Effects of Wind Velocity and Slope on Fire Behavior

DAVID R. WEISE[1]
Pacific Southwest Research Station
U.S.D.A. Forest Service
4955 Canyon Crest Dr., Riverside, California 92507, USA

GREG S. BIGING
145 Mulford Hall
Department of Environmental Science, Policy and Management
University of California
Berkeley, California 94720, USA

ABSTRACT

Effects of wind velocity and slope on fire spread rate and flame length were examined. Fuel beds of vertical sticks (13.97 cm x 0.455 cm x 0.110 cm) and coarse excelsior were burned in an open-topped tilting wind tunnel. Mean fuel moisture content of sticks and excelsior was 11% and 12%, respectively. Mean surface area to volume ratio was 23 cm^{-1}. Five slopes (negative, positive, none) were combined with five wind velocities (heading, backing, none). Spread rate was measured with thermocouples; flame length was estimated from video imagery. Mean spread rate ranged from 0.001 to 0.06 m/s. Spread rate of downslope heading fires exceeded spread rate of no-wind/no-slope fires. Mean flame length ranged from 0.08 to 1.69 m; 0.25 m was the maximum observed for most backing fires. Increased fuel moisture reduced spread rate and flame length. Data indicate that the current formulation of an empirical wildland fire spread model is inappropriate.

KEYWORDS: spread rate, flame length, heading fire, backing fire

INTRODUCTION

Wind velocity and slope are incorporated into models of wildland fire behavior. We know of no studies in which their combined effects on fire spread rate and flame length have been examined experimentally concurrently in porous, thermally thin fuels. Only four rate of spread models containing wind velocity and slope have been found [1-4]. Two of these models were developed using statistical model-fitting techniques (eq. 1, 2) [3, 4] and are based in part on observed wildland fire spread rates [4-6]. Parameters of the third model, which is based on the conservation of energy, were estimated from experimental data (eq. 3) [7, 1]. The last model(eq. 4) is the only true physical model in the sense that many heat transfer components were explicitly included [2].

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$$ROS_N = \exp(f(\theta_s))*g(\exp(U)) \quad (1)$$

$$ROS_C = h(1\text{-}\exp((\exp(U))) \quad (2)$$

$$ROS_R = R_0(1 + j(U) + k(\theta_s)) \quad (3)$$

$$ROS_P = l(m(U) + n(\theta_s + p(U))) \quad (4)$$

ROS_R, ROS_N, ROS_C and ROS_P are spread rate predicted by the Rothermel [1], Noble [3], Canadian [4], and Pagni and Peterson [2] models, respectively. R_0 is spread rate for no-wind/no-slope, $f()$ through $p()$ denote various functions, U is wind velocity, and θ_s is slope angle. The functions of U and θ_s can be quite complex and all are nonlinear in form. The interested reader is referred to the original references [1-4] for explicit form of the functions.

COMBINING WIND AND SLOPE

Wind velocity and slope have been incorporated as multipliers of spread rate expected in the absence of wind and slope [1, 3, 4] (eq. 1, 2, 3). The Pagni and Peterson model [2] included a term that combined wind and slope effects on flame angle and, thus, heat transfer from the flame to unburned fuel via radiation (eq. 4). The idea that the effect of slope on spread rate is similar to the effect of wind and, as such, can be viewed as an added component of wind velocity was discussed as early as 1946 [8]. All of these models were originally formulated for wind-aided fire spread upslope.

In order to extend the utility of models that have been operationally implemented, procedures to combine wind and slope effects have been devised. Vector addition to combine wind and slope factors into an "effective" wind speed is presently used in the U.S. and Canadian systems [9, 4]. An elaborate vector-based system that has not been implemented in the U.S. system was devised by Albini [10].

Dimensional analysis was used to derive an equivalence relation between wind speed and slope angle [11]. This analysis was then extended to derive a correlation between spread rate and interaction between wind and slope [12]. The correlation was restricted to wind-aided fires on any slope. Wind and slope effects on fire behavior have been studied experimentally separately, i.e. when one of the two factors has been zero. The combined effects of wind velocity and slope on the spread rate of non-flaming combustion have been examined [13]. Combined effects of wind velocity and slope angle on spread rate or flame length have not been determined experimentally.

