# Influence of Slope on Fire Spread Rate

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***Abstract**—Data demonstrate the effect of slope on heading and backing fires burning through woody fuels. The data indicate that the upper limit of heading fire rate of spread is defined by the rate of spread up a vertical fuel array, and the lower limit is defined by the rate of spread of a backing fire burning downslope. The minimum spread rate is found to occur at nominally –16 degrees slope.*

# Introduction

Terrain slope can be a primary influence on wildland fire behavior (Weise 1993; Murphy 1963). This effect can be observed on any fire burning in mountainous terrain; however, few data exist that explore this phenomenon in a quantitative manner. This study reports the results of a set of experiments that were designed to provide direct measurements of fire spread and intensity as a function of terrain slope. The fuel used was shredded aspen (*Populus tremuloides*) heart wood, otherwise known as excelsior.

While some work has explored the relationship between fire spread rate and slope, understanding and data are limited. Curry and Fons (1938, 1940) posited that slope resulted in increased heat transfer between the flame and fuel ahead of it and that the effect of slope is relatively low in the absence of wind, but that the combined effect of wind and slope can be dramatic. Barrows (1951) indicates that as the slope increases so does the average size of the fire. McArthur (1968) suggests that slope can significantly affect fire rate of spread, especially immediately following ignition. He suggests that when compared to flat terrain, heading fire spread rates will increase by two times on 10 degree slopes and four times on 20 degree slopes. Murphy (1963) conducted a set of experiments using a paste consisting of wood flour mixed with sodium nitrate in a 4:1 ratio as the fuel. This mixture resulted in smoldering combustion. Both heading and backing fires were observed at slopes of 0, 14, 27 degrees over a range of wind speeds varying from 0 to 4.4 m/s in increments of 0.4 m/s. The data showed that backing fire rate of spread exceeded heading fire rate of spread for all slopes and wind speeds less than 2.7 m/s. For higher wind speeds the heading fire rate of spread significantly exceeded the backing fire spread rates. Weise (1993) presents results from a set of 65 fire experiments subjected to slope angles between –30 and +30 percent and wind speeds from –1.1 to 1.1 m/s. He compares the measurements to several published models for the slope and wind influence on fire spread rate. His data indicate that wind is the dominant variable affecting fire spread. Viegas (2005) discusses the relation between fire spread rate and

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terrain slope in the context of a model of fire spread in upward sloping canyons. He approximates the effect of terrain slope as an artificial wind parameter, recognizing that the theoretical upward flame spread limit for fire burning along a semi-infinite solid is approximated as an exponentially increasing function, which agrees with other reported studies (Alpert and Ward 1984). Other studies have been presented that explore the relation between flame spread rate on cloth and solid surfaces for purposes of determining spread rates in structural fires (for example, Markstein and DeRis 1973). The studies referenced above indicate that slope is a critical component in wildland fire spread; however, the data are insufficient to fully understand the pertinent physical mechanisms occurring in slope-driven fire growth.

For this study a set of experiments were designed to measure fire spread rate for sloped fuel beds ranging from –16 to 31 degrees. Table 1 lists the experiments and associated conditions. All tests were conducted at nominally 6 percent fuel moisture (dry mass basis), 27 °C ambient air temperature and 20 percent relative humidity.

