ESTIMATING MIDFLAME WINDSPEEDS

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Wind is one of the major factors involved in predicting forest fire behavior. Fire behavior models require wind information to predict fire spread in various fuel types and within forest stands in complex terrain. The means of providing the necessary wind data in remote areas, however, are presently not available in usable forms. Studies are now underway at the Northern Forest Fire Laboratory to develop ways of estimating or predicting wind velocities on a local scale of a fire given various topographic and vegetative conditions.

Rothermel (1972) gives a mathematical model for predicting the rate of spread of a surface fire. This model uses an average windspeed at "midflame height" to account for the influence of wind on the rate of spread. But the windspeed is usually measured or forecast at a standard height of 20 feet (6 m) above the vegetation (Fischer and Hardy 1972), making it necessary to approximate the "midflame" windspeed given the 20-foot standard height wind. Recently, Albini and Baughman (1979) published a mathematical treatment of the problem. But the analytical development was not in a form convenient for application, so a more practical tabular form was subsequently produced. The two forms, analytical and tabular, are discussed here to provide continuity and proper documentation. The basic concepts and results are presented along with the more convenient tabular data presently used by fire behavior officers.

We first describe the wind field over a vegetative cover that is a single-stratum fuel (grass, brush, and so forth). The second part of the paper deals with wind under a forest canopy.

WINDSPEED OVER THE VEGETATION COVER

The windspeed above a vegetative cover was determined by using the logarithmic wind profile in the following form (Monteith 1972, p. 91).

$$\overline{U}_z = \frac{U_*}{K} \ln\left(\frac{z-D_o}{z_o}\right)$$

where

$\overline{U}_z$ is the average windspeed at height z

U_* is the friction velocity $U_* = \sqrt{\tau/\rho}$, τ is the horizontal shear stress and ρ is air density)

$K = 0.4$ (the von Kármán constant)

z is height above ground

D_o is the zero-plane displacement

z_o is the roughness length.

Although this profile depends somewhat upon temperature lapse rate, it holds over a wide range of atmospheric conditions above vegetative cover (Van Hylckama 1970, Oliver 1971).

Values for the zero-plane displacement and the roughness length factors are given by Monteith (1973, p. 88 and 90) as $D_o = 0.63H$ and $z_o = 0.13H$ where H is the height of the vegetation. A slightly different value of $D_o = 0.64H$ was used by Albini and Baughman (1979). The works of Cowan (1968) and Stanhill (1969) show that these values are quite acceptable for practical use. Note that by expressing D_o and

z_0 as fractions of H, the log-wind profile equation becomes a function of z/H only. This means that a universal dimensionless wind profile applies above any vegetation, from short grass to tall trees. This universal windspeed profile is shown in figure 1. The dashed line represents an assumed extension of the wind profile into the vegetation cover (see next section).

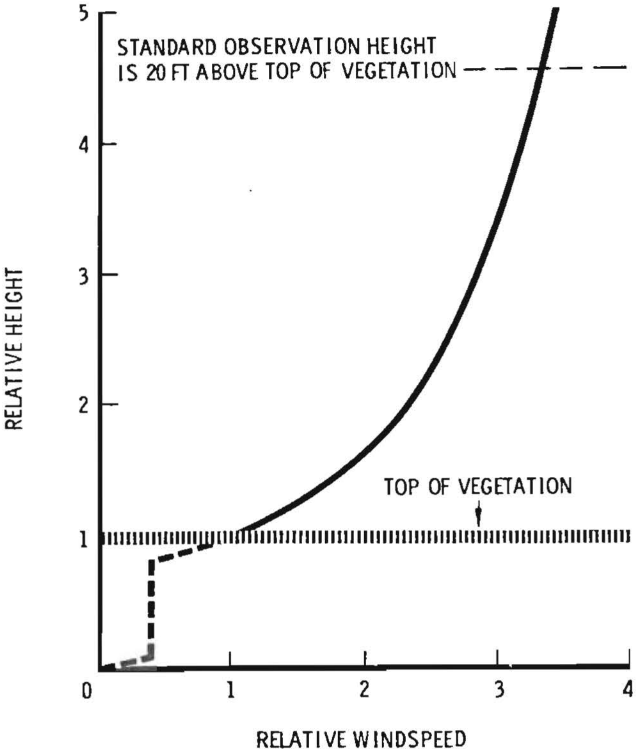

Figure 1.--Wind profile.

Considering the windspeed profile as well-defined, we then establish a relationship between the "midflame" windspeed and the windspeed at 20 feet above the fuel surface. Mathematical details of this are given by Albini and Baughman (1979). The relationship was found to be

$$\frac{\overline{\overline{U}}}{U_{20+H}} = \frac{1 + 0.36H/H_F}{\ln\left(\frac{20 + 0.36H}{0.13H}\right)}\left[\ln\left(\frac{H_F/H + 0.36}{0.13}\right) - 1\right]$$

where

$\overline{\overline{U}}$ is the midflame windspeed,
U_{20+H} is the 20-ft standard wind,
H is the height of the vegetation,
and H_f is the extension of the flame above the fuel surface.

