United States
Department of
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Forest Service

**Intermountain
Forest and Range
Experiment Station**

Research Note
INT-309

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Frank A. Albini[1]

ABSTRACT

This note extends a predictive model for estimating spot fire distance from burning trees (Albini, Frank A. 1979. Spot fire distance from burning trees--a predictive model. USDA For. Serv. Gen. Tech. Rep. INT-56, 73 p. Intermt. For. and Range Exp. Stn., Ogden, Utah). A formula is given for the maximum firebrand lofting height by continuous flames, such as from burning piles, jackpots of woody fuel, and so forth. This height may be used directly in the algorithm detailed in the earlier work. Also, formulas and graphs are given for estimating maximum spot fire distance when the terrain downwind of the source of firebrands is covered by vegetation of low height, bare ground, or water, rather than forest. This extension is implemented by establishing an "effective" or minimum vegetation height to be used in the formulas given in the earlier work. The effective vegetation cover height so derived depends on the firebrand initial height.

KEYWORDS: spot fire, spotting, firebrands

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A predictive model for the maximum distance between a source of firebrands--a burning tree or group of trees--and a potential spot fire has been published (Albini 1979) and used as the basis for a field application procedure.[2] The model is an assemblage of six separate submodels, each for a distinct aspect of the overall process involved. The six submodels describe the following processes or phenomena:

1. The structure of a steady (time-invariant) flame that consumes the combustible pyrolyzate from the foliage of a tree or from a group of identical trees burning simultaneously that provides the aerodynamic environment for the initial lofting of a firebrand particle into a quiescent atmosphere.

2. The structure of the steady buoyant plume established by the flame in a quiescent atmosphere that provides the aerodynamic environment that lofts the particle to its ultimate height.

3. The rate at which a woody particle burns as it moves relative to the atmosphere.

4. The trajectory of an inert cylinder (a surrogate for firebrand particles of cylindrical or platelike structure) in the steady, but nonuniform, flow field of the flame and the buoyant plume above it. The predicted height as a function of time is the key result of this model.

5. The structure of the surface wind field over rough terrain--idealized as a sinusoidal elevation-versus-distance contour--that transports the firebrand from its maximum height above its burning tree origin to its downwind destination.

6. The trajectory of a burning woody cylinder in a steady, but nonuniform, wind field.

A host of assumptions is needed to complete each of the separate submodels and an additional set is needed to link them in a procedure for predicting the maximum spot fire distance. These assumptions are spelled out completely in the cited work and will not be repeated here, except for those germane to the extensions presented.

Two extensions of the procedure are offered here. The first removes the restriction that the entire firebrand lofting process is driven by the transient flame from "torching" trees. Instead, the continuous steady flame from any isolated source, such as burning piles of harvest debris, "jackpots" of heavy fuel, and so forth, may be assumed to be a potential firebrand source, described only by the height of the continuous flame. The second extension relaxes the implicit assumption that the terrain over which the firebrand particle flies is forest-covered land. Thus spotting over water, meadowland, or bare ground can be estimated, extending the scope and utility of the original procedure.

FIREBRAND LOFTING BY CONTINUOUS FLAMES

If a firebrand is lofted by the flame/plume structure from a torching tree, the particle is assumed to be lifted from the treetop at the start of the steady burning

[2]National Wildfire Coordinating Group, 1979: Fire behavior officers' field reference. USDA For. Serv. Natl. Adv. Resour. Technol. Cent., Marana Air Park, Ariz., looseleaf.

period. The particle would continue to rise until its weight was just balanced by the aerodynamic drag exerted on it by the buoyant plume flow, were it not for the fact that the fire goes out when the fuel is consumed. When the fire goes out, the plume flow structure collapses and the demise of the vertical airflow pattern limits the height achieved by the potential firebrand. So for each particle size, there is a maximum height that can be achieved for a given "steady" flame duration.

Since larger (heavier) particles rise more slowly than do smaller ones, another competition comes into play. Small particles do not continue to burn for as long a time as large ones and so cannot fall from as great a height and still start fires. By this reasoning, there is a particle size that can be lofted to such a height that it will just be consumed upon returning to the ground. A larger particle could not be lofted that high and so would fall back sooner (hence at not so great a distance downwind), while a smaller one could be lofted higher, but would be burned up before it fell back. The particle that is just consumed as it returns to the ground thus represents the firebrand that can start a spot fire at the greatest possible distance from its origin.

The equations that express quantitatively all of the relationships outlined above are to be found in the appendices, especially B and D, of Albini (1979).

