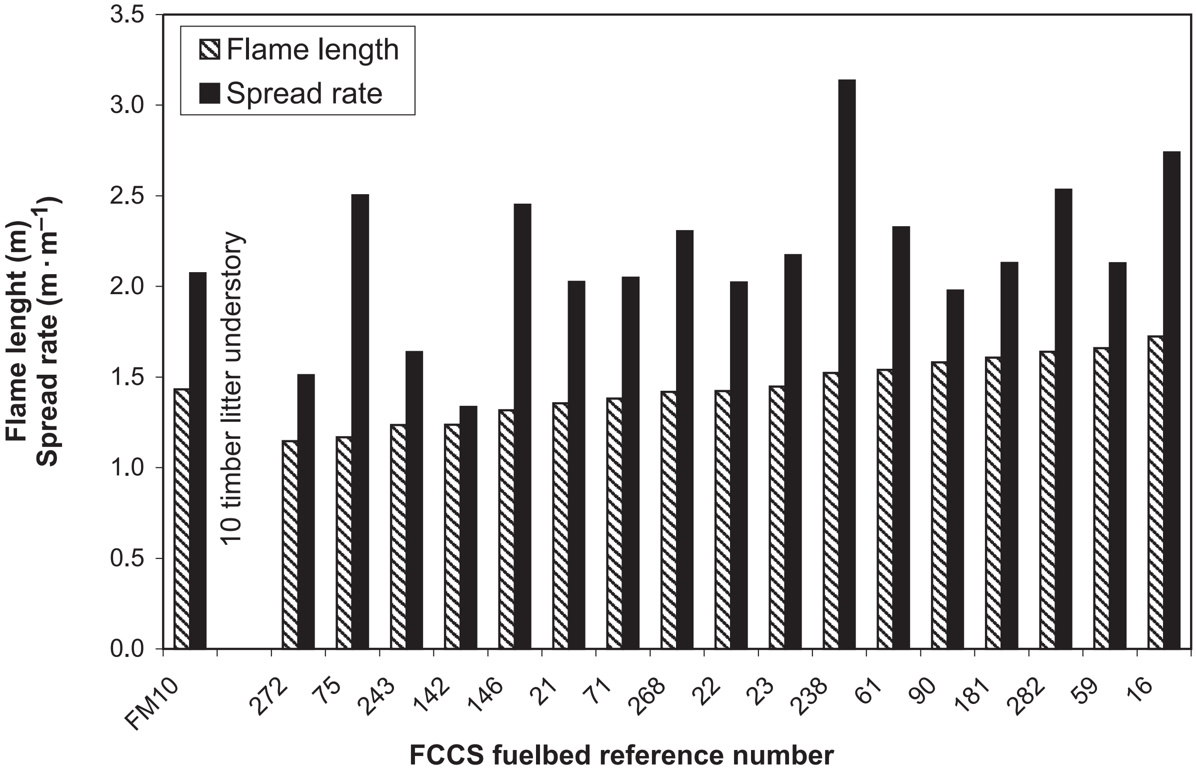
Note in Fig. 6 that the response of FCCS fuelbeds to a change in moisture scenario is similar but not identical to the response of the fuel models in BehavePlus. The difference in response, first of all, is due to the "dynamic" nature of FCCS fuelbeds, similar to the dynamic nature of some of the 40 standard fuel models by Scott and Burgan (2005), in that they reflect a dynamic response to the state of curing of the herbaceous fuelbed component, while all of the 13 original models are "static" in that regard. Second, BehavePlus assigns different moisture-at-extinction values to each fuel model. For example, fuel model 1 (short grass) does not include any herbaceous fuel, so it is affected only by dead fuel moisture content. Also, the moisture at extinction of fuel model 1 is 12%, so that no spread occurs at moisture scenario D4L4, which assigns a moisture content higher than 12% for dead fuels.

Forty-six FCCS fuelbeds in which nonwoody fuels contribute most to reaction intensity have predicted rates of spread most similar to that predicted by BehavePlus for fuel model 2 (timber, grass, and understory). They include fuelbeds whose "cover type" is identified by FCCS (Riccardi et al. 2007) as "grassland", "savanna", "broadleaf forest", and "conifer forest", but where nonwoody fuels are the dominant component. We recommend a crosswalk to fuel model 2 if the user wants to access applications of Rothermel (1972). A random sample of those fuelbeds is compared with model 2 predictions in Fig. 7.

Twenty FCCS fuelbeds with the same mixture of cover types (Fig. 8), but whose reaction intensity was dominated by the shrub component, were compared with fuel model 7 (southern rough).