**Table 1**—Sloped fire experiments.

| Test | Fuel | Packing ratio | Slope (%) | Fuel depth (cm) | Objectives |
|---|---|---|---|---|---|
| 1 | EXSC | 0.01 | –30, 0, 15, 30, 45, 60 | 2.5 | Fire spread on slope |
| 2 | EXSC | 0.03 | –30, 0, 15, 30, 45, 60 | 2.5 | Fire spread on slope |
| 3 | EXSC | 0.005 | –30, 0, 15, 30, 45, 60 | 2.5 | Fire spread on slope |
| 4 | EXSC | 0.01 | –30, 0, 15, 30, 45, 60 | 7.62 | Fire spread on slope |
| 5 | EXSC | 0.03 | –30, 0, 15, 30, 45, 60 | 7.62 | Fire spread on slope |
| 6 | EXSC | 0.005 | –30, 0, 15, 30, 45, 60 | 7.62 | Fire spread on slope |
| 7 | EXSC | 0.01 | –30, 0, 15, 30, 45, 60 | 15.24 | Fire spread on slope |
| 8 | EXSC | 0.03 | –30, 0, 15, 30, 45, 60 | 15.24 | Fire spread on slope |
| 9 | EXSC | 0.005 | –30, 0, 15, 30, 45, 60 | 15.24 | Fire spread on slope |

# Methods

Figure 1 is a photograph of the experiment apparatus. The fuel consisted of shredded aspen (*Populus tremuloides*) heartwood, selected for nominally uniform size shape (approximately 2.5 x 0.8 mm cross-section) and because it is readily formed into a randomly oriented fuel array with uniform bulk density and controllable bed depth. The depth and bulk density were adjusted by varying the mass of fuel per unit volume of the fuel bed. Rather than reporting bulk density, we use the term “packing ratio” (volume of fuel per unit volume of fuel bed), a term more common to wildland fire. Bulk density is the product of packing ratio and fuel density. Efforts were taken to maintain the fuel particle moisture content as uniform as possible between burns by conditioning fuel beds prior to the experiment at fixed temperature and humidity (nominally 27 °C and 25 percent RH) and burning the experiments at the same conditions. Measured fuel moistures ranged from 5 to 8 percent on a dry mass basis. The fuel tray was 1 m wide by 4.6 m long; slope angle was measured from the horizontal plane. The fires were ignited by applying electric current to a coiled nichrome wire placed in a 2 cm deep by 1 m wide tray of gasoline/diesel mixture at the base of the starting location for the fuel bed.

**Figure 1**—Photograph of experiment, upward spreading fire, excelsior fuel, bed measured 1 m wide by 3.5 m long.

Fire rate of spread was measured by dividing the length of the fuel bed by the time required for the flame front to move from the ignition location to the opposite end of the fuel bed. Time for all fuel on the bed to complete burning was not measured. In some cases fire rate of spread was also gathered from analysis of video footage. Generally these two methods agreed within ±10 percent.

## Results

Figures 2 through 4 present rate of spread data from the slope burns. The data have been normalized by dividing by the zero slope rate of spread. The horizontal axis is slope measured from the horizontal in degrees.

Figure 2 presents the data from the 2.5 cm deep fuel arrays. For all three packing ratios and all but the steepest slopes, these fires burned as individual flamelets along each individual fuel particle. In the case of the 0.005 packing ratio, the fire did not burn at all except for the steepest (31 degree) slope. The data from the fuel beds with packing ratio of 0.01 and 0.03 show a 25 percent decrease in spread rate between horizontal conditions and 16 degree downward sloped beds. No increase in spread rate was observed for slopes from 0 to 10 degrees. For slopes between 10 and 25 degrees and packing ratios of 0.01 and 0.03, fire spread rates increased slightly with slope. A dramatic acceleration in spread rate was observed from 25 to 31 degrees.

The burn data from the 7.6 cm deep fuel beds are presented in figure 3. These data suggest that for slopes less than 25 degrees, fuel bed rate of spread increases with increasing packing ratio. But as slope increases to 30 degrees, the relation reverses, and the more tightly packed bed burns approximately 15 percent slower than the bed with the lowest packing ratio. The data also indicate that when backing down a 16 degree downward slope, the rate of spread is 17 percent less than for flat conditions.

