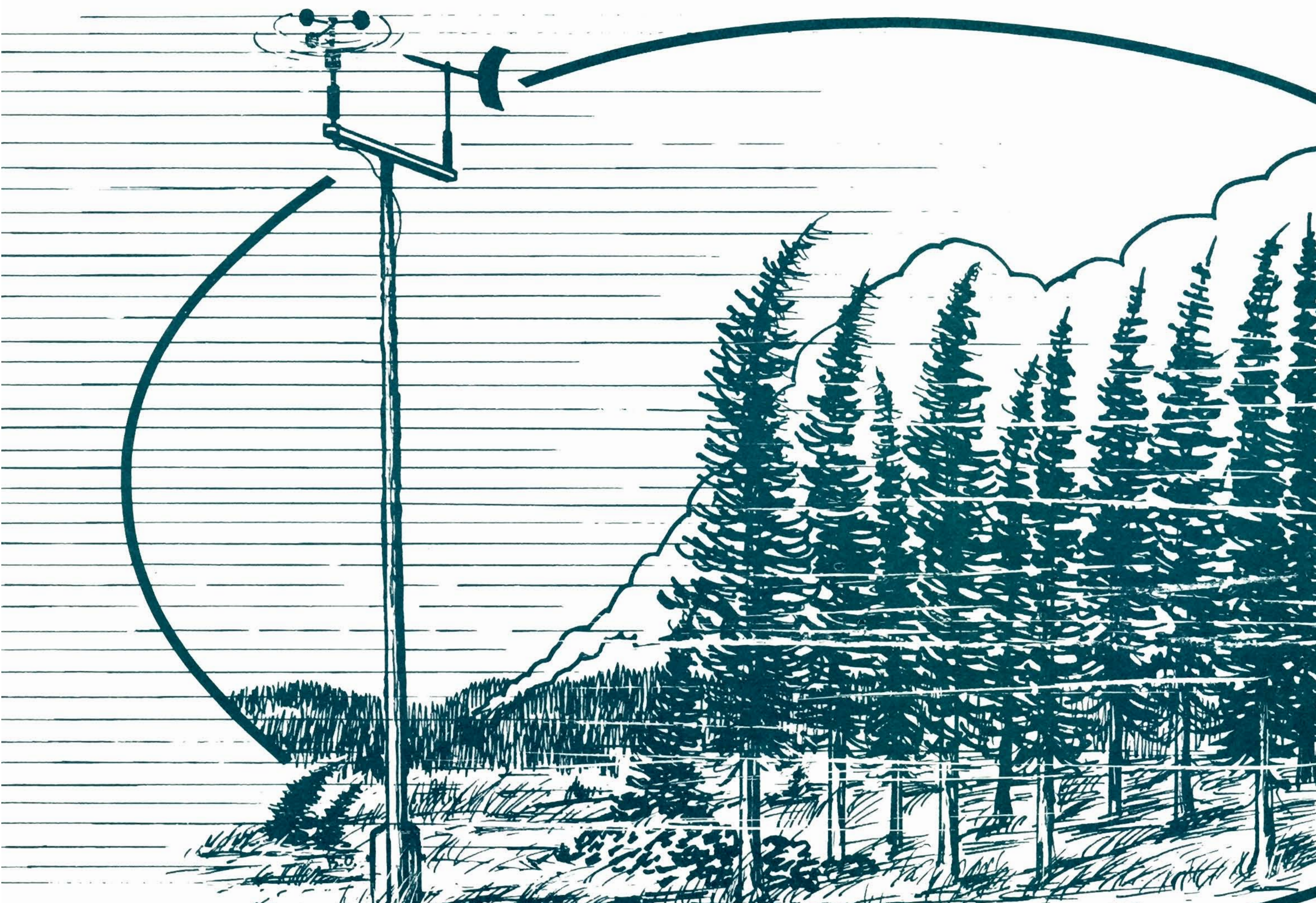
ESTIMATING WINDSPEEDS FOR PREDICTING WILDLAND FIRE BEHAVIOR

F.A. ALBINI AND R. G. BAUGHMAN



USDA FOREST SERVICE RESEARCH PAPER INT-221
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

USDA Forest Service
Research Paper INT-221
June 1979

ESTIMATING WINDSPEEDS FOR PREDICTING WILDLAND FIRE BEHAVIOR

F. A. Albini and R. G. Baughman

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

THE AUTHORS

FRANK A. ALBINI is a Mechanical Engineer, assigned to the Fire Fundamentals research work unit at the Northern Forest Fire Laboratory in Missoula, Montana. He earned a Ph.D. from the California Institute of Technology in 1962, where he also obtained his undergraduate training (B.S. 1958, M.S. 1959). He joined the Forest Service in October 1973 after 12 years of pure and applied research and systems analysis both in private industry and at the nonprofit Institute for Defense Analyses.