All 17 other shrub-dominated FCCS fuelbeds were identi-

Fig. 11. A sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 10 (timber litter understory) at fuel moisture scenario D2L2 and at 1.79 m·s^{-1} midflame wind speed. FCCS fuelbed 16, Jeffery pine – ponderosa pine – Douglas-fir – black oak forest; fuelbed 21, lodgepole pine forest; fuelbed 22, lodgepole pine forest; fuelbed 23, lodgepole pine forest; fuelbed 59, subalpine fir – Engelman spruce – Douglas-fir – lodgepole pine forest; fuelbed 61, whitebark pine – subalpine fir forest; fuelbed 71, Ohio Florida hopbush – kupaoa forest; fuelbed 75, slash pine – New Caledonia pine forest; fuelbed 90, white oak – northern red oak forest; fuelbed 142, trembling aspen – paper birch forest; fuelbed 146, jack pine forest; fuelbed 181, pond pine forest; fuelbed 238, Pacific silver fir – mountain hemlock forest; fuelbed 243, pitch pine – scrub oak shrubland; fuelbed 272, red mangrove – black mangrove forest; fuelbed 282, loblolly pine forest; and fuelbed 288, bald-cypress – water tupelo forest.



fied as shrubland cover type by FCCS and compared by us to fuel model 6 (Fig. 9). None had flame lengths or spread rates as great as predicted by BehavePlus for fuel models 4, 5, or 6, as none had either as great a fuel loading or near optimum depth as the fuel models. It is worth noting that comparisons of eight spread model predictions with observed fire behaviour in Mediterranean shrublands by Sauvagnargues-Lesage et al. (2001) concluded that BehavePlus overpredicted observed spread rates by a factor of 2.9. Therefore, pending further investigation, we warn that the surface fire behaviour predicted by our reformulation for FCCS shrubland fuelbeds may be consistently lower than expected by users of Rothermel's formulation.

All FCCS fuelbeds dominated by the combination of woody fuels and litter in their contribution to reaction intensity were compared with BehavePlus predictions of flame length for fuel models 8, 9, 10, 12, and 13. The 26 fuelbeds with the lowest flame lengths (Fig. 10) were crosswalked to fuel model 8 (closed timber litter); 31 to fuel model 9; 34 to fuel model 10 (timber litter understory) (Fig. 11); 18 to fuel model 12; and 18 fuelbeds with the highest flame length to fuel model 13 (heavy slash) (Fig. 12).

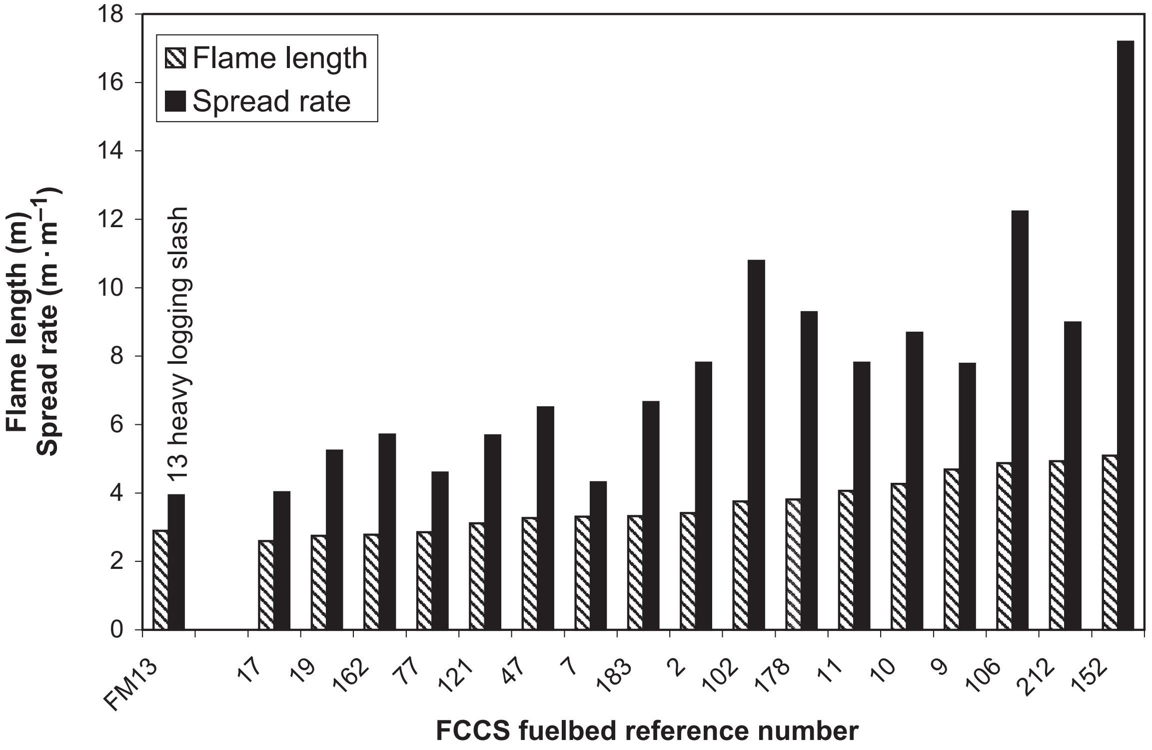
Satisfied that we have formulated a fire spread model that behaves similarly to the applications of Rothermel, we look forward to testing our results against other models and with fire observations in the future. Several robust data sets exist against which we will test the new formulation in the future, either to validate or to calibrate our formulation to those controlled observations.