Figure 4 presents the normalized rate of spread data from the 15 cm deep fuel beds. Trends similar to those observed in the 7.6 cm deep beds are observed over the slope range of –16 to +30 degrees. Additional data

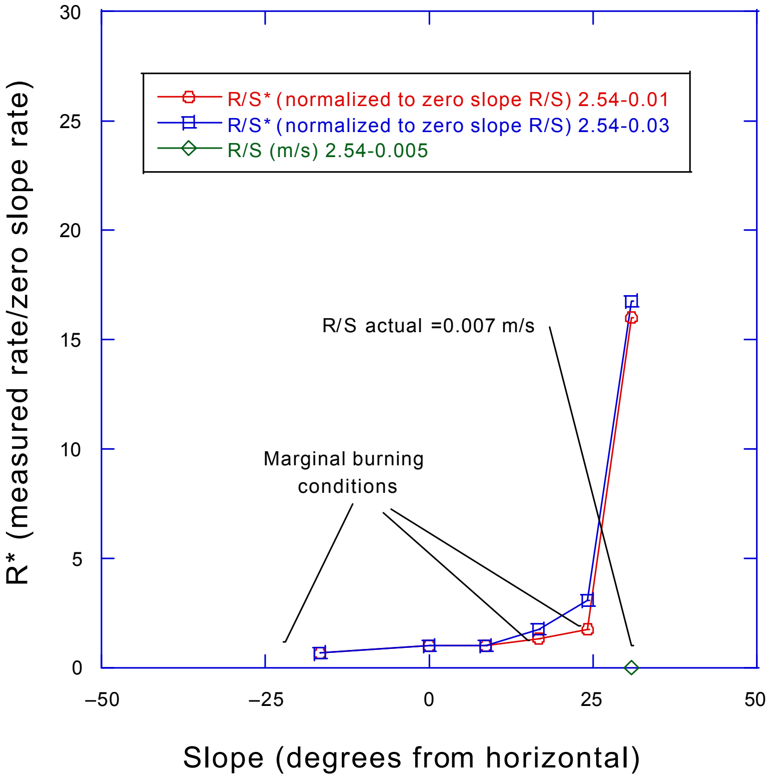

**Figure 2**—Normalized rate of spread for the 2.54 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

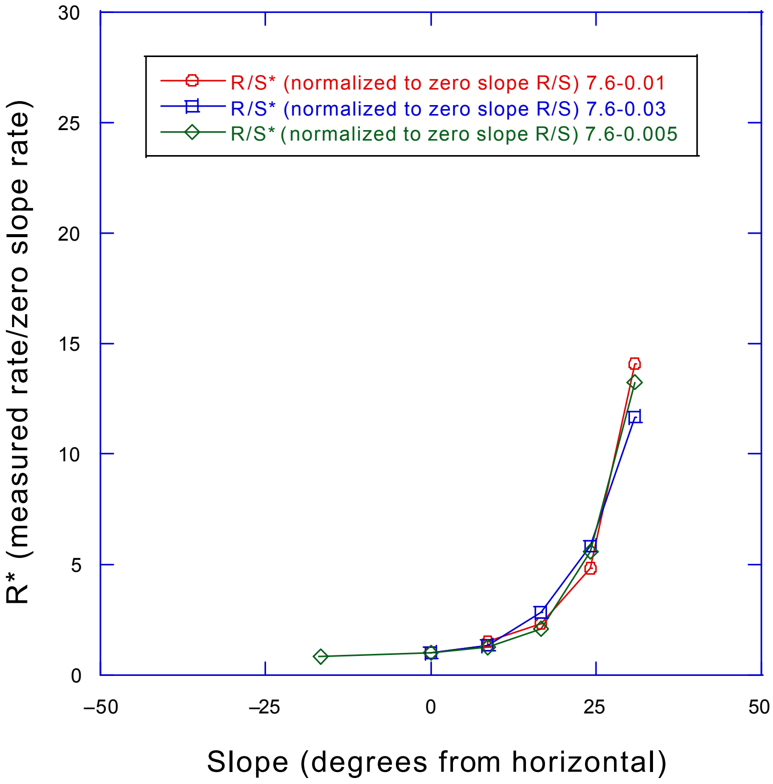

**Figure 3**—Normalized rate of spread for the 7.62 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

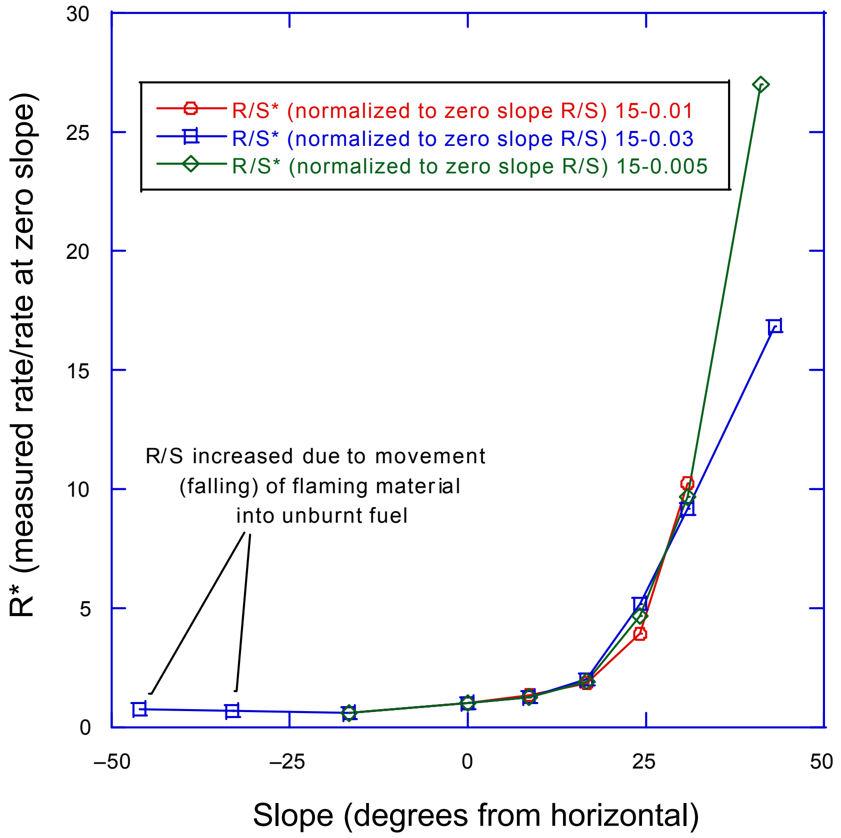

**Figure 4**—Normalized spread rate for 15 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

were collected for steep down slope backing fires to a slope of –47 degrees. These data indicate that the minimum rate of spread occurs at approximately 15 degrees downslope. For steeper slopes, the downhill rate of spread increases. The increase is attributed to burning fuel "falling" down into the bed accelerating the overall spread rate. A steeper slope of 43 degrees was explored in the lowest and highest packing ratios. These data show for these relatively steep slopes that the lower packing ratio bed spreads significantly faster. For the steepest slopes, the fires burned quickly up the 4 m long bed (approximately 20 seconds), but took significantly longer to burn down through the bed, indicating that spread occurred over the topmost layer of the fuel array.

## Discussion

The data indicate at least three unique burning regimes. The first is indicated by individual flamelets burning separately along each fuel particle. This type of burning occurred in the 2.5 cm deep fuel beds for slopes less than 25 degrees. The fire spread process for the slopes less than 25 degrees seems to be dominated by energy transfer along the individual strands, with radiant or convective energy transport insufficient to "bridge" the gap between individual particles. As slope increased above 25 degrees, an abrupt increase in spread rate with slope occurred (see fig. 2) where the fire changed from flamelets burning along fuel strands to a more coherent flame front. This change suggests a corresponding shift in the fundamental physics behind the fire spread process. We posit that radiant and convective energy transfer provides sufficient heating of the fuel ahead of the fire front to produce a more uniform flame front.