ROBERT G. BAUGHMAN holds a B.S. and M.S. degree in meteorology and climatology from the University of Washington. From 1954 to 1958 he was engaged in arctic research with the U.S. Corps of Engineers. Since joining the Forest Service in 1958, he has held the position of research meteorologist at the Northern Forest Fire Laboratory and has been involved in research on thunderstorms, lightning, weather modifications, and forest meteorology.

CONTENTS

Page

INTRODUCTION 1

LOGARITHMIC WIND PROFILE 1

WINDSPEED AT THE TOP OF THE VEGETATION COVER . . 3

GENERAL USE OF THE LOGARITHMIC WIND PROFILE EQUATION 6

WIND UNDER A CANOPY 6

COMPARISON WITH MEASUREMENTS 10

APPLICABILITY OF RESULTS 11

PUBLICATIONS CITED 12

RESEARCH SUMMARY

This paper presents formulae tables, and figures that can be used to estimate the ratio of mean windspeed acting on the flame from a spreading wildland fire to the mean windspeed 20 ft (6 m) above the vegetation cover. The formulae are based upon the logarithmic windspeed variation law characteristic of constant shear turbulent flow, and are restricted to flat terrain with uniform, continuous vegetation cover.

By equating integrated bulk drag due to crown foliage to the shear stress at the top of the crown layer, a model for relating windspeed within and below a uniform forest canopy to windspeed 20 ft (6 m) over the canopy is developed. Important variables in this model include stand height, crown closure, foliar surface/volume ratio, and crown bulk density. Comparison of model predictions with reported experimental measurements shows good agreement.

INTRODUCTION

The behavior of fire in wildland fuels is influenced strongly by the wind acting on the fire. Predicting fire behavior for fire control planning or preparing burning prescriptions must include this influence. Rothermel (1972) gives a mathematical model for predicting the rate of spread of a surface fire in wildland fuels. This model uses an average windspeed "at midflame height" to account for the influence of wind on the rate of spread. But windspeed is usually measured or forecast at a standard height 20 ft (6 m) above the vegetation (Fischer and Hardy 1972), and varies with height and vegetation cover. The poorly defined "midflame" windspeed can be approximated by using a spatially averaged value of the windspeed over an appropriate height range.

Presented here is a means of estimating the windspeed over various wildland fuel types from the "standard" windspeed at 20 ft above the vegetative cover. The report is divided into two major sections. The first deals with the wind above a vegetative cover that is a single-stratum fuel (grass, brush, etc.). The second part deals with wind under a forest canopy. The windspeed at the top of the forest canopy is found by use of a logarithmic wind profile. Windspeed beneath the canopy layer is estimated from the canopy-top value by use of a model based on mechanical force balance.

This research report deals only with the steady, undisturbed windfield and its influence on fire in surface fuels. No account is taken of the influence of the fire on the windspeed, wind direction, or the profile of windspeed with height. Furthermore, flat terrain and uniform continuous vegetation cover are assumed.

These restrictions clearly limit the applicability of the results, but even the extent and severity of the restrictions is uncertain. Rothermel's model implicitly accounts for local (near-flame) influence of the fire on the windfield. At what intensity or size the fire's influence on the prevailing windfield becomes significant can only be estimated by order-of-magnitude arguments at present. Future research should help to clarify this situation.

The restriction to flat terrain can probably be relaxed to "smooth" or "slightly uneven" terrain, but numerical descriptions of adequate "flatness" are not presently available. Similar considerations apply to the uniformity and continuity of vegetation cover required, and these matters are under study in the field of applied meteorology (Bergen 1976).

With these restrictions in mind, this effort is seen as a small first step in the direction of a more complete description of the complex phenomena with which we are dealing.

