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An effective wind speed for models of fire spread*

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Abstract. In previous descriptions of wind-slope interaction and the spread rate of wildland fires it is assumed that the separate effects of wind and slope are independent and additive and that corrections for these effects may be applied to spread rates computed from existing rate of spread models. A different approach is explored in the present paper in which the upslope component of the fire's buoyant velocity is used with the speed and direction of the ambient wind to produce effective values of wind speed and direction that determine the rate of spread vector. Thus the effective wind speed can replace the ambient wind speed in any suitable fire spread model and provide a description of the combined effects on the fire behavior. The difference between current and threshold values of the effective wind speed also can be used to determine whether fire will spread in a given fuel type. The model is tested with data from experiments reported by Weise (1993) in which fire spread was in response to variation in both wind speed and slope angle. The Weise spread rate data were satisfactorily correlated using dimensional methods and the observed spread rate was reasonably well predicted with an existing rate of spread model. Directional aspects of the model were not tested because the Weise (1993) study did not include winds with a cross-slope component.

Additional keywords: wind/slope interaction; threshold wind speed; fire behavior; spread direction.

Introduction

The interaction between wind speed and topography and its effect on the behavior of wildland fires have been studied only superficially in recent years because fire researchers generally must comprehend simple, or limiting, cases of a fire phenomenon before progressing to the more complex case. Most research studies of the effects of wind or slope angle on rate of fire spread have been conducted with laboratory fires. Examples are studies by Byram *et al.* (1966), Fang (1969), Sheshukov (1970), Rothermel (1972), Van Wagner (1988), Burrows (1994), and Mendes-Lopes *et al.* (1998). Van Wagner (1977), citing the work of others, was one of the first researchers to express the effect of slope angle on rate of spread with a mathematical equation. More recently, a physical model for predicting numerically the effects of fuel loading and slope angle on rate of spread in the absence of ambient wind was presented by Dupuy and Larini (1999).

The experimental and theoretical studies mentioned above are limited in two respects. First, the studies were conducted with no consideration of threshold values of wind speed and slope angle. Fuels burned in the experimental

fires were always sufficiently compact and continuous to allow passage of flame from one end of the fuel bed to the other even when the wind speed and slope angle had zero values. Under field conditions, however, this is not always the case. Fire can spread in some fuels only when a minimum, but non-zero, wind speed or slope angle is influencing the process. For example, Lindenmuth and Davis (1973) stated that a wind velocity of at least 3.1 m s^{-1} is needed for the clumpy oak chaparral fuel of Arizona to burn well on level ground. The same is true in the grasslands of Australia for which Cheney *et al.* (1998) found that the wind speed at 10 m above the ground should exceed 1.4 m s^{-1} for fire to spread consistently well in natural or cut/grazed pastures.

Second, all but one of the experimental and theoretical studies cited above (Mendes-Lopes *et al.* 1998) consider the effects of wind and slope on spread rate separately—i.e. the effects of wind on spread rate were observed or calculated only for zero slope angle and, similarly, slope angle effects were studied only for zero wind.

The present paper utilizes data from an experimental study conducted by Weise (1993) in which fire spread rates

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were influenced by simultaneous wind and slope effects. In this laboratory research, heading and backing fires in wood stick fuels were burned in a small tilting wind tunnel with a movable roof in response to wind speeds and percentage slopes with maximum values of 1.15 m s^{-1} and 30% (16.7° from horizontal). These values, of course, are near the low end of the range over which variation is possible. On the other hand, several attempts to mathematically model the rate of spread due to combined effects of wind and slope have been reported. In the Rothermel (1972) model, the two effects are measured separately and then assumed to be additive. In an unpublished note, Albini (1976) modified the Rothermel wind and slope correction factors, ϕ_w and ϕ_s , and presented equations for estimating the magnitude and direction of fire spread from information on the calm-air, level-ground spread rate R_o , the slope angle, and the wind angle with respect to the uphill direction.

The theory of Pagni and Peterson (1973) utilized an effective flame tilt angle that is the sum of the slope angle and the flame tilt angle that would result from wind only. This effective angle then was used to estimate radiative heat transfer to unburned fuel. Rothermel (1983) outlined a method using contour maps for determining the resultant rate of spread from vector addition of rate of spread components calculated separately from the wind direction (with no slope) and the slope angle (with no wind). McAlpine *et al.* (1991) evaluated the effect of slope on spread rate for zero wind from an existing fire behavior model (the Canadian Forest Fire Behavior Prediction System, CFFBPS) and then converted this value to an equivalent wind speed. The actual and equivalent wind speeds then were used with their corresponding directions from north to determine through vector addition the net effective wind speed and direction. The procedure of McAlpine *et al.* has been incorporated into the CFFBPS (Alexander *et al.* 1992) and used by Richards (1999) to mathematically model the growth of wildland fires burning on gently-, moderately-, and steeply-sloped terrain.