As bed depth is increased from 2.5 to 7.6 cm, a uniform flame front was observed in all cases (see fig. 3). Minimum spread rates occurred not at flat slopes (0 degrees) but at downward spreading slopes of –16 degrees. As downslope (backing fire) slope was increased further, the rate of spread was observed to increase (see note on fig. 4). For slopes between –16 and + 10 degrees the rate of spread increases at a rate roughly linearly proportional to slope. Fuel array packing ratio was not observed to be significant in this slope range. For upward spreading fires between 10 and 25 degrees, the fire rate of spread accelerates and the fuel arrays with the highest packing ratio burn fastest. As slope increases further, it appears that the fires with the highest packing ratios do not accelerate as fast as the lower packing ratios. At slopes greater than 25 degrees, spread rate was observed to increase again in a roughly linear but much greater proportion to slope.

Figure 4 presents the data from the deepest fuel bed (15 cm). Fire spread rates seemed to respond similarly at this depth to the observations for the 7.6 cm deep beds. Again the minimum spread rate occurred at roughly –16 degrees downslope. A roughly linear increase in fire spread rate with slope is observed from –16 to +16 degrees. From 16 to 25 degrees the data indicate some separation as a function of packing ratio with the more tightly packed beds burning faster. As slopes increase above 25 to 45 degrees, the lower beds with lower packing displayed much faster increases in spread rates than the more tightly packed beds. From these data we identify a third burning regime where convective energy transfer dominates the energy transfer process. The lower resistance to convective flow that is present in the less tightly packed beds results in the fastest fire spread rates. The beds with tightest packing, and highest loading, resulted in the tallest flames, but the fact that the lower packing ratio fires burned faster indicates that while radiant energy transfer is still present and probably necessary, it does not seem to dominate. However, the beds with lower packing ratios will also be conducive to the transport of radiant energy farther into the bed, which may lead to an increase in preheating. But this mechanism is believed to be secondary as the bulk of the flame transport and spread for the steepest slopes seems to occur along the top surface of the fuel array.

A transition zone, characterized by an increase in the spread rate of the less tightly packed beds that was more rapid than tightly packed beds, seemed to occur in all of the fuel beds as slopes exceed 25 degrees (see fig. 5). The result is a dramatic shift in the spread rate. This is supported by the observation that the fastest spread rates are exhibited by the beds with the lowest packing ratio. These lower density fuel arrays would be less restrictive to fluid flow and thus could be associated with enhanced convective heating.

## Conclusions

The data presented suggest three burning regimes with respect to fires on slopes. The first is dominated by fire spread along individual fuel particles and can be characterized as primarily a conductive process. However, as either fuel