LOGARITHMIC WIND PROFILE

The windspeed above a vegetative cover was determined by using the logarithmic wind profile in the following form (Sutton 1953, p. 239):

$$\bar{U}_z = \frac{U_*}{K} \ln\left(\frac{z-D_0}{z_0}\right) \qquad (1)$$

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.

The values for D_o and z_o were taken from the works of Cowan (1968) and Stanhill (1969). Figure 1, taken from Stanhill, shows a plot of D_o versus vegetation height. The plot agrees with the relationship $D_o = 0.64H$ derived by Cowan, where H is the vegetation height. The derived relationship was based on $z_o = 0.13H$ as found by Tanner and Pelton (1960).

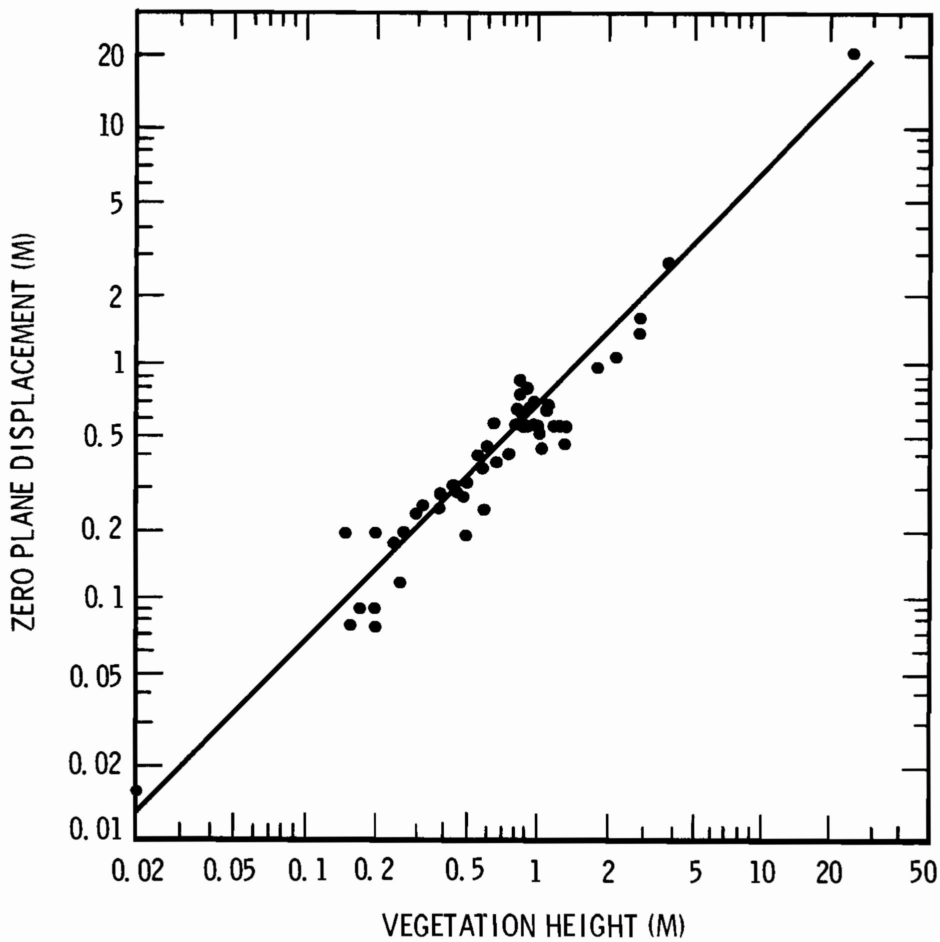


Fig. 1.--Relationship between zero-plane displacement D_o and vegetation height H for different vegetation types (after Stanhill 1969).

WINDSPEED AT THE TOP OF THE VEGETATION COVER

To predict wildland fire behavior, the "standard" windspeed at 20 ft must be converted to a value representing the actual motion of the air in the vicinity of the fuel and flame structure. As a first step, we related the 20-ft windspeed (U_{20+H}) to the windspeed at the top of the vegetation (U_H).