Application to the field

The model reformulation described in this paper can be used to assess, map, and characterize surface fire potential based on fuelbed characteristics alone, by evaluating only the first three terms in eq. 4. By ignoring the influence of wind speed and fuel moisture, comparisons can still be made between the relative fire potential expressed by dissimilar fuelbeds. These comparisons provide fire behavior predictions in relative, not absolute units. Ottmar et al. (2007) describe the calculation of "surface fire behaviour potentials" that use this approach to rate FCCS fuelbeds on a scale of 0–9. Fire potential ratings will not be affected by future modifications of, or substitutions for, current equations that express the effects of wind speed or moisture.

By evaluating all of the terms in eq. 4, fuelbeds can be assessed, mapped, or characterized by absolute predictions of surface fire behaviour. This approach requires input of specific fuel moisture and effective wind speed and implicit user acceptance of the algorithms included to model their effects.

Fig. 12. A sample of Fuel Characteristic Classification System (FCCS) fuelbeds with predicted spread rates and flame lengths similar to fuel model 13 (heavy logging slash) at fuel moisture scenario D2L2 and at 1.79 m·s^{-1} midflame wind speed. FCCS fuelbed 2, western hemlock – western redcedar – Douglas-fir forest; fuelbed 7, Douglas-fir – sugar pine – tanoak forest; fuelbed 9, Douglas-fir – western hemlock – western redcedar – vine maple forest; fuelbed 10, western hemlock – Douglas-fir – Sitka spruce forest; fuelbed 11, Douglas-fir – western hemlock – Sitka spruce forest; fuelbed 17, red fir forest; fuelbed 19, white fir – giant sequoia – sugar pine forest; fuelbed 47, redwood – tanoak forest; fuelbed 77, eucalyptus plantation forest; fuelbed 102, white spruce forest; fuelbed 106, red spruce – balsam fir forest; fuelbed 121, oak – pine – mountain laurel forest; fuelbed 152, red pine – white pine forest; fuelbed 162, loblolly pine – slash pine forest; fuelbed 178, loblolly pine – shortleaf pine forest; fuelbed 183, loblolly pine – shortleaf pine forest; and fuelbed 212, Pacific ponderosa pine forest.



Fuelbed evaluations and comparisons can be made, in absolute terms, at any benchmark set of user-defined environmental conditions including the moisture scenarios employed by Andrews et al. (2003) and by Scott and Burgan (2005). Fuelbeds are dynamic in that they respond to moisture content changes in any surface fuelbed stratum. Absolute surface fire behavior predictions are expected to be in the range of values familiar to users of BehavePlus at wind speeds near 1.8 m·s^{-1}, but may differ significantly at much higher wind speeds

Summary

Reformulation and amendment of the widely used Rothermel spread model (Rothermel 1972) was undertaken to calculate energy release and one-dimensional spread rate in quasi-steady-state fires in heterogeneous but spatially uniform wildland fuelbeds. This new formulation is primarily intended for use in the Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007; Sandberg et al. 2001) that allows land managers, policy makers, and scientists to build and calculate characteristics of fuelbeds with as much or as little site-specific information as is available. The reformulation was done to

(1) predict surface fire behaviour directly for any wildland fuelbed using observed or inventoried bulk properties as inputs;
(2) enable modeling of heterogeneous fuel mixtures (i.e., mixtures of litter, shrub, woody, and nonwoody vegetation) of different depths, sizes, and moisture contents in a more physically logical way by accounting for the heat sink of each of *n* fuelbed components individually;
(3) maintain reasonable consistency with the physical assumptions in the widely implemented Rothermel (1972) model outputs, to reduce the effort and confusion caused by the transition to the new formulation;
(4) provide improved resolution to measure changes in expected fire behaviour among fuelbeds, especially those caused by management activities or natural processes; and
(5) facilitate future substitutions for the moisture damping and wind speed multiplication coefficients calculated by Rothermel (1972).

Applications of Rothermel's (1972) fire spread model have provided scientific support for tactical and strategic fire and fuels management decisions in the United States for three decades. Our reformulation of his approach to predict fire behaviour in heterogeneous fuelbeds can add value to those applications without much change to the original mathematical framework or to the basic spread equations, providing fire behaviour predictions are in about the same range of absolute values. We find the consistency of predictions from our reformulation to be a positive validation of the original and valuable work in the 1960s and 1970s by Richard Rothermel, Hal Anderson, William Frandsen, Frank Albini, and others.

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