A common feature of these models is that the effects of wind and slope on the spread rate are assumed to be independent and additive. None of the models accounts explicitly for an interaction between the wind and slope components. The purpose of the present paper is to propose a model for calculating an effective wind speed from knowledge of the slope angle and ambient wind speed and direction. An interaction term arises when fire spreads in response to non-zero wind and slope effects that are not aligned. The vector addition concept of Rothermel (1983) and McAlpine *et al.* (1991) is utilized, but the slope effect is developed from buoyancy flux considerations rather than from a model for fire spread rate. Graphs depicting variation in the effective wind speed and direction are presented in terms of the ratio of the ambient air velocity to the buoyant velocity generated by the fire. A simple criterion utilizing a

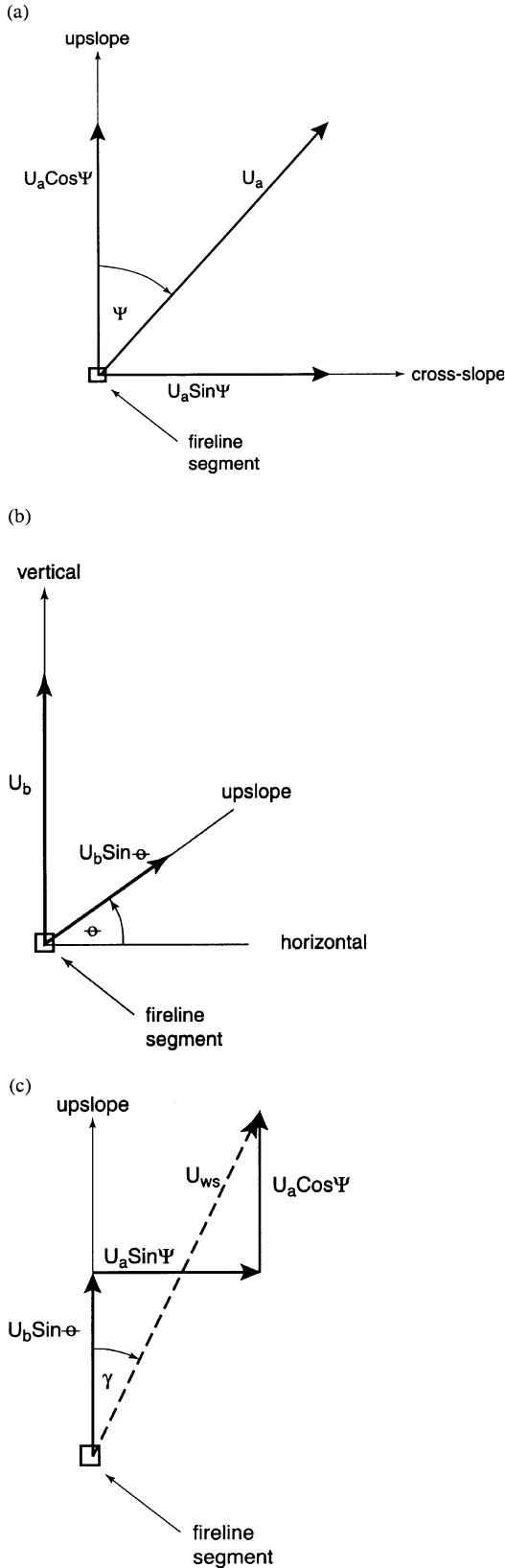
threshold effective wind speed that produces a barely sustained rate of spread can be used to ascertain general features of the fire spread. This minimum speed likely is a function of fuel type, quantity, arrangement, and moisture content, and is not evaluated in this paper. Next, the heading and backing fire spread rates reported by Weise (1993) are plotted against ambient wind speed and slope angle and then compared with plots of the same spread data versus the effective wind speed to illustrate how the new model can unify the effects of the two variables. Finally, the correlation procedures of Nelson and Adkins (1988) and the fire spread model of Rothermel (1972) are used with the Weise (1993) headfire data to demonstrate how the new model can account for the effects of wind and slope on rate of fire spread.

Effective wind speed and direction

In the work of McAlpine *et al.* (1991), the effective wind speed and direction are determined from the upslope component of spread and a spread component associated with the ambient wind. The slope component of spread is found by setting the wind to zero in the ISI component of the CFFBPS, calculating the rate of spread due to slope, and then calculating backward to find the equivalent wind speed that would cause the spread rate due to slope. In the present paper, a trigonometric method is used to combine the wind and slope effects. Consider a small segment within a line fire burning on relatively smooth terrain that makes an angle θ with the horizontal. In addition, wind of magnitude U_a blows steadily across the segment at angle ψ , measured clockwise with respect to the maximum upslope, or uphill, direction. For wind blowing in this direction, $\psi = 0$. Wind speed U_a refers to that wind influencing the rate of flaming combustion, so may be considered a mid-flame wind speed. A plan view of the ambient wind and its vector components is given in Fig. 1a. The cross-slope (normal to the uphill direction) and upslope components of U_a are $U_a \sin\psi$ and $U_a \cos\psi$, respectively. Let U_b represent the velocity at which combustion products rise vertically due to buoyancy generated by the fire. A side view showing a cross-section of the fire and slope angle θ is given in Fig. 1b. The orthogonal projection of U_b on the sloping surface, U_s , is taken as the upslope component of the buoyant velocity and is given by

$$U_s = U_b \sin\theta. \quad (1)$$

Thus if U_a were zero the fire would burn uphill at a rate dependent on U_s . In general, ψ is not zero and this causes a deflection that results in a spread direction of angle γ (measured clockwise) with respect to the uphill direction. As indicated in Fig. 1c, the buoyancy-generated velocity interacts with the ambient wind to determine a combined velocity that describes the dual effects of wind and slope. Vector addition shows that the effective angle of the wind with respect to uphill may be written as



$$\gamma = \arctan\{(U_a/U_b) \sin \psi / [\sin \theta + (U_a/U_b) \cos \psi]\}. \quad (2)$$

The limiting case of zero slope ($\theta = 0$) leads to $\gamma = \psi$; the limiting case of zero wind ($U_a = 0$) gives $\gamma = 0$. These results are physically reasonable.