If the steady burning period for a torching tree were to be extended indefinitely, the flame/plume flow structure would be permanent and one of the steps in the process described above would be eliminated. For such a continuous flame, the height that a particle can achieve in the buoyant plume is not limited by the flame's duration; so it can be assumed to reach the ultimate height where its weight and drag force are in balance. Expressed another way, the particle will rise until the vertical gas velocity in the plume is equal to the terminal velocity of the particle falling freely in the reduced-density environment of the hot plume.

The dynamic pressure distribution in the plume is given by[3]

$$q/q_F = (8/3)\left(1 - (5/8)(z_F/z)^{5/3}\right)(z_F/z)^{2/3} \qquad \text{(B10)}$$

where

q is the dynamic pressure
z is height

and subscript F implies the value at the tip of the flame. From the steady flame structure model, we have

$$q_F = 0.0078 z_F \qquad \text{lbf/ft}^2 \qquad \text{(A60)}$$

when z_F is measured in feet.

Equating the weight of the particle to the drag it experiences, we find the dynamic pressure, q, needed to suspend a cylindrical particle of diameter D:

$$qC_D \cdot \ell D = \rho_s g \pi D^2 \ell/4$$

or

$$q = \rho_s g \pi D/4C_D$$

where

[3]Numbered equations correspond to the equations in Albini (1979). Letters preceding the numbers identify the appendices in which the equations appear.

C_D is the drag coefficient = 1.2 (D20)

$\rho_s g$ is the weight density of the particle = 19 lbf/ft^3 (D21)

ℓ is the particle length (irrelevant)

D is the particle diameter, feet.

The maximum height from which a particle can fall and still be burning when it hits the surface is given by

$$\max(z) = 0.39 \cdot 10^5 D \quad \text{ft.} \tag{D44}$$

Using (D44) to replace D in the last equation for q and using the result, along with (A60), in (B10), we can solve for the height z from which would come the firebrand particle with the greatest potential spotting distance. From (B10) and (A60) we have

$$q = (0.0078 z_F)(8/3)\left(1 - (5/8)(z_F/z)^{5/3}\right)(z_F/z)^{2/3},$$

which must equal the needed dynamic pressure. Using the equation for q and (D44), then

$$q = (19)(\pi)(z/0.39 \cdot 10^5)/(4)(1.2).$$

Equating these two expressions for q and dividing the resulting expression by z gives an equation quadratic in the ratio $x = (z_F/z)^{5/3}$, with dimensionless numerical coefficients:

$$x(1 - 5x/8) = (3/8)(19\pi)/(4)(1.2)(0.39 \cdot 10^5)(0.0078) = 0.0153$$

or

$$x^2 - 1.6x + 0.0245 = 0.$$

From this equation we obtain one physically meaningful root which gives

$$z/z_F = x^{-3/5} = (0.0155)^{-3/5} = 12.2.$$

This general result states that the height of a continuous flame multiplied by 12.2 gives the maximum viable firebrand lofting height. This height may be used directly in the nomograph (fig. 8 in Albini, 1979) to solve for maximum spot fire distance. It is denoted by z(0) in appendix F of the cited work, where the spotting distance formula is derived.

SPOTTING OVER TERRAIN NOT FOREST-COVERED

In the development of the spotting distance model, it was necessary to integrate the equations of motion of the firebrand particle as it was borne along by the wind field. The approximations justified in that development are that the particle falls with a relative vertical velocity that decreases linearly in time, while it is carried horizontally at the local horizontal windspeed. The resulting equation for the trajectory over flat terrain can be written as

$$\frac{dx}{dz} = -\left(\frac{z(0)}{z}\right)^{1/2}\frac{u(z)}{v_o(0)} \qquad \text{(F18)}$$

where

x is the horizontal (map) distance from the spot source in the direction of the prevailing wind

z is the height of the particle at distance x

z(0) is the initial firebrand height

u(z) is the x-direction (horizontal) windspeed at the height of the particle, z

$v_o(0)$ is the terminal falling velocity of the particle when it first begins to descend.