This paper presents experimental data from a study in which wind velocity and slope percent were varied concurrently. The results of statistical analysis to determine the effects of wind velocity and slope on spread rate and flame length are presented. No attempt to develop a physical model for spread rate was made because several such models already exist. The data presented in this paper were used to validate existing models (eq. 1-4).

Details of model validation are beyond the scope of the present paper; however, both the Pagni and Peterson model (eq. 4) and the Rothermel model (eq. 3) coupled with Albini's vector system [10] compared favorably [14].

EXPERIMENTAL SETUP

Fuel beds were constructed using white birch (Betula papyrifera Marsh.) sticks (L = 13.97 cm, W = 0.455 cm, D = 0.110 cm) and coarse excelsior made from quaking aspen (Populus tremuloides Michx.). Stick size and spacing of fuel particles, particularly sticks, have been shown to affect spread rate [15]. However, the effect of spacing was not examined in the present study. The spacing was arbitrarily chosen within the range of other similar experiments while considering the cost of fuel bed construction. Sticks were placed vertically in soft insulating brick using a rectangular grid (2.86 cm x 2.26 cm). This spacing resulted in a stick density of one stick per 6.45 cm^2. This technique has been widely used in laboratory-based spread rate studies [16, 17]. Fuel bed dimensions were 2.52 m (L) x 0.69 m (W) x 0.11 m (D). To ensure successful spread for the no-wind/no-slope treatment, 0.2 kg of coarse excelsior was uniformly distributed over the each fuel bed. Average excelsior depth was less than 0.5 cm. Mean surface area to volume ratios for the birch sticks and aspen excelsior were 22.75 cm^{-1} and 24.90 cm^{-1}, respectively. Mean total fuel bed dry weight was 1.14 kg and mean weight per unit area was 0.66 kg/m^2.

Recognizing that orientation of a noncircular stick may be critical to heat transfer, we held stick orientation constant within each fuel bed. As detailed below, 25 combinations of wind velocity and slope were examined. To determine if stick orientation affected the results, the experiment (30 fires) was run twice--once with the 0.5-cm face toward the flame and once with the face perpendicular to the flame. Fuel moisture was not controlled; however, ambient conditions in the test facility did not vary greatly during the experiment, and fuel moistures were fairly constant.

All tests were conducted in the combustion laboratory of the U.S.D.A. Forest Service Southern Forest Fire Laboratory in Macon, GA between July 24 and August 17, 1992. The combustion laboratory is a room approximately 12.2 m x 12.2 m x 10 m tall. A 3.66-m diameter circular hood, centered in the room, exhausted the room through a 0.356-m diameter stack. The fuel beds were burned in a small, open-topped wind tunnel centered under the hood [14].

Fires were ignited at one end of a fuel bed. After the first two or three rows were burning, the fan was turned on to induce flow. Steady-state spread was achieved within the next fifteen rows for all but one wind velocity and slope combination. The one exception is noted below.

MEASUREMENTS

An array of 3-mm (30 gauge) chromel-alumel thermocouples (TCs) were inserted through the ceramic brick base of the fuel bed. Height of the TCs above the fuel bed base was approximately 5 cm. Two rows of nine TCs arranged on a 22.5-cm by 22.5-cm spacing were located equidistantly from the edge of the fuel bed. The TCs were connected to two

Keithley-Metrabyte[2] EXP-16A multiplexer boards. A Keithley-Metrabyte DAS-8 eight-channel analog input board gathered TC voltages that were then converted to temperatures. A single reference junction was used for all TCs. Voltages were collected at a sample rate of 10 Hz for all TCs.

Spread rate (R_f) was estimated using eq. 5. The distance from thermocouple *a* to thermocouple *b* was 0.225 m, t_z is the time at which thermocouple *z* ($z = a, b$) first reached the reference temperature, and R_f is spread rate in m/s. Mean spread rate was estimated for each fire with the harmonic mean [18]. Spread rate variation within a fuel bed was estimated with the standard error. Sample size of 16 was not obtained in all instances because of (a) failure of fire to spread or (b) failure of a TC.

$$R_f = 0.225(t_b - t_a)^{-1} \tag{5}$$

A video camera recorded each fire. The equipment and procedures used to measure flame length (L_f) have been described [19, 20]. The video image was digitized using a standard length placed in the field of view, and flame properties were calculated using geometric properties of photographs. Arithmetic means for flame length were estimated using a sample size of ten for each fire. Sample sizes used by others ranged from four to eighteen [21].