The relationship between U_H and U_{20+H} is then:

$$U_{20+H} = (U_*/K)\ \ell n \left(\frac{20+H - 0.64H}{0.13H} \right) \quad \text{for H measured in feet.} \tag{2}$$

Since

$$U_H = (U_*/K)\ \ell n \left(\frac{H - 0.64H}{0.13H} \right) = 1.02\ U_*/K \doteq U_*/K \tag{3}$$

we can write equation (2) as follows:

$$\frac{U_H}{U_{20+H}} \doteq \frac{1}{\ell n \left(\frac{20+0.36H}{0.13H} \right)} \tag{4}$$

WINDSPEED FOR PREDICTING FIRE SPREAD IN SURFACE FUEL (NO CANOPY CASE)

With the profile of windspeed variation defined, we need only choose an appropriate height range over which to average to obtain a relationship between "midflame" windspeed and windspeed at 20 ft above the fuel surface. For this purpose here we assume that the flame extends to some height above the surface vegetation and average the windspeed between the top of the vegetation and this height.

Consider an average windspeed over the height range H to H + H_F, where H_F is the extension of the flame above the fuel bed.

$$\overline{\overline{U}} = \frac{1}{H_F} \int_{H}^{H + H_F} \overline{U}\, dz = \frac{1}{H_F} \frac{U_*}{K} \int_{H}^{H + H_F} \ln\left(\frac{z - D_o}{z_o}\right) dz \tag{5}$$

let $x = \left(\frac{z - D_o}{z_o}\right)$

$$\frac{z_o}{H_F} \frac{U_*}{K} \int_a^b \ln x \, dx = \frac{z_o}{H_F} \frac{U_*}{K} \left. x\,(\ln x - 1) \right|_a^b$$

$$\overline{\overline{U}} = \frac{z_o}{H_F} \frac{U_*}{K} \left(\frac{z - D_o}{z_o}\right) \left[\ln\left(\frac{z - D_o}{z_o}\right) - 1 \right] \Bigg|_{H}^{H + H_F} \tag{6}$$

Note that at the lower limit (H) the value is nearly zero since:

$$\ln\left(\frac{H - 0.64H}{0.13H}\right) \doteq 1 \tag{7}$$

Thus we find

$$\overline{\overline{U}} = \frac{U_*}{K} \frac{H + H_F - 0.64H}{H_F} \left[\ln\left(\frac{H + H_F - 0.64H}{0.13H}\right) - 1 \right]$$

$$= \frac{U_*}{K} \left(1 + 0.36 \frac{H}{H_F}\right) \left[\ln\left(\frac{H_F/H + 0.36}{0.13}\right) - 1 \right] \tag{8}$$

Values of $\bar{U}$ can be calculated for various windspeeds at (20+H) ft over single stratum fuels. Using equation (2), we find:

$$\frac{\bar{U}}{U_{20+H}} = \frac{1 + 0.36H/H_F}{\ln\left(\frac{20 + 0.36H}{0.13H}\right)} \left[\ln\left(\frac{H_F/H + 0.36}{0.13}\right) - 1\right] \tag{9}$$

The graph of figure 2 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.