This equation is graphed in figure 2.

The graph can be used to establish the ratio of the "midflame" windspeed to the windspeed 20 ft over the vegetation cover for various fuel heights H and flame extensions H_f. A tabular form developed from this relationship is given later.

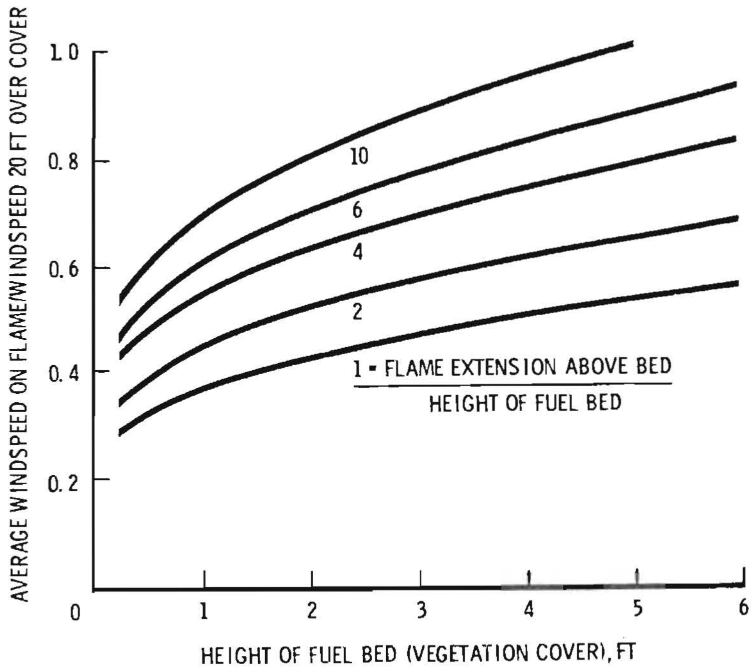

Figure 2.--Average windspeed acting on a flame extending above a uniform surface fuelbed layer (vegetation cover), due to log windspeed variation.

WIND UNDER A FOREST CANOPY

To model the windspeed under a forest canopy, several assumptions were involved: (1) that the windspeed through most of the canopy is constant with height, (2) that the live crown foliage provides a bulk drag force that resists the airflow, (3) that the shear stress at the canopy top surface (equal to that in the constant stress layer above the canopy) balances the integrated bulk drag force in the constant windspeed layer. The assumption of a constant windspeed with height through the canopy seems quite robust according to various published data (Fons 1940, Shaw 1977). The appropriate shear stress is given by the definition of the friction velocity, thus $\tau = \rho U_*^2$. Again, the details of the mathematical solution are given in Albini and Baughman (1979).

Canopy characteristics are accounted for in the model. The volume of the canopy occupied by tree crown was estimated for dense and open forest stands of shade-tolerant and shade-intolerant trees. A factor f was used to represent the portion of the canopy volume that is filled with tree crowns. Since this factor appears as a parameter in the mathematical solution (equation 3), values of f are given here (table 1).

Table 1.--Volume filling fractions (factor f), percent.

Stand stocking	Tolerant		Intolerant	
	Young	Mature	Young	Mature
Dense	32	24	16	8
Open	9	7	7	5

The equation for calculating the windspeed in the canopy (U_c) for arbitrary values of f and H, given the 20-ft standard windspeed, is:

$$U_c/U_{20+H} = 0.555 \Big/ \left\{ \sqrt{fH}\ \ln\left((20+0.36H)/0.13H\right) \right\} \quad (3)$$

where the stand height, H, is measured in feet. Since U_c applies almost all the way to the ground, it is the "midflame" windspeed.

The ratio U_c/U_{20+H} is plotted in figure 3 for the typical and extreme values of f.

An initial verification was obtained by comparing these results with field measurements obtained by others (table 2). The agreement appears to be close enough for most practical use.

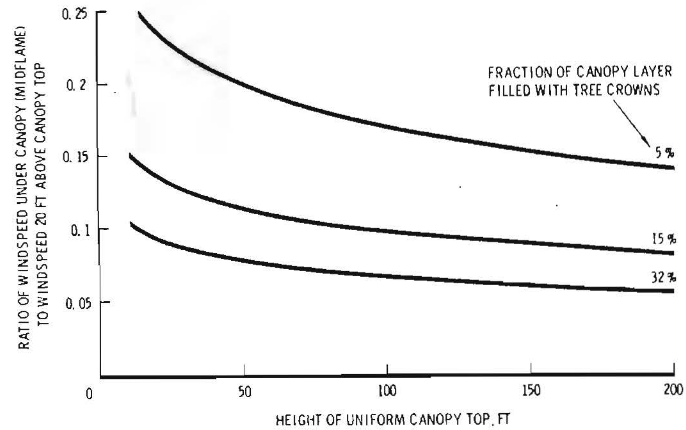

Figure 3.--Ratio of windspeed within (and below) forest canopy to windspeed 20 ft above canopy top.