More general expressions for γ may be written to extend the applicability of equation (2) to the full range of ψ from 0 to 2π . A reference frame is suggested in Fig. 1a in which x represents the cross-slope direction and y the upslope direction. The clockwise measurement of γ and ψ from the y -axis differs from the customary formulation in which angles are measured counter-clockwise from the x -axis. If velocity components are specified such that $U_x = U_a \sin \theta$ and $U_y = U_b \sin \theta + U_a \cos \psi$, then γ is obtained from

$$\tan \gamma = (\text{Arg}); U_y > 0, \text{Arg} > 0$$

$$\tan(\gamma - \pi) = (\text{Arg}); U_y < 0, \text{all Arg}$$

$$\tan(\gamma - 2\pi) = (\text{Arg}); U_y > 0, \text{Arg} < 0. \quad (3)$$

The argument of the arctan function is given by

$$\text{Arg} = U_x/U_y = U_a \sin \psi / (U_b \sin \theta + U_a \cos \psi). \quad (4)$$

When $\text{Arg} < 0$ in the second and third of equations (3), the equality $\tan(-A) = -\tan A$ is used to express Arg as a positive number and solve for γ . Clearly, equation (2) applies to only a portion of the total range in ψ .

According to Fig. 1c, the effective wind speed, U_{ws} , is given by

$$U_{ws} = [(U_a \sin \psi)^2 + (U_b \sin \theta + U_a \cos \psi)^2]^{1/2} \quad (5)$$

which can be expressed as

$$U_{ws} = U_b [(U_a/U_b)^2 + 2(U_a/U_b) \sin \theta \cos \psi + \sin^2 \theta]^{1/2}. \quad (6)$$

The middle term on the right side of this equation is a wind/slope interaction term that appears only when both U_a and $\theta \neq 0$ (or 180°) and $\psi \neq 90^\circ$ or 270° .

A factor not considered in these equations is the convection associated with smoldering combustion behind the flame front. This factor aids the spread rate of upslope fires and opposes that of downslope fires. Equation (6)

Fig. 1. Geometrical considerations leading to effective wind speed U_{ws} acting on a segment of fireline. (a) components of a wind of speed U_a blowing across a slope at angle ψ with respect to the maximum upslope direction; (b) side view of slope angle θ and upslope component of the buoyant velocity U_b ; (c) combined effects of wind and slope determine the effective wind speed U_{ws} and direction γ .

shows that fire will spread at a rate exceeding the minimum rate R_0 only when $U_{ws} > 0$. If the threshold value of U_{ws} is U_0 , then the simple difference $(U_{ws} - U_0)$ can gauge the nature of fire spread. If $U_{ws} > U_0$, $R > R_0$; if $U_{ws} = U_0$, $R = R_0$; if $U_{ws} < U_0$, $R = 0$. The optimum method of evaluating U_0 remains as a separate research problem.

In general, $U_0 \neq 0$ in outdoor fires. For many laboratory burns, however, the fuels are sufficiently compact to permit fire spread when $U_a = U_s = 0$ so that U_0 may be set to zero also. Limiting cases give $U_{ws} = U_a$ when $\theta = 0$ and $U_{ws} = U_s$ when $U_a = 0$. It is noted that special conditions occur when $U_a = U_s = 0$. Equations (3) and (4) show that γ is undefined (no preferred spread direction), and equation (6) produces $U_{ws} = 0$.

All variables except U_b appearing on the right side of equations (4) and (6) are considered as known or available because they can be measured and/or obtained from weather forecasts and terrain maps. For a line fire whose flame depth is much shorter than the length of fireline, the vertical buoyant velocity may be estimated as

$$U_b = (2 g I_B / \rho_a c_p T_a)^{1/3}, \quad (7)$$

where g is the acceleration due to gravity and I_B is the convective fireline intensity given by

$$I_B = H_c W_a R. \quad (8)$$

In equation (7), the individual quantities ρ_a , c_p , and T_a refer to ambient air mass density, constant-pressure specific heat, and Kelvin temperature. This equation implies that the upward velocity of the flame gases is of the same order as the cube root of the vertical flux of buoyancy (Taylor 1961). In equation (8), H_c is considered a convective heat of combustion in the sense that the low heat of combustion is reduced by a factor of 15–20% to account for heat loss due to evaporation of water and flame radiation to the surroundings (Byram 1959). The quantities W_a and R denote the available fuel loading and rate of fire spread.

Information on U_a , θ , and ψ may be combined with equations (3), (4), (6), (7) and (8) for correlating rate of spread R to U_{ws} (when R is known) or for computing R from a prediction model (when R is unknown). In the latter case, a complicating factor is introduced because I_B depends strongly on U_a and θ through the dependence of R on these variables. Thus an iterative procedure must be used to determine R from a prediction model in which U_{ws} from equation (6) is substituted for the usual wind variable, U_a .