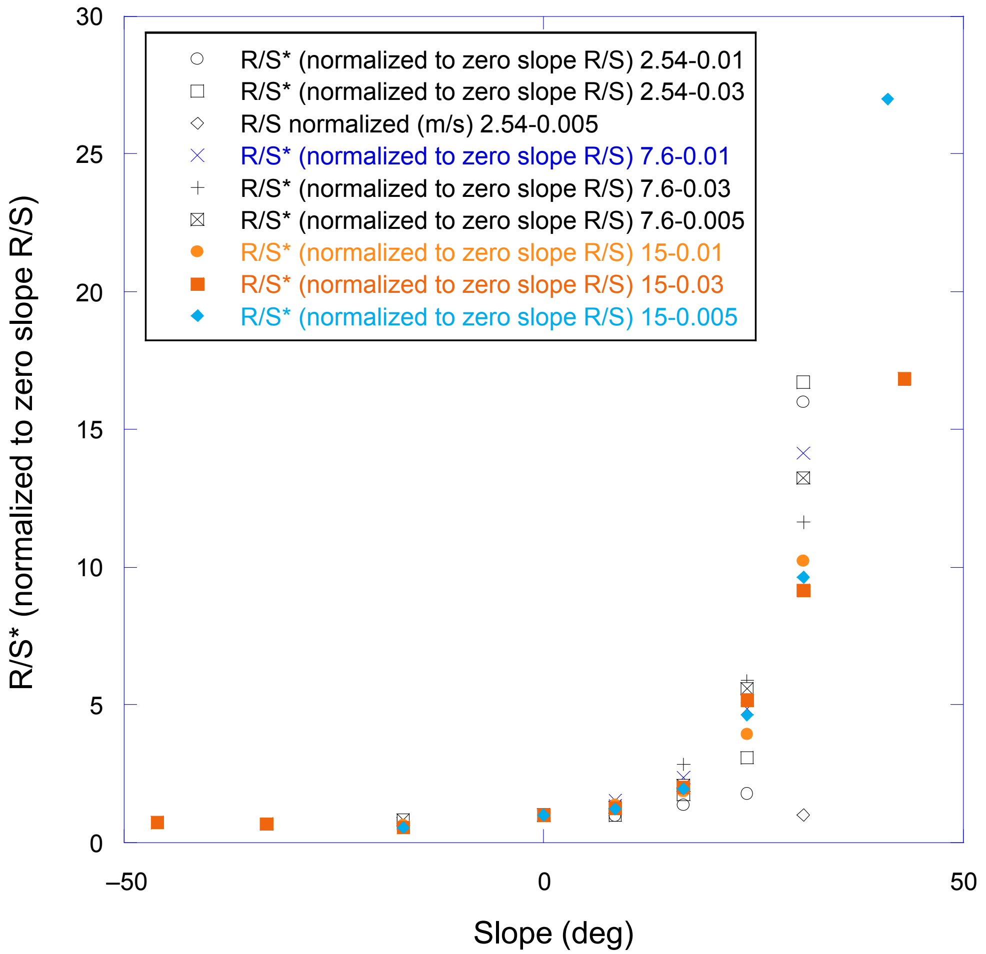

**Figure 5**—Normalized spread rate for all fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

particle density or fuel bed depth increases, fires begin to burn as a coherent front. The behavior of this front in the mid slope range (that is, slopes less than 25 degrees) indicates that fuel bed bulk densities favoring increased fuel loading burn slightly faster; we posit that this is indicative of a radiatively controlled regime. Greater fuel loading will likely result in larger and taller flames, which implies more radiatively efficient emitters of radiant energy. As slopes increase further (that is, greater than 25 degrees) beds that are less tightly packed begin to burn faster. This implies a convective dominated regime where fluid flow within and over the surface of the fuel array dominates the flame spread rate. The data indicate the need for further experiments and comparison of the data against existing fire/slope relations.

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# References

Alpert, R.L.; Ward, E.J. 1984. Evaluation of Unsprinklered Fire Hazards. Fire Safety Journal 7, 127-143

Barrows, J.S. 1951. Fire behavior in northern Rocky Mountain forests. Pub. No. 29. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Curry, J.R.; Fons, W.L. 1938, Rate of spread of surface fires in the ponderosa pine type of California. J. Agr. Res. 57:239-267.

Curry, J.R.; Fons, W.L. 1940. Forest fire behavior studies. Mech. Engng. N.Y. 219-25.

Markstein, G.H.; DeRis, J.N. 1973. Upward Fire Spread over Textiles. Proc. Fourteenth Symposium (Intl) on Combustion. The Combustion Institute: 1085-1097.

McArthur, A.G. 1968. Fire Behaviour in Eucalypt Forests. Leaflet No. 107. Ninth Commonwealth Forestry Conference, India, 1968.

Murphy, P.J. 1963. Rates of fire spread in an artificial fuel, MSc. Thesis. Bozeman, MT: Montana State University.

Viegas, D.X. 2005. A mathematical model for forest fires blowup. Combust. Sci. and Tech. 177:27-51.

Weise, D.R. 1993. Modelling wind and slope-induced wildland fire behavior. Ph.D. Dissertation. Berkeley: University of California at Berkeley. 130 p.