Since the terminal falling velocity at the time the particle first starts to fall is related to its size by the restriction that it still be burning at impact, it can be shown that

$$z(0) = \beta^2 v_o^2(0)/g \qquad \text{(F9)}$$

where β is a dimensionless constant and g is the acceleration of gravity. Using this form in the equation for the trajectory gives:

$$\frac{dx}{dz} = -\beta u(z)/(gz)^{1/2}.$$

From this equation, we have the general form for the spot fire distance, X*, over flat terrain:

$$X^* = \beta \int_{z(u=0)}^{z(0)} u(z)/(gz)^{1/2} dz.$$

In the original formulation, the profile of horizontal windspeed with height was assumed to be of the form

$$u(z) = u_H \ln(z/z_o)/\ln(H/z_o) \qquad \text{(F14)}$$

where

u_H is the windspeed at treetop height, H

z_o is the "friction length," estimated to be about 0.13H for forest-covered terrain under neutrally stable conditions.

This form leads to the equation used in the nomograph (fig. 8 in Albini 1979) for spotting distance:

$$X^* = 21.9 u_H \left(\frac{H}{g}\right)^{1/2}\left\{0.362 + \left(\frac{z(0)}{H}\right)^{1/2} \frac{1}{2} \ln\left(\frac{z(0)}{H}\right)\right\}. \qquad \text{(F22)}$$

Clearly it is implicit in the use of (F14) in the integral for X* that the height of the particle should not exceed the range of validity of the windspeed formula by enough to distort the result significantly. When the terrain downwind of the spot source is forest covered, the aerodynamic scale parameter called the "friction length" will be on the order of meters (Baughman and Albini 1980) and since we are concerned with atmospheric conditions of at least neutral stability, the windspeed profile of (F14) should be applicable with high reliability to at least 150 m (Thuillier and Lappe 1964; Carl, Tarbell, and Panofsky 1973). The precise role of the friction length parameter, z_o, in determining the maximum height to which the logarithmic profile is applicable is not completely clear and may, in fact, be irrelevant (Tennekes 1973). It is usually assumed that z_o serves as a length scale for the friction-dominated surface layer of the atmospheric boundary layer (Plate 1971, Maitani 1979). If one interprets the data presented in the cited sources as defining the maximum height, measured in friction lengths, of the logarithmic profile's validity, then one must conclude that the maximum height is a few thousand friction lengths, depending upon stability and other considerations.

In any case, one can readily appreciate that (F22) should overestimate the maximum spotting distance if for the value of "tree height," H, one used the height of mown grass instead. The source of the error that would be made is obviously use of an inappropriate windspeed profile. To extend the applicability of the model to situations in which the firebrand trajectory is over short grass, bare ground, or even water, we need a different description of the windspeed profile that does not exhibit the singular behavior of (F22).

Boundary-layer studies on smooth, flat plates and pipe flow studies have repeatedly confirmed (Schlichting 1968) a velocity profile for turbulent flows that is of the form

$$u(z)/u_B = (z/B)^{1/7}.$$

Here B is any distance from the wall within the variable-speed layer and u_B the flow speed at that position. This form has been found to have broad applicability in meteorological work as well (Sutton 1953; Plate 1971), although exponents other than 1/7 are often used to correlate data taken in the atmospheric boundary layer. Sutton (1953) relates the exponent to stability conditions, suggesting use of 1/7 for neutral or greater stability, while Plate (1971) graphs a relationship between the exponent and aerodynamic friction length. For very small friction lengths (1 cm and less), the suggested exponent is 0.1, rising semilogarithmically to 0.4 for a 3 m friction length. For "flat, open country," the suggested exponent shown is about 1/7. The thickness of the air layer over which the power law profile is applicable in no case is less than 270 m, according to Plate, and reaches twice this value over woodlands.

On the basis of these considerations, the power law profile with an exponent of 1/7 may be used as a replacement for the logarithmic profile whenever the height of the vegetation cover is small enough and the initial height of the firebrand is large enough that the logarithmic profile becomes suspect. This "decision point" for shifting from one windspeed profile model to another should be determined, ideally, on the basis of fidelity of the models in the situation. Yet, operationally, it makes no difference whether or not the windspeed profile model employed gives an accurate description of the wind field. What matters is the spot fire distance that is predicted by the use of the windspeed model. And since both models demand a reference windspeed at a reference height from which extrapolations are made, either input variable can be adjusted artificially to provide the same prediction as would the use of the other model.