Effective wind direction γ , given by equations (3) and (4), was computed for five values of θ , five values of ψ , and nine values of (U_a/U_b) . Values of wind angle ψ were assigned as 30°, 60°, 90°, 120°, and 150° clockwise from uphill. Angle θ was assigned values of 7.5°, 15°, 30°, 45°, and 60° from horizontal. Degrees are used in place of percentage slope to

facilitate the calculations; the corresponding percentage slope values are 13, 27, 58, 100, and 173%. When $\theta = 0$, $\gamma = \psi$ and the direction of spread is that of the ambient wind. The dimensionless wind speeds (U_a/U_b) were 0, 0.0625, 0.125, 0.25, 0.5, 0.75, 1, 2.5, and 5. Fig. 2a shows plots of γ versus (U_a/U_b) for the five levels of ψ and a constant θ of 30°; Fig. 2b is a similar plot for five levels of θ and a constant ψ of 60°. For a given wind direction ψ , angle γ increases rapidly but approaches a constant value as (U_a/U_b) increases beyond 1. For small (U_a/U_b) , γ tends to be independent of ψ and strongly dependent on (U_a/U_b) whereas, for large (U_a/U_b) , γ approaches ψ and tends to become independent of (U_a/U_b) —as would be expected. Spread direction γ is most strongly affected by θ as U_a/U_b approaches unity.

The dimensionless ratio U_{ws}/U_b from equation (6) is plotted in Fig. 3a for the values of (U_a/U_b) , ψ , and θ used in Fig. 2a, except that calculations for $\psi = 180$ have been added to the plot. In Fig. 3b, U_{ws}/U_b is plotted versus U_a/U_b for variable θ and a ψ of 60°. Fig. 3a shows that U_{ws}/U_b tends to be weakly dependent on wind angle ψ for small U_a/U_b , but the influence of ψ becomes more important as U_a/U_b and θ increase. It is clear that U_{ws}/U_b tends to decrease as ψ increases and (U_a/U_b) increases toward unity. This effect is caused by the negative component of the ambient wind operating through the interaction term in equation (6) as ψ increases from 90

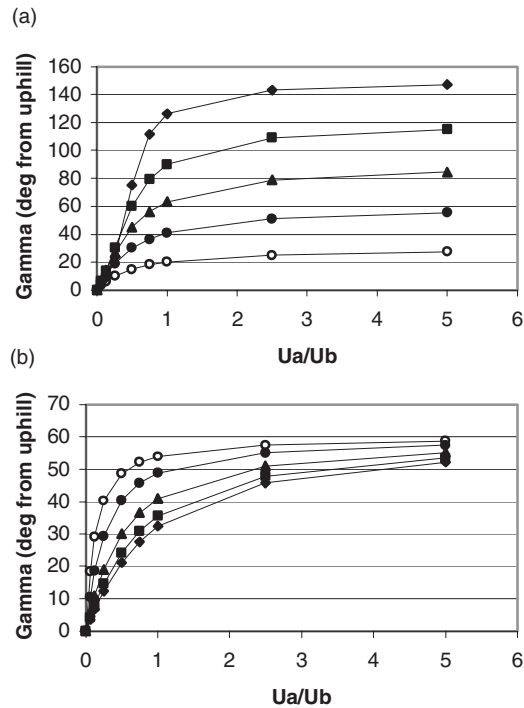


Fig. 2. Spread direction versus dimensionless wind speed for various values of slope angle θ and wind angle ψ . (a) $\theta = 30^\circ$, ψ given by: open circles = 30, dark circles = 60, triangles = 90, squares = 120, diamonds = 150° from uphill; (b) $\psi = 60^\circ$, θ given by: open circles = 7.5, dark circles = 15, triangles = 30, squares = 45, diamonds = 60° slope.

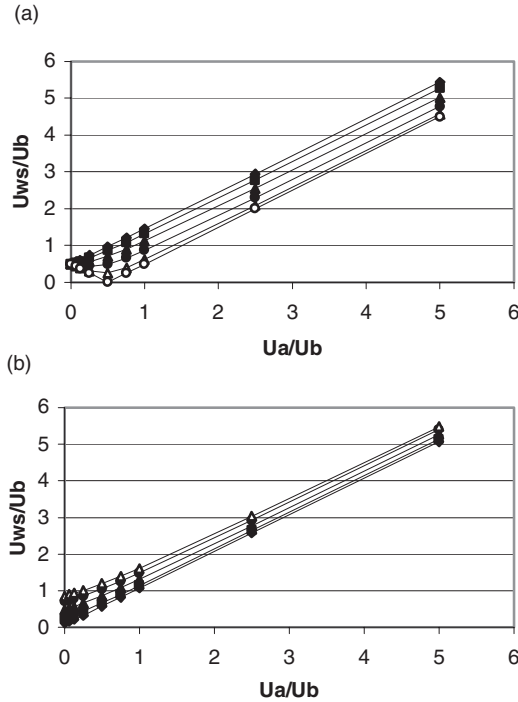


Fig. 3. Dimensionless form of effective wind speed versus ambient wind speed for various values of slope angle θ and wind angle ψ . (a) $\theta = 30^\circ$, ψ given by: diamonds = 30, squares = 60, triangles = 90, dark circles = 120, open triangles = 150, open circles = 180° from uphill; (b) $\psi = 60^\circ$, θ given by: diamonds = 7.5, squares = 15, dark triangles = 30, circles = 45, open triangles = 60° slope.

toward 180° . In such cases, this term becomes more negative and U_{ws}/U_b tends toward zero. It is also evident from Fig. 3b that U_{ws}/U_b at $(U_a/U_b) = 0$ increases as θ increases.