Table 2.--Windspeed ratio U_c/U_{20+H}

Species	Stand description	Data source		U_c/U_{20+H} Calculated	from published data
Ponderosa pine	70 ft, S.I., open	Fons	(1940)	0.185	ave. 0.182
Red and white pine	34.5 ft, S.I., dense	Raynor	(1971)	0.119	ave. 0.145
Japanese larch	34.1 ft, S.I., open	Allen	(1968)	0.180	ave. 0.147

Table 3.--Wind reduction table.

To use this table, find the approximate reduction factor and multiply it by the 20-foot windspeed. Use the result as the midflame windspeed.

	Fuel model	Reduction factor
	1	0.36
- Fuel exposed directly to the wind-- no overstory or sparse overstory	2[1/]	.36
	3	.44
- Fuel beneath timber that has lost its foliage	4	.55
	5	.42
	6	.44
- Fuel beneath timber near clearings or clearcuts	7[1/]	.44
	8[2/]	.36
- Fuels on high ridges where trees offer little shelter from wind	9[2/]	.36
	10[2/]	.36
	11	.36
	12	.43
	13	.46
- Fuel beneath patchy timber where it is not well sheltered - Fuel beneath standing timber at midslope or higher on a mountain with wind blowing directly at the slope	All fuel models	0.25

	All fuel models			
	Shade tolerant species		Shade intolerant species	
Fuel sheltered beneath standing timber with foliage on flat or gentle slope or near base of mountain with steep slopes	Sparse	Dense	Sparse	Dense
	0.14	0.08	0.17	0.12

1/ These fuels are usually partially sheltered.
2/ These fuels are usually fully sheltered.

APPLICATION

These results have been compiled in a more convenient tabular form (table 3). In this form, stylized fuel models (Albini 1976) that include the fuel height are used to describe the surface cover. Brief descriptions of these fuel models are given in table 4. The reduction factors given in table 3 are used to reduce the 20-ft wind to the windspeed at midflame height. Reduction factors are given for exposed, partially sheltered, and fully sheltered fuels. Since the wind field over partially sheltered fuels is not well known, the reduction factor for partially sheltered fuels was found by interpolating between the exposed and fully sheltered values.

Each midflame windspeed obtained by use of table 3 implies a midflame height. For example, consider a fuel model 3 and the corresponding reduction factor of 0.44. From table 4, fuel model 3 is found to be 2.5 ft high tall grass. These values of 0.44 and 2.5 ft are used to enter figure 2 where the ratio of the flame height to the fuel bed height is found to be about 1. Thus the flame height extends about 2.5 ft above the tall grass. The flame height of the other fuel models can be found in a similar fashion.

The National Interagency Fire Training Center now uses these results for instruction of fire behavior officers, who then carry the information to practical application in the field. Recent developments enable the calculation of fire behavior values by use of a handheld calculator (Cohen and Burgan 1979). The midflame windspeed values entered into the calculator are made manually using the results in tabular form as shown here.

Table 4.--Stylized fuel models

Model	Generic description	Fuel height (ft)
	GRASS AND GRASS-DOMINATED	
1	Short grass	1.0
2	Timber (grass and understory)	1.0
3	Tall grass	2.5
	CHAPARRAL AND SHRUBFIELDS	
4	Chaparral	6.0
5	Brush	2.0
6	Dormant brush, hardwood slash	2.5
7	Southern rough	2.5
	TIMBER LITTER	
8	Closed timber litter	0.2
9	Hardwood litter	.2
10	Timber (litter and understory)	1.0
	LOGGING SLASH	
11	Light logging slash	1.0
12	Medium logging slash	2.3
13	Heavy logging slash	3.0

LITERATURE CITED

Albini, Frank A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30, 92 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Albini, F. A., and R. G. Baughman. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA For. Serv. Res. Pap. INT-221, 12 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Cohen, Jack D., and Robert E. Burgan. 1979. Handheld calculator for fire danger/fire behavior. Fire Management Notes, Winter 1978-79, p. 8-9. USDA For. Serv., Washington, D.C.

Cowan, I. R. 1968. Mass, heat and momentum exchange between stands of plants and their atmospheric environment. Quart. J. Roy. Meteorol. Soc. 94(402):523-544.

Fischer, W. C., and C. E. Hardy. 1972. Fire-weather observers' handbook. USDA For. Serv. Agric. Handbook 494, 152 p. Washington, D. C.

Fons, W. L. 1940. Influence of forest cover on wind velocity. J. For. 38(6):481-486.

Monteith, John L. 1973. Principles of environmental physics, 241 p. American Elsevier Publishing Co., New York.

Oliver, H. R. 1971. Wind profiles in and above a forest canopy. Quart. J. Roy. Meteorol. Soc. 97(414):548-553.

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. INT-115, 40 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Shaw, R. H. 1977. Secondary windspeed maxima inside plant canopies. J. Appl. Meteorol. 16(5):514-521.

Stanhill, G. 1969. A simple instrument for the field measurement of turbulent diffusion flux. J. Appl. Meteorol. 8(4):509-513.

Van Hylckama, T. E. A. 1970. Winds over salt cedar. Agric. Meteorol. 7(3):217-233.