Symbolically, the spot fire distance predicted by the logarithmic windspeed profile model can be written as X_1^*, where

$$X_1^* = \beta u_H\left(z(0)/g\right)^{1/2}\left\{\ln\left(\frac{z(0)}{H}\right) + 0.724/\left(\frac{z(0)}{H}\right)^{1/2}\right\}.$$

Likewise the spot fire distance predicted by the power law windspeed profile model can be written as X_2^*:

$$X_2^* = \beta u_B\left(z(0)/g\right)^{1/2}\left\{\frac{14}{9}\left(\frac{z(0)}{B}\right)^{1/7}\right\}.$$

Taking u_B to be the windspeed at the standard height, B = 20 ft (6 m), and assuming that the form X_2^* gives a valid spotting distance prediction, we can discover at what value of z(0) the log formula overpredicts for a given value of H, once we assign the value of u_H. We do this by equating X_1^* to X_2^* and solving the resulting expression for z(0)/B as a function of z(0)/H and u_H/u_B. For a fixed value of u_H/u_B, inserting an assumed value for z(0)/H gives the value of z(0)/B and hence the pair (z(0),H). The graphs shown in figure 1 are plots of this relationship for different values of the windspeed ratio u_H/u_B.

Of particular interest in figure 1 is the curve for $u_H/u_B = 2/3$. This is the value that is assumed for this ratio in the current version of the Fire Behavior Officers' (FBO) Field Reference (see footnote 1). Consequently, when the material in that field guide is used to estimate spotting distance, the log formula will overpredict when the firebrand height is greater (for a given cover height) than the value read from that curve. Switching to the power law profile at that height renders the prediction then insensitive to the vegetation cover height.

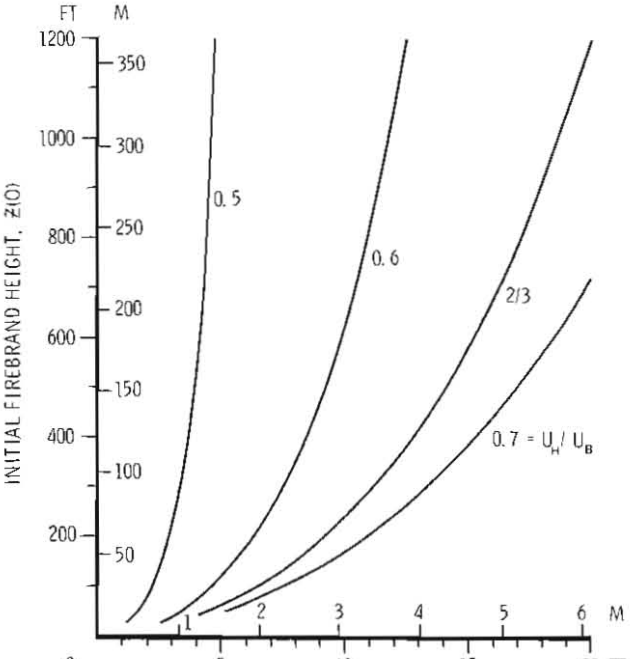

Figure 1--Decision curves for choice of windspeed profile model. Above appropriate curve, use power law model; below, use log profile. u_B is 20 ft (6 m) windspeed, u_H is windspeed used to represent value at height of top of vegetation cover.

Operationally, one need never employ the power law profile explicitly. All one need do is determine the minimum vegetation height (for a given firebrand height) required to use the log profile--by reading the graph of figure 1 "backward"--and, if necessary, to use this minimum value as an "effective" height, H*, in the log formula. In the case of the FBO Field Reference assumption, $u_H/u_B = 2/3$, the curve in figure 1 is well approximated by a simple power law relationship:

$$H^* = \begin{cases} 2.2z(0)^{0.337} - 4.0 & \text{ft, } z(0) \text{ in feet} \\ z(0)^{0.337} - 1.22 & \text{m, } z(0) \text{ in meters.} \end{cases}$$

This relationship directly gives H* as a function of z(0), as needed for the substitution. If the actual vegetation cover height is less than this value, one should merely use the "effective" value from this formula in the nomograph (or manual) calculations using the log profile formula. The obvious reason is that this "effective" value of H is just the one that will cause the log profile formula to yield the spotting distance that would be found from the power-law formula for the value of z(0) used.

The equations given in Albini (1979) for adjusting the spot fire distance in flat terrain to predict the distance in high-relief terrain are not affected by the shift in windspeed profile models. Once the flat-terrain spotting distance is predicted, it can be adjusted for terrain relief by the method outlined in the cited paper.[4]

The adjustment of spotting distance for the effect of terrain relief is included in a pocket calculator program (Chase 1981) that automates the computation of spotting distance outlined in Albini (1979). The extensions presented in this note are also included in the pocket calculator program.

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[4]There is a typographical error in Albini (1979), page 72. The "ridgetop" value of the parameter mX_1 listed on that page *should* be $\pi/2$, not π.

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