A special condition sometimes discussed in the literature is the case when wind blows downslope in opposition to a fire that is spreading upslope. Equation (5) permits an estimate of the value of (U_a/U_b) for which the equal but opposite wind and slope effects create an effective wind $U_{ws} = 0$. This condition is derived by setting $U_{ws} = 0$ and $\psi = 180^\circ$ in equation (5). The result is

$$(U_a/U_b)_o = \sin\theta, \quad (9)$$

where subscript o denotes a value of (U_a/U_b) for which the opposing wind and slope effects cancel for a given value of θ . For example, $\theta = 30^\circ$ and $(U_a/U_b) = 0.5$ presumably define a condition that would allow fire to spread in directions where unburned fuel is available, but at a rate close to R_o .

Model applications

Models for the direction and magnitude of an effective wind speed resulting from combination of wind and slope effects

are presented in equations (3), (4) and (6). In this section, the experimental rate of spread data of Weise (1993) are used to show how the U_{ws} model can reduce scatter in plots of spread rate and to illustrate application of the model for correlation and prediction. Because the Weise data involve fire spread in only two directions (uphill or downhill), no further discussion of the γ model is given.

The Weise experiments

In the mid-1990s, D.R. Weise published a series of papers reporting experimental results from burns of mixed fuels consisting of quaking aspen (*Populus tremuloides* Michx.) excelsior (long wood filaments used for packing) and white birch (*Betula papyrifera* Marsh.) sticks (14 cm long, 0.46 cm wide, 0.11 cm thick) in a small wind tunnel which could be tilted (Weise 1993; Weise and Biging 1994, 1997). The roof of the tunnel was adjustable and moved with the fire in a way that minimized ceiling effects. Wind speeds of magnitude 0, 0.41, and 1.15 m s^{-1} were utilized with slope angles of 0° , 8.5° , and 16.7° to measure the combined effects of wind and slope on rate of fire spread. Backing, heading, and no-wind, no-slope fires were burned in two blocks. In block 1, the vertical fuel sticks were oriented with their flat surfaces normal to the direction of fire spread; in block 2, the sticks were oriented so that their smaller edges were normal to the spread direction. The results from an additional brief study (only five fires) of the effects of large moisture contents on fire spread are not considered here.

Weise (1993) found from statistical tests that fuel stick orientation did not have a significant effect on the rate of fire spread in his experiments. Thus he combined data from the two blocks, and the same procedure is followed here. The mean no-wind, no-slope spread rate among blocks (four observations) was 0.00268 m s^{-1} . The combined heading fire rate of spread data (28 fires) are plotted versus θ and U_a in Figs 4a and 4b to illustrate scatter in the data. Differing levels of U_a are not identified in Fig. 4a, but larger R values correspond to larger values of U_a . Negative θ indicates downslope fire spread. Similarly, the larger R values in Fig. 4b correspond to larger values of θ . Negative values of U_a indicate that the wind was in a direction opposite to the direction of fire spread. In Fig. 4c, R is plotted versus U_{ws} from equation (6). The ability of U_{ws} to correlate the combined effects of θ and U_a on R is evident for both headfires and backfires. In this graph, the sign of U_{ws} is determined by whether the wind aids or opposes the fire spread.

For the 28 headfires considered, the wind effect dominated the slope effect. For two additional fires that normally would have been considered backfires, the angle of the flame was directed away from the wind direction. Both of these fires were backing upslope against a downslope wind of 0.41 m s^{-1} , but the flame angle data presented by Weise (1993) showed that the flame was tilted upslope. Even

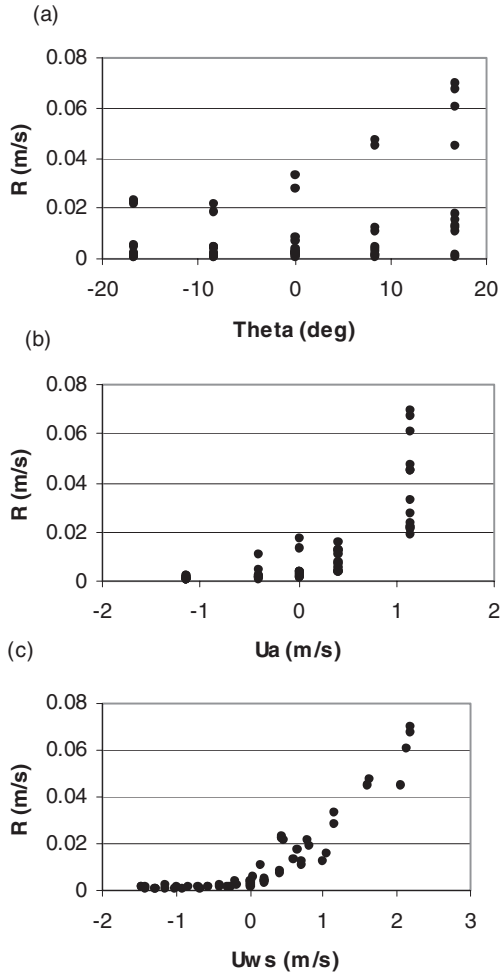


Fig. 4. Rate of spread in wood stick fuel beds for combined wind and slope from experimental data of Weise (1993). (a) Effect of slope angle θ ; (b) effect of ambient wind speed U_a ; (c) effective wind speed U_{ws} from equation (6).

though their spread direction was into the wind, these fires were considered headfires in this combined wind/slope context, and U_{ws} was taken as positive. Thus a total of 30 heading fires was available for further analysis.