EXPERIMENTAL DESIGN AND ANALYSIS

Five nominal wind velocities (-1.1, -0.4, 0, 0.4, and 1.1 m/s) were combined with five slope percentages (-30%, -15%, 0%, 15% and 30%). Wind velocities < 0 denote backing fires and slope percentages < 0 indicate downslope fires (Fig. 1). The experiment of 30 fires consisted of all 25 wind and slope combinations (treatments) and a partial replication consisting of the four treatment extremes and the no-wind/no-slope treatment. The four treatment extremes were (a) -1.1 m/s wind velocity, -30%; (b) -1.1 m/s, 30%; (c) 1.1 m/s, -30%; (d) 1.1 m/s, 30%. These 60 fires (30 fires per experiment x 2 stick orientations) will be referred to as the "main" experiment.

To determine if the relationship between wind velocity and slope angle was invariant under different fuel moisture regimes, a second experiment was conducted in which stick fuel moisture was increased by soaking the sticks prior to fuel bed construction. The partial replication described above was applied to fuel beds with a higher moisture content. These fires are referred to as the "moisture" experiment. Excelsior moisture content was not controlled.

Response surface methodology (RSM) was used to analyze the experiment. RSM is a statistical process that includes (a) setting up an experiment(s) that yields reliable measurement of the response of interest, (b) determining a mathematical model that fits the observed data best by using hypothesis testing, and (c) determining the optimal settings of the experimental factors that produce a maximum (or minimum) response [22]. If no

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theoretical relationship between the variables of interest exists, a polynomial approximation is often used. We initially analyzed the data using a 2nd order polynomial model (eq. 6), but ultimately chose a 3rd order model that fit the data (eq. 7). Analysis of variance (ANOVA) was used to test the significance of each of the terms in eq. 6, 7.

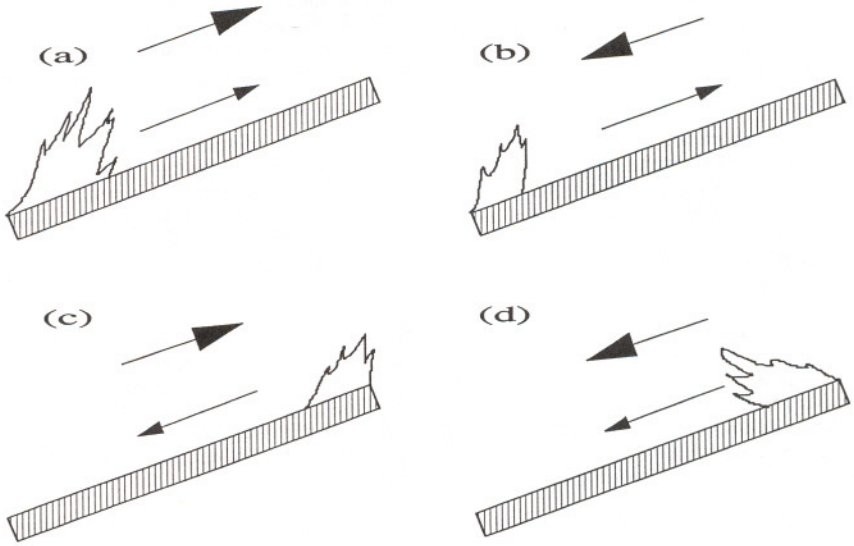

Figure 1. Various combinations of wind velocity and slope: (a) upslope heading fire, (b) upslope backing fire, (c) downslope backing fire, (d) downslope heading fire. Small arrows indicate direction of fire spread, large arrows indicate wind direction.