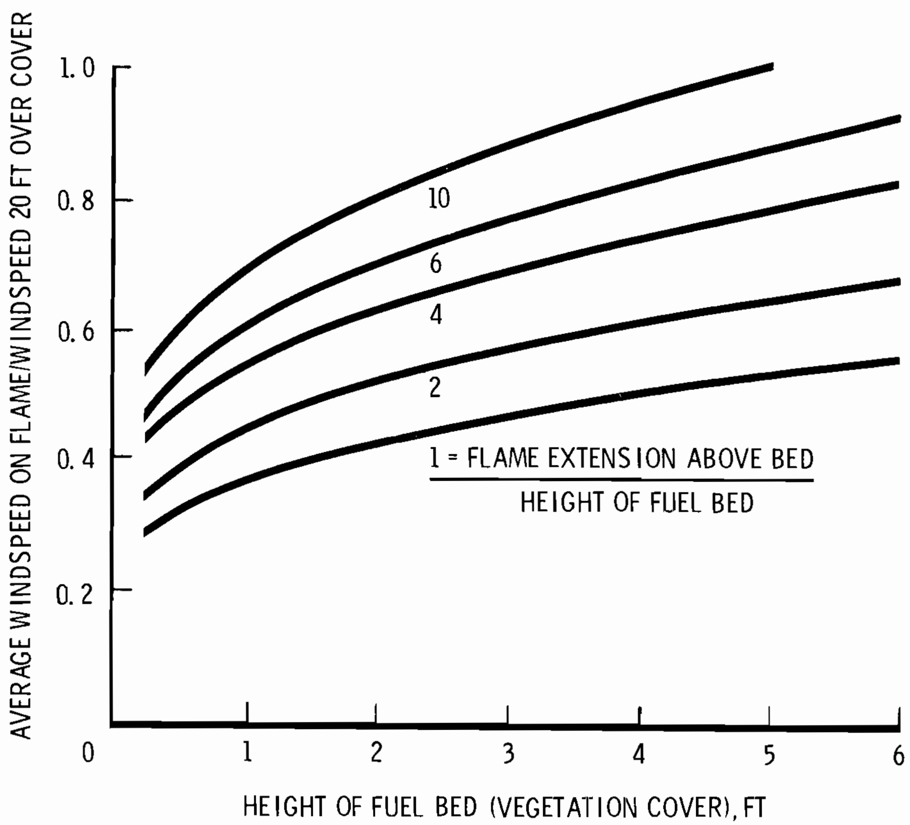


Fig. 2.--Average windspeed acting on a flame extending above a uniform surface fuelbed layer (vegetation cover), due to log windspeed variation.

GENERAL USE OF THE LOGARITHMIC WIND PROFILE EQUATION

According to several authors, the log-wind profile represents the actual wind profile near the surface of the earth only under neutral stability condition. However, various researchers have found that the log-wind profile represents the wind above a vegetative cover (very rough surface) over a wide range of atmospheric conditions. For example, van Hylckama (1970) reports that a log-wind profile represented the wind variation above a salt cedar stand (*Tamarix pentandra*) for all his afternoon observations and for many night conditions. Of 744 data sets, only 84 were too irregular for log-wind representation. Oliver (1971) found the wind profile above a pine forest to be well described by the logarithmic form over a wide range of stability conditions.

Apparently, large temperature gradients cannot be maintained above a forest canopy due to air movement through the canopy (Munn 1966, p. 158) and due to mixing by which the wind blowing over a very rough surface reduces air temperature variations above the canopy. Thus extreme lapse or inversion temperature conditions are unlikely to obtain over a vegetative cover, resulting in a broad applicability of the log-wind profile. However, we advise that this form not be used to estimate winds under conditions of strong surface air temperature inversions. In summer this happens most often at night under clear skies with very low surface wind speeds. So when wind represents an important influence on fire behavior, the log profile usually is applicable.

WIND UNDER A CANOPY

To model the variation of windspeed with height for air flow through and under a forest canopy, we make several simplifying assumptions:

1. Below some height, z_M, near but below the top (height H) of the uniform forest canopy, the windspeed is approximately constant with height.

2. The foliage within the height range from z_M down to the bottom of the live crowns at height z_m provides a bulk drag force that resists the airflow.

3. Shear stress (equal to that in the constant stress layer above) on the surface $z = z_M$ balances the integrated bulk drag force in the constant speed layer.

The approximate windspeed profile is thus:

$$\overline{U}(z) = \begin{cases} (U_*/K) \quad \ell n \left(\dfrac{z - 0.64H}{0.13H}\right) & , \quad z \geq z_M \\ U_c & , \quad z \leq z_M \end{cases} \qquad (10)$$

The assumption of a constant windspeed beneath the canopy seems quite reasonable according to various authors (Fons 1940, Geiger 1966, Shaw 1977). Now the resistance to airflow in the canopy can be expressed as a force/unit volume, R, due to drag on the canopy foliage (conifer needles in most applications). The value of R is given by:

$$R = \frac{1}{2} \rho \; U_c^2 \; \tilde{C}_D \, A\eta, \qquad (11)$$

where

ρ is the air density

U_c windspeed in canopy

$\tilde{C}_D$ the average drag coefficient (random foliage orientation)

A the side view area of needle = ℓD (length × diameter)