Correlation with dimensional analysis

The headfires reported by Weise (1993) were correlated with the techniques of dimensional analysis utilized by Nelson and Adkins (1988). Effective wind speed U_{ws} potentially is a key variable for describing rate of wildland fire spread in such an analysis because it incorporates wind speed, wind angle, slope angle, and fire buoyancy into a single variable. Dimensional analysis, while not providing specific information on mechanisms of fire behavior, has been useful for modeling the convective features of free-burning fires (Byram 1966; Byram and Nelson 1970; Emori and Saito 1983; Soma and Saito 1991). The correlation between

dimensionless expressions of spread rate and ambient wind speed (Nelson and Adkins 1988) used the following variables: wind speed U_a , reaction intensity I_R (considered here as the unit area rate of convective heat release), acceleration of gravity g , volumetric enthalpy of the ambient air $\rho_a c_p T_a$, and fuel bed reaction time τ (sometimes referred to as flame residence time). The analysis of the present paper is similar except that reaction time τ is omitted as a variable because its influence on the spread process is assumed to be wholly contained in I_R . Flame depth D is modified to address the threshold wind/slope problem discussed earlier. Thus flame displacement $(D-D_0)$ is used in place of D . Here D_0 is the value of D observed when fire spreads in a given fuel bed at the rate R_0 in response to the threshold wind speed U_0 .

Three additional assumptions in this approach are consistent with the analysis of Nelson and Adkins (1988). The first of these is that the effective wind speed U_{ws} accounts for all effects of ambient wind speed and direction, slope angle, and fire buoyancy on the rate of fire spread. Second, variables I_R and $(D-D_0)$ incorporate the effects of all geometric fuel bed descriptors, wind shear near the ground, and fuel moisture content and distribution on fire spread. Third, the fire spread mechanism is essentially a convective process in which displacement (or extension along the upper surface of the fuel bed) of flame beyond the depth D_0 is determined by the combined action of wind and slope as expressed by U_{ws} . The physical process through which this mechanism operates is not clear, but possibly is related to shear stress at the fuel surface and/or at the internal surfaces of the vegetative canopy (if such a canopy is present). Weise (1994) concluded that headfire rates of spread in his laboratory burns were dependent on shear stress and that the relationship was affected by slope angle. Thus a mechanism in which $(D-D_0)$ is proportional to shear stress but is modified by buoyancy of the fire appears to be consistent with variables in the analysis. Knowledge of the heat transferred during preheating of fuel ahead of the fire front is not required. Preheating is considered to depend strongly on flame properties such as dimensions, shape, and angle as determined by flame depth, fuel burning rate, and ambient wind speed.

The five variables associated with flame displacement may be arranged by inspection or by the matrix methods of Langhaar (1951) to give the two dimensionless groups

$$\pi_1 = g(D-D_0)(\rho_a c_p T_a)^2 / I_R^2 \quad (10)$$

$$\pi_2 = U_{ws}(\rho_a c_p T_a) / I_R, \quad (11)$$

where the π numbers represent dimensionless expressions of flame displacement and effective wind speed. If all variables essential to describing the fire spread process are included in the analysis, then

$$\pi_1 = f(\pi_2) \quad (12)$$

and the suitability of equation (12) for correlating data may be determined from trial plots. The most desirable of all possible outcomes would be for equation (12) to provide a universal correlation applicable to headfires of all sizes spreading on any slope, in any mean wind, and in any fairly uniform fuel type. This equation will not apply to backing or flanking fires because convective heating of unburned fuels in these fires is small compared with radiative heating. In this case, there is little flame displacement because $D \approx D_o$.

Initial fuel loading in the Weise (1993) laboratory fires was 0.66 kg m^{-2} . It was assumed that the amount of ash and char remaining after the burns was negligible, so the available fuel load also was 0.66 kg m^{-2} . Experimental measurements based on temperatures from nine pairs of thermocouple readings were made for 11 of the 60 fires in blocks 1 and 2 (Weise 2000). Of these, four were headfires, three were backfires, and four were no-wind, no-slope fires; the corresponding mean reaction times were 10, 25, and 13 s. Thus for the no-wind, no-slope fires, D_o was computed as 0.0348 m. For one of the 30 fires, these approximate figures caused a $(D-D_o)$ value of -0.0008 m —a value slightly below the theoretical minimum value of zero. Reaction time was defined for a given thermocouple as the time during which the couple stayed above 600K. Based on a low heat of combustion of 18608 kJ kg^{-1} , I_R was computed as 1228 kW m^{-2} ; ambient air enthalpy ($\rho_a c_p T_a$) was constant at 360 kJ m^{-3} . Fig. 5 is a plot of equation (10) versus equation (11) for the Weise headfire data. The equation of a linear regression through the data is

$$\pi_1 = -0.0236 + 0.7716\pi_2 \quad (13)$$

with coefficient of determination $r^2 = 0.874$. Thus for $\pi_2 < 0.0306$, $\pi_1 < 0$. An alternative form of equation (13) is

$$D = D_o - 0.028 + 0.2687U_{ws}, \quad (14)$$

showing that, for Weise's headfires, $D-D_o$ and $R-R_o$ are linearly related to U_{ws} . On the basis of these data, equation

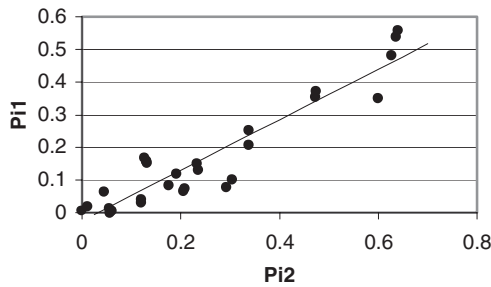


Fig. 5. Heading fire data of Weise (1993) plotted in the form π_1 versus π_2 from equations (10) and (11). The solid line is the regression result given by equation (13). The negative value of π_1 is due to variability in the experimental data.