$$Y = \beta_0 + \beta_1(SO) + \beta_2(EMC) + \beta_3(SMC) + \beta_4(U) + \beta_5(SP) + \beta_6(U)^2 + \beta_7(SP)^2 + \beta_8(U*SP) \quad (6)$$

$$Y = \beta_0 + \beta_1(SO) + \beta_2(EMC) + \beta_3(SMC) + \beta_4(U) + \beta_5(SP) + \beta_6(U)^2 + \beta_7(SP)^2 + \beta_8(U*SP) + \beta_9(U)^3 + \beta_{10}(SP)^3 + \beta_{11}(U*SP^2) + \beta_{12}(U^2*SP) \quad (7)$$

where Y is a fire behavior measure (R_f, L_f), SO is birch stick orientation, EMC is excelsior moisture content, SMC is stick moisture content, U is wind velocity in m/s, SP is percent slope ($100\tan(\theta_s)$ where θ_s is slope angle) and β_0 - β_{12} are model parameters. The data from the 60 fires was used to estimate the parameters of eq. 6 and 7. The effects of stick orientation and moisture content were included as covariates in the models.

RESULTS

Ambient conditions remained relatively constant for the duration of the experiment. Mean air temperature and relative humidity for the main experiment were 30.2°C and 52.8%, respectively. Relative humidity ranged from 40% to 70%. Ambient air temperature ranged from 27 to 33°C. Mean moisture contents of the birch sticks and excelsior were 11.45% and 12.03%, respectively, for the main experiment and 35.94% and 12.62%, respectively, for the moisture experiment fuel beds. Fuel moisture variability, expressed as the coefficient of variation (CV), was 25.3% and 8.2% for the excelsior and sticks, respectively, for the main experiment.

Quasi-steady-state spread rate and flame length were estimated for most fires. Missing data was due to equipment malfunction. In the main experiment, seven fires failed to burn the entire length of the fuel bed. Fire was backing into a wind velocity of 1.1 m/s in six of seven instances. For fires that spread the entire length of the fuel bed, spread rate ranged from 0.0008 to 0.0697 m/s. Flame length ranged from 0.07 to 2.06 m. These extremes were observed at the treatment extremes (-1.1 m/s, 30% downslope and 1.1 m/s, 30% upslope).

Mean spread rate for 16 of 25 treatments was < 0.01 m/s. Mean spread rate for all backing fires except for the -0.4 m/s, 30% upslope treatment fell below this threshold as did spread rate for most no-slope or downslope spread. Mean spread rate ranged by 1 order of magnitude from 0.001 to 0.06 m/s. Spread rate for heading/downslope fires was greater than spread rate of the no-wind/no-slope fires. Mean flame length ranged from 0.08 to 1.69 m. Flame length for 7 of 10 backing fires was less than 0.25 m. 14 of 25 treatment combinations yielded mean flame length < 0.3 m.

Eq. 7 fit the data and explained 96.2% and 95.3% of R_f and L_f variation, respectively. The covariates (stick orientation, stick moisture content and excelsior moisture content) were not significant in the model. 2nd and 3rd order wind velocity terms were significant for the R_f and L_f models. Significant crossproduct (interaction) terms indicated that the shape of spread rate and flame length responses to wind changed as slope percent changed. Parameter estimates, used to test if each term in eq. 6 and 7 differed from 0, are not presented and can be found elsewhere [14].

As mentioned above, 16 of 25 treatments resulted in spread rate < 0.01 m/s. The relative flatness of the rate of spread response for most backing fires is evident (Fig. 2). Note the close agreement within most replicates for both R_f and L_f as indicated by the vertical error bars (Fig. 2, 3). The latter 3 standard errors are 3 of the 4 largest errors observed. The 1.1 m/s, 30% slope treatment exhibited the widest range of spread rate. If steady-state spread was achieved, for a specific wind and slope combination, a smaller range in observed spread rate among the various replicates of the treatment would be expected. This, coupled with the visual observation that flame zone depth did not appear constant for this treatment, indicated that quasi-steady-spread was probably not achieved for this treatment.

The interaction of wind and slope can be observed in Fig. 2 and 3. The rate of increase in R_f increases as slope percent increased for all heading fires (U > 0 m/s). This increase is also visible for L_f. Note the apparent decrease in R_f and L_f for the 30% slope between U = 0 and U = 0.4 m/s. The L_f error bars overlap for the 0.4 m/s heading wind velocity. Flame length standard errors for the -30%, -15%, 0%, 15%, and 30% slopes were 0.033, 0.013, 0.129, 0.115, and 0.101, respectively. Given the standard errors reported, we

can not statistically that the mean flame lengths differ. The same is true for spread rate; however, the observed value departs from what would be expected given the other observed means.