η is the average number of needles per unit volume

$\eta \frac{\pi}{4} D^2 \ell = \bar{\beta}$, the average "packing ratio" (Rothermel 1972) (12)

thus

$$\eta A = \eta \, \pi \frac{D^2}{4} \ell \cdot \frac{4}{\pi D} = \frac{\bar{\beta}\sigma}{\pi} \tag{13}$$

where σ is the surface-area-to-volume ratio of a single needle. This bulk resistive force, integrated over the height range z_m to z_M, provides the shear stress requirement (τ) for the upper surface:

$$\tau = R \cdot (z_M - z_m) \tag{14}$$

Since at z_M the shear stress is assumed to be that of the constant-shear layer, we have

$$\tau = \rho \, U_\star^2 \tag{15}$$

and so

$$\left(z_M - z_m\right) \rho \, U_c^2 \, \tilde{C}_D \, \bar{\beta}\sigma/2\pi = \rho \, U_\star^2 \tag{16}$$

From this last expression and equation (3) we find

$$\left(U_c/U_H\right)^2 = 2\pi K^2 / \left(\tilde{C}_D \, \bar{\beta}\sigma \, (z_M - z_m)\right) \tag{17}$$

For a uniform stand of nearly identical trees we can replace $z_M - z_m$ by H·(CR) where H is tree height and CR is the crown ratio. Likewise, the average packing ratio, $\bar{\beta}$, can be expressed as

$$\bar{\beta} = F\beta \tag{18}$$

where β is the packing ratio for a single tree crown and F is the fraction of the canopy layer filled with tree crowns. The fraction F is to be approximated by the product of crown closure and a fraction accounting for the tapering of crowns that results in additional void volume higher in the canopy. Finally, the product of F and CR can be represented by f, a fraction that represents the portion of volume under the canopy top that is filled with tree crowns.

Typical crown ratios[1] are displayed in table 1. The fraction of the canopy layer that is occupied by tree crowns (F above) we take to be 0.4 for dense stands and 0.1 for open stands. Table 2 gives the volume-filling fractions (f above) resulting from the products of the crown ratios of table 1 and these closure factors. In terms of the volume fraction, f, equation (17) provides a relationship for the windspeed under the canopy, U_c, and the windspeed at the top of the canopy, U_H:

$$U_c/U_H = K\left(2\pi/\tilde{C}_D\beta\sigma fH\right)^{1/2} \tag{19}$$

Table 1.--*Typical crown ratios, percent*

Stand stocking	Shade-tolerant trees: Young	Shade-tolerant trees: Mature	Shade-intolerant trees: Young	Shade-intolerant trees: Mature
Dense	80	60	40	20
Open	90	70	70	50

Table 2.--*Volume filling fractions (factor f), percent*

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

This expression can be reduced to a simpler form by using nominal numerical values for the parameters that are essentially constant. The value of K can be taken as 0.4, $\tilde{C}_D$ is approximately 1.0 (Schlichting 1968), and the product $\beta\sigma$ can be treated as a constant[2] equal to 3.26 ft^{-1}. So for H measured in feet,

$$\frac{U_c}{U_H} = K\sqrt{\frac{2\pi}{\tilde{C}_D\ \beta\sigma\ fH}} = 0.4\sqrt{\frac{2\pi}{(1)(3.26)\ fH}} = \frac{0.555}{\sqrt{fH}} \tag{20}$$

Values of U_c/U_H for three tree heights are given in table 3, based on the f values of table 2.

---

[1] The authors are indebted to Dr. James K. Brown of the Northern Forest Fire Laboratory for providing these typical quantities.

[2] This is an average value for 10 Rocky Mountain conifers. Data were taken from study material by J. K. Brown (on file at NFFL, Missoula) used in establishing crown foliage weight relationships (see Brown 1976). The standard deviation of the product $\beta\sigma$ for these species is 1.08 ft^{-1}.

Table 3.--*Windspeed ratio* U_c/U_H

Stocking level	Tolerant species: Young 40'	Tolerant species: Mature 100'	Tolerant species: Pacific 180'	Intolerant species: Young 40'	Intolerant species: Mature 100'	Intolerant species: Pacific 180'
Dense	0.155	0.113	0.084	0.220	0.196	0.146
Open	0.293	0.210	0.156	0.332	0.248	0.185

Three "typical" tree heights are used in this table to represent young stands (40 ft), mature stands (100 ft) and old-growth Pacific Coast stands (180 ft). For the latter, the crown ratios of "mature" stands from table 2 were used.

