Wind Barriers: A Reevaluation of Height, Spacing, and Porosity

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ABSTRACT

Wind barriers are an important method to control soil erosion by wind. A review of the literature revealed that the equation currently in use to predict length of protection is not precise and does not satisfy known boundary conditions. Various data sets were studied and an alternative equation was formulated that both matches the published data and correctly fits the boundary conditions. This equation also included the variable of barrier porosity. The new equation was verified to fit published measurements with an R^2 of 0.97 and was highly signifient ($\alpha = 0.001$). A check was also made with data for a snow fence that were independent of the data used for calibration. For this data set, the R^2 was 0.703, which was significant ($\alpha = 0.001$). It was concluded that the new equation was an improvement over the equation currently in use.

INTRODUCTION

Wind barriers of various kinds are used to modify the wind profile and protect against the damaging effects of wind. Vegetative wind barriers are most often used in agriculture, but artificial wind barriers such as wood or fabric fences can also be used. Artificial wind barriers are especially valuable in dealing with wind erosion problems associated with construction, storing hazardous wastes, or providing protection in agriculture when insufficient time exists to establish vegetative cover or vegetative wind barriers. Barrier technology can also be used to design truck beds and railroad cars to minimize material loss during transport.

Barriers, like any obstruction of air flow, bring about three effects on their environment. First, the flow of the approaching wind is changed in magnitude and direction before it crosses the barrier. Second, the leeward air flow pattern is changed. Third, changes occur in the microclimate (temperature, vapor pressure, and evapotranspiration) surrounding the barrier (Rosenberg, 1976). To take full advantage of the positive effecıs of barriers, precise relationships are needed for their design.

A simple linear relationship between length of protection and height of barrier was reported by Schwab et al. (1966) and is currently used by the Soil Conservation Service (SCS). However, this relationship does not match experimental data over a wide range of lengths of protection nor does it contain the variable of barrier porosity. The purpose of this article is to develop more precise mathematical relationships between height, porosity, and spacing of wind barriers used for mitigating damage from winds.

BACKGROUND

Researchers have studied the decrease in wind velocities on the leeward side of barries (windbreaks) in the field and in wind tunnels (Woodruff and Zingg, 1952; Moysey and McPherson, 1964; Hagen and Skidmore, 1971a & b; Tabler and Veal, 1971; Raine and Stevenson, 1977; and Hagen, 1980). Bates (1924) was one of the first to study the effects of height and density of shelter belts on leeward velocites. He stated that a windbreak of moderate effectiveness reduces the velocity of a 32 km/hour wind, striking normal to the windbreak, for a distance of 30 times the height of the windbreak (in his case, trees). This finding has been verified repeatedly