(6) provides a way to correlate rate of spread or flame depth data with values of ambient wind speed and slope angle.

Though equation (13) appears useful for finding correlations between D or R and the combined effects of wind and slope, the present results are derived from a very small portion of the possible range of variation in wind and slope. Moreover, the important variables I_R and τ are treated as constants. Whether such simple correlations will be possible over a much greater range of fire behavior and for cases when $U_o > 0$ remains to be determined.

Spread rate prediction with the Rothermel model

Correlations like the one just described imply knowledge of the rate of spread, but spread rate often is required when only fuel loading, slope angle, and wind speed and direction are known. As an illustration of the application of equation (6) to fire spread prediction, the Rothermel (1972) fire spread model is used with headfire data from the Weise (1993) laboratory burns to evaluate spread rate R assuming that the no-wind, no-slope spread rate R_o is known, available from an independent source, or taken from the Rothermel model itself. Though the Rothermel model is used here, any suitable spread model can be employed. As before, spread direction is not considered. The Rothermel model is given by

$$R = R_o(1 + \phi_w + \phi_s), \quad (15)$$

where ϕ_w and ϕ_s are correction factors applied to R_o to account for wind and slope effects. McAlpine *et al.* (1991) suggested that equation (15) can be simplified with a single factor representing the combined wind and slope effects. An equation incorporating this idea is

$$R = R_o(1 + \phi_{ws}), \quad (16)$$

where the sum $(\phi_w + \phi_s)$ is replaced by a wind/slope factor ϕ_{ws} that contains U_{ws} .

Factor ϕ_{ws} is computed from the five equations of Rothermel (1972) needed to evaluate wind factor ϕ_w . These equations, which depend strongly on mean values of the fuel bed surface/volume ratio and packing ratio, are not reproduced here. Because Weise's fires burned in heterogeneous fuel beds composed of vertical sticks and a thin layer of excelsior, factor ϕ_{ws} must account for the two fuel types. Let σ denote the mean surface/volume ratio of the bed and β the corresponding mean packing ratio. If it is assumed that the spread rate of fire in the mixed-fuel bed is the same as that in a homogeneous bed of packing ratio β composed of particles with surface/volume ratio σ , these equivalent quantities may be estimated from

$$\sigma = [(\sigma\beta\delta)_s + (\sigma\beta\delta)_e] / [(\beta\delta)_s + (\beta\delta)_e] \quad (17)$$

$$\beta = [(\beta\delta)_s + (\beta\delta)_e] / \delta, \quad (18)$$

where subscripts *s* and *e* refer to sticks and excelsior. Quantities δ_s and δ_e denote layer thickness of the respective fuel components, and the overall bed thickness, δ , equals δ_s for the fuel beds of the Weise experiments. It is noted that the parameters for evaluating ϕ_w in the Rothermel model must be calculated in engineering units. Data presented by Weise (1993) were used with equations (17) and (18) to find $\sigma = 710 \text{ ft}^{-1}$ (2330 m^{-1}) and $\beta = 0.0109$. Similarly, the optimum fuel bed packing ratio was calculated as $\beta_{op} = 0.0155$. In the engineering system of units used by Rothermel (1972), $\phi_w = 0.0662U_a^{0.875}$. When U_a (ft min^{-1}) is replaced by U_{ws} in m s^{-1} , ϕ_{ws} is given by

$$\phi_{ws} = 6.732U_{ws}^{0.875} \quad (19)$$

and the modified Rothermel model becomes

$$R - R_o = R_o \phi_{ws}, \quad (20)$$

where $R_o = 0.00268 \text{ m s}^{-1}$.

Fig. 6 is a plot of $(R - R_o)$ versus ϕ_{ws} for the Weise (1993) heading fire experimental data. The solid line is the corresponding plot derived from equations (19) and (20). The Rothermel model represents the data well up to $\phi_{ws} = 8$, beyond which point $(R - R_o)$ is underpredicted. The three fires that form a cluster at about $\phi_{ws} = 3.2$ are downslope heading fires; the four fires at $\phi_{ws} = 13$ are upslope fires at the larger values of slope and wind speed. The data suggest that the exponent 0.875 on U_{ws} should be closer to unity; such a result would improve agreement with the correlation result from equation (14).

As pointed out earlier, calculation of U_{ws} from equation (6) requires knowledge of R , the quantity being predicted. Thus an iterative solution of equations (6) and (8) is required to calculate R ; this method was not utilized here because I_B was known.

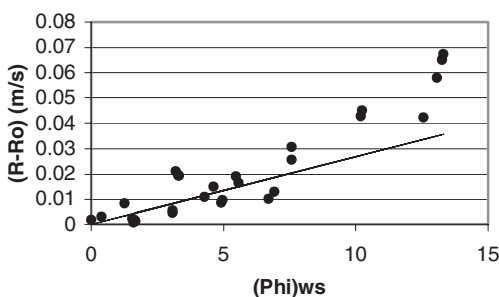


Fig. 6. Heading fire data of Weise (1993) showing the increase in spread rate over the threshold value versus a factor ϕ_{ws} that accounts for combined effects of wind and slope as computed from the Rothermel (1972) spread model. The solid line is the model result according to equations (19) and (20).