Since U_c applies (almost) all the way to the ground, it is the "midflame" windspeed. Hence the "midflame" windspeed in relation to the windspeed 20 ft over the canopy can be found by using equation (4) and choosing the ratio U_c/U_H from table 3 or calculating it from equation (20).

The equation for calculating U_c for stands with arbitrary values of f and H is:

$$U_c/U_{20+H} = 0.555 \Big/ \left\{ \sqrt{fH} \;\; \ln\left((20 + 0.36H) / 0.13H \right) \right\} \tag{21}$$

The ratio U_c/U_{20+H} is plotted in figure 3 for the typical and extreme values of f (table 2).

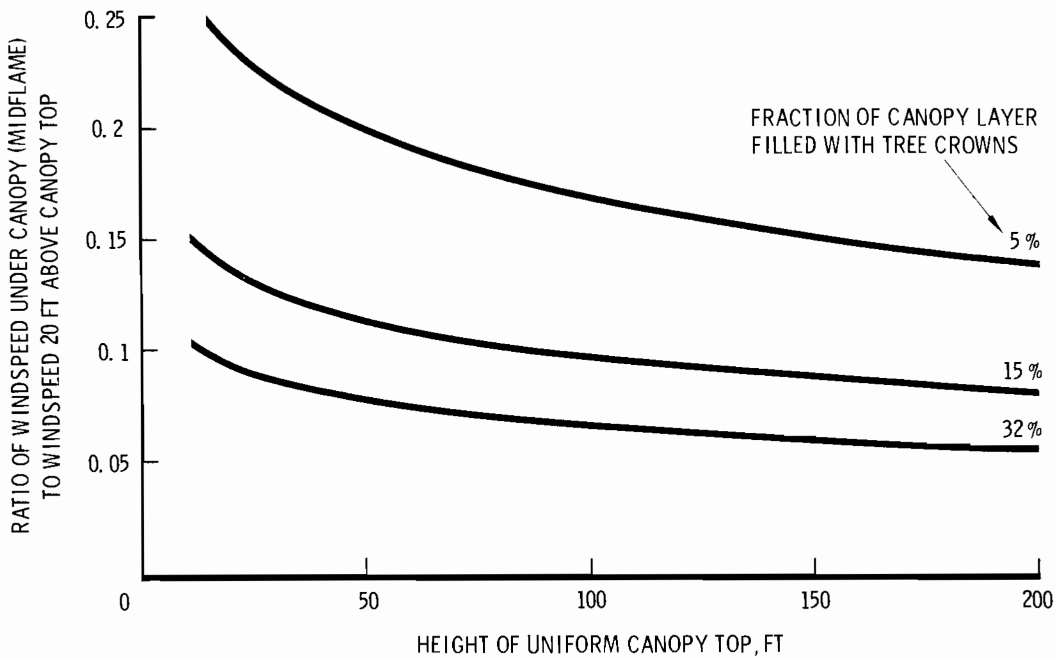


Fig. 3. Ratio of windspeed within (and below) forest canopy to windspeed 20 ft above canopy top.

COMPARISON WITH MEASUREMENTS

Table 4 compares data reported by Shaw (1977) and Berglund and Barney (1977) with our calculated windspeed ratios U_c/U_H from equation (20) using the values of f from table 2. Table 5 compares calculated values of U_c/U_{20+H} from equation (21) and table 2 with data taken from Fons (1940), Raynor (1971), and Allen (1968). The agreement between model results and measurements is surprisingly good in all cases.

Table 4.--*Windspeed ratio* U_c/U_H

Species	Stand description	Data source	U_c/U_H Calculated	U_c/U_H from published data
Sitka spruce	H = 34.5 ft, S.T., dense	Shaw (1977)	0.167	0.16
Scots pine	H = 50.9 ft, S.T., open	Shaw (1977)	0.259	0.24
Ponderosa pine	H = 70 ft, S.I., open	Shaw (1977)	0.297	0.34
Japanese larch	H = 34.1 ft, S.I., open	Shaw (1977)	0.359	0.36
Black spruce	H = 11.5 ft, S.T., open	Berglund & Barney (1977)	0.619	0.63*

*p. 10, Table 2, ratio of slopes of regression equations relating windspeeds within and above the stand.