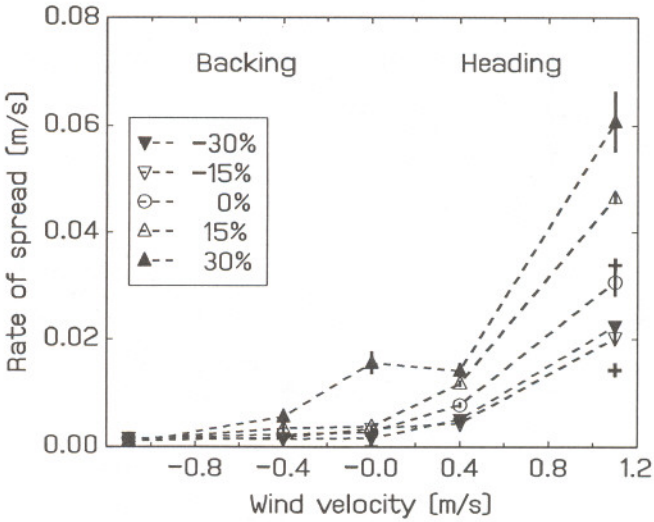

Figure 2. Actual spread rate response to various levels of wind velocity and slope percent. Vertical lines indicate +/- one standard error. Spread rate for fuel beds with stick moisture content > 35% denoted by "+".

FUEL MOISTURE

Spread rate and flame length were depressed by fuel moisture. Increasing the stick fuel moisture content had a marked effect on spread rate for the no-wind/no-slope fire as well as both backing fires. These fires all failed to spread the length of the fuel bed. Both heading fires spread successfully upslope and downslope even though fuel moisture was greater than 35%. Spread rate of the upslope fire (0.034 m/s) was nearly double that of the downslope fire (0.014 m/s). This relationship was also true for the spread rate of the same fires at the lower moisture content (0.061 vs 0.022 m/s). It was not possible to fit eq. 7 to the moisture data; however, the responses of spread rate and flame length to wind velocity and slope percent at the higher fuel moisture appeared to be similar in shape to the response from the main experiment (Fig. 2, 3). High fuel moisture fires are denoted by plusses.

No-wind/no-slope flame length for the high fuel moisture fires was 0.15 m while mean flame length for the same wind and slope was 0.6 m in the main experiment. However, flame length for the -1.1 m/s, -30% fire at the higher moisture content (0.08 m) was not that

dissimilar from mean flame length in the main experiment (0.09 m). Flame length for the 1.1 m/s, 30% fire was reduced by approximately 50% as fuel moisture increased from 11% to 36% (1.69 m vs 0.83 m).

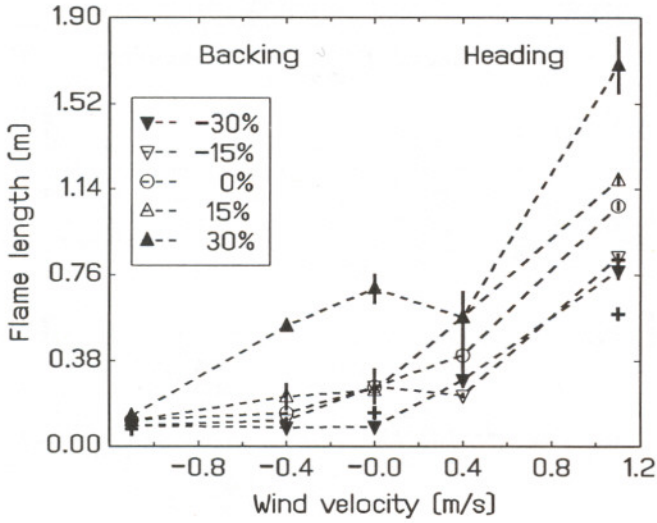

Figure 3. Actual flame length response to various levels of wind velocity and slope percent. Vertical lines indicate +/- one standard error. Spread rate for fuel beds with stick moisture content > 35% denoted by "+".