Summary

The interaction of ambient wind and terrain slope angle with fire-generated buoyancy can affect the spread direction and rate of spread of two-dimensional heading fires. In all earlier attempts to model these phenomena, the effects of wind and slope on spread rate are assumed to be independent and additive. In this paper, a trigonometric method is used to combine the ambient wind velocity with the upslope component of the fire's buoyant velocity to derive an effective wind velocity. The general character of fire spread in a given fuel type can be evaluated by comparing the current value of the effective wind speed with the critical value of this speed for which the fire spreads at a rate that is barely sustained. It is demonstrated that the effective wind speed correlates spread rate data from the Weise (1993) experiments in which both wind and slope were influencing the rate of fire spread. These data were from beds of nearly uniform construction and the range of variation in wind and slope was small. The model's versatility when it is applied over a larger range of wind and slope variables and for different fuel types remains to be determined. Because fire spread was directly upslope or downslope in the Weise (1993) experiments, the spread direction aspects of the model were not tested.

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References

- Albini FA (1976) Combining wind and slope effects on spread rate. Memorandum to RC Rothermel dated January 19, 1976. On file at the Fire Sciences Laboratory, Missoula, MT.
- Alexander ME, Lawson BD, Lynham TJ, McAlpine RS, Stocks BJ, Van Wagner CE (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada Fire Danger Group, Information Report, ST-X-3. 63 pp.
- Burrows ND (1994) Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. PhD thesis, Department of Forestry, Australian National University, Canberra. 293 pp.
- Byram GM (1959) Combustion of forest fuels. In 'Forest fire: control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)
- Byram GM (1966) Scaling laws for modeling mass fires. *Pyrodynamics* **4**, 271–284.
- Byram GM, Nelson RM Jr (1970) The modeling of pulsating fires. *Fire Technology* **6**, 102–110.
- Byram GM, Clements HB, Bishop ME, Nelson RM Jr (1966) Final Report: Project Fire Model—an experimental study of model fires. Office of Civil Defense Contract OCD-PS-65-40. USDA Forest Service, Southeastern Forest Experiment Station. Asheville, NC. 46 pp.
- Cheney NP, Gould JS, Catchpole WR (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire* **8**, 1–13.

- Dupuy JL, Larini M (1999) Fire spread through a porous fuel bed: a radiative and convective model including fire-induced flow effects. *International Journal of Wildland Fire* **9**, 155–172.
- Emori RI, Saito K (1983) A study of scaling laws in pool and crib fires. *Combustion Science and Technology* **31**, 217–231.
- Fang JB (1969) An investigation of the effect of controlled wind on the rate of fire spread. PhD thesis, University of New Brunswick, Fredericton. 169 pp.
- Langhaar HL (1951) 'Dimensional analysis and theory of models.' 166 pp. (Wiley: New York)
- Lindenmuth AW Jr, Davis JR (1973) Predicting fire spread in Arizona's oak chaparral. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station Research Paper RM-101. Fort Collins, CO. 11 pp.
- McAlpine RS, Lawson BD, Taylor E (1991) Fire spread across a slope. In 'Proceedings of the 11th Conference on Fire and Forest Meteorology'. pp. 218–225. (Society of American Foresters: Missoula, MT)
- Mendes-Lopes JMC, Ventura JMP, Amaral JMP (1998) Rate of spread and flame characteristics in a bed of pine needles. In 'Proceedings of the III International Conference on Forest Fire Research, Fourteenth Conference on Fire and Forest Meteorology'. Vol. I, pp. 497–511. (Luso)
- Nelson RM Jr, Adkins CW (1988) A dimensionless correlation for the spread of wind-driven fires. *Canadian Journal of Forest Research* **18**, 391–397.
- Pagni PJ, Peterson TG (1973) Flame spread through porous fuels. In 'Proceedings of the 14th Symposium (International) on Combustion'. pp. 1099–1107. (The Combustion Institute: Pittsburgh)
- Richards GD (1999) The mathematical modeling and computer simulation of wildland fire perimeter growth over a 3-dimensional surface. *International Journal of Wildland Fire* **9**, 213–221.
- Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-115. Ogden, UT. 40 pp.
- Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-43. Ogden, UT. 161 pp.
- Sheshukov MA (1970) Effect of the steepness of the slope on the propagation rate of fire. *Lesnoye Khozyaystvo* **1**, 50–54. [English translation by Library, Environment Canada]
- Taylor GI (1961) Fire under the influence of natural convection. In 'International Symposium on The Use of Models in Fire Research, National Academy of Sciences–National Research Council'. (Ed. WG Berl) pp. 10–31. (Washington, D.C.)
- Van Wagner CE (1977) Effect of slope on fire spread rate. *Bi-monthly Research Notes* **33**, 1–2.
- Van Wagner CE (1988) Effect of slope on fires spreading downhill. *Canadian Journal of Forest Research* **18**, 818–820.
- Weise DR (1993) Modelling wind and slope-induced wildland fire behavior. PhD thesis, University of California, Berkeley. 130 pp.
- Weise DR (1994) The ups and downs of wall shear-stress. In 'Proceedings of the 12th Conference on Fire and Forest Meteorology, Society of American Foresters'. Jekyll Island, GA. pp. 572–578.
- Weise DR (2000) Personal written communication, May 2000.
- Weise DR, Biging GS (1994) Effects of wind velocity and slope on fire behavior. In 'Proceedings of the Fourth International Symposium on Fire Safety Science'. (Ed. T Kashiwagi) pp. 1041–1051. (Ottawa)
- Weise DR, Biging GS (1997) A qualitative comparison of fire spread models incorporating wind and slope effects. *Forest Science* **43**, 170–180.