Table 5.--*Windspeed ratio* U_c/U_{20+H}

Species	Stand description	Data source	U_c/U_{20+H} Calculated	U_c/U_{20+H} from published data
Ponderosa pine	70 ft, S.I., open	Fons (1940)	0.185	ave. 0.182
Red & 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

APPLICABILITY OF RESULTS

The numerical results derived in this report are subject to the restrictions listed below. The reader is cautioned to be certain that the specified conditions prevail when using these results.

1. Flat terrain has been assumed throughout. If the terrain has substantial slope or roughness, the windfield will reflect this fact, and substantial deviations from these results may occur.

2. Adequate fetch to establish a uniform friction layer has been assumed. The definition of "adequate" fetch is the subject of current research (Shaw 1977), so numerical limits cannot be stated at this time. But near forest edges, lakeshores, or transitions in surface vegetation cover, the results given here may not be accurate.

3. A "well-behaved" windfield is modeled by the relationships herein. If the windfield is not steady, but fluctuates significantly in speed, direction, or both, the friction layer will be continually in a transient state as it responds to the forces at play. During the periods of such variability the results given here may not be applicable.

4. Any interaction between the fire and the windfield that substantially influences the speed or direction of the wind should invalidate these results. We have dealt here with a windfield whose structure is dominated by the influence of the vegetation cover on the friction layer and any factor that disturbs this condition negates the validity of the results given here.

PUBLICATIONS CITED

Allen, L. H., Jr.
1968. Turbulence and windspeed spectra within a Japanese larch plantation. J. Appl. Meteorol. 7(1):73-78.

Bergen, J. D.
1976. Air flow in the forest canopy - a review of current research on modeling the momentum balance. USDA For. Serv. Gen. Tech. Rep. RM-32, 239 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Berglund, E. R., and R. J. Barney.
1977. Air temperature and wind profiles in an Alaskan lowland black spruce stand. USDA For. Serv. Res. Note PNW-305, 12 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Brown, James K.
1976. Predicting crown weights for 11 Rocky Mountain conifers. Int. Union For. Res. Organ. 16th Congr. Proc. Subj. Group 4.01, p. 101-115. Coll. Life Sci. and Agric., Univ. Maine, Orono.

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. Ser. Agric. Handb. 494, 152 p. Washington, D.C.

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

Geiger, R.
1966. The climate near the ground. Harvard Univ. Press. Cambridge, Mass. 611 p.

Munn, R. E.
1966. Descriptive micrometeorology. Academic Press, New York. 245 p.

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

Raynor, G. S.
1971. Wind and temperature structure in a coniferous forest and a contiguous field. For. Sci. 17(3):351-363.

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

Schlichting, Hermann.
1968. Boundary-layer theory. Sixth Ed., McGraw-Hill, New York, 747 p. Lib. Congr. Cat. 67-29199.

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.

Sutton, O. G.
1953. Micrometeorology. McGraw-Hill. New York. 333 p.

Tanner, C. B. and W. L. Pelton.
1960. Potential evapotranspiration estimates by the approximate energy balance of Penman. J. Geophys. Res. 65:3391-3413.

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

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979—677-019/97 REG. 8

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 84401.

This paper presents formulae, tables, and figures that can be used to estimate the ratio of mean windspeed acting on the flame from a spreading wildland fire to the mean windspeed 20 ft (6 m) above the vegetation cover. The formulae for windspeed above uniform, continuous vegetation cover are based upon the logarithmic wind profile over flat terrain. A model for estimating windspeed within a forest canopy is developed to extend the application to surface fires in forests.

KEYWORDS: windspeed in forest canopy, windspeed profile, wind influence on fire.

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 84401.

This paper presents formulae, tables, and figures that can be used to estimate the ratio of mean windspeed acting on the flame from a spreading wildland fire to the mean windspeed 20 ft (6 m) above the vegetation cover. The formulae for windspeed above uniform, continuous vegetation cover are based upon the logarithmic wind profile over flat terrain. A model for estimating windspeed within a forest canopy is developed to extend the application to surface fires in forests.

KEYWORDS: windspeed in forest canopy, windspeed profile, wind influence on fire.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

- Billings, Montana
- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)