DISCUSSION AND SUMMARY

Spread rates observed in this study were of the same order of magnitude as results of other experiments in similar fuels [23]. Rates of spread of 0.002 to 0.042 m/s for small-scale backing fires in ponderosa pine needle fuel beds have been reported [24, 8]. A "rule-of-thumb" estimate of spread rate for backing fires in natural fuels is generally 0.006 to 0.017 m/s [25]. The spread rates for backing fires in this study, while of the same order of magnitude, are reduced in comparison to spread rate observed in natural settings. The relative insensitivity of backing fire spread rate to different wind velocities observed in the present study has been previously described [24] and is the basis for some operational methods of combining wind and slope. To our knowledge, no physical model for backing fires in porous fuels has been explicitly formulated. However, as noted above, the physical model (eq. 4) compared well with the observed data [14]. In eq. 4, convective heating terms vanish for backing fires and the only modes remaining are conduction and radiation.

Wind velocity and slope angle can be viewed as two forces acting on a flame and its spread rate. Much attention has been focused on the situation in which these forces act in concert on spread rate. However, many situations arise in which wind and slope forces oppose one another. The relative magnitude of each force then is critical. If wind velocity dominates, then one of two outcomes results. If wind transfers heat to unburned fuel in advance of the flame, then the fire should spread successfully. An example of this is wind-aided fire spread down slopes. This phenomenon is known as a "Sundowner" fire in southern California and has been responsible for much property damage. Observed spread rate and flame length in this study for this combination of wind and slope were significantly greater than spread rate and flame length for the no-wind/downslope fires.

The second outcome of wind dominance is failure of the fire to spread. Six of the seven fires that failed to spread the length of the fuel bed were backing fires. In all six instances, wind was cooling the unburnt fuel in advance of the flame even though slope angle would increase heat transfer via radiation.

Fuel moisture reduces spread rate and flame length and is treated as such in spread rate models. In the Rothermel model [1], if fuel moisture exceeds 30 to 35%, the no-wind/no-slope fire will not spread. Because of model formulation, if the no-wind/no-slope fire will not spread, predicted spread with wind will be 0 (eq. 3). Fuel moisture content must be less than 30% for the Noble model [3] to predict a positive spread rate in grasses. The Canadian system [4] restricts fuel moisture to less than 250% [26]. Observed spread rate and flame length were reduced by increasing fuel moisture content; however, the flame front spread successfully at a moisture content that the Rothermel and Noble models predict would preclude successful spread. Flame angles of 40° for these fires indicated that the flame was tilted by the force of wind velocity over the fuel, thereby increasing heat transfer from the flame to the fuel. Slope effect may be reduced in this situation so that the effect is primarily caused by wind, but this was not possible to determine in this limited test. Successful fire spread required a wind velocity adding to the process. However, finite rates of spread were observed in an experiment examining fire spread in live fuels [27]. Fuel beds of live French broom (Cytisus monspessulanus L.) with moisture contents ranging from approximately 30% to 100% were burned on slope angles ranging from 0° to 90°. No ambient wind flow was imposed. The results from the present study combined with the French broom results indicate that modelling of the role of moisture content in fire spread needs improvement. The functional requirement that spread in the no-wind/no-slope setting must be finite and nonzero in order for spread with wind and slope to occur is not supported by results of this experiment.

The range in wind velocity and slope used in this study was small due to the physical limitations of the wind tunnel. Note that steady state spread was not achieved for the high heading/high upslope treatment in this wind tunnel because fuel bed length was insufficient. The range of wind velocity studied is also a small percentage of the possible range of values. The steepness of the slope of the spread rate response between $U = 0.4$ m/s and $U = 1.1$ m/s may change as U increases beyond the present range. In a similar fuel, $U = 2.5$ m/s was found to be a breakpoint at which the exponent of U changed from approximately 0.5 to 3 [28]. Other studies have indicated other breakpoints and exponents. Extrapolation beyond the limits of the data should be undertaken carefully. However, the shapes of the response curves with respect to upslope spread and heading wind are similar to those reported in the literature [1, 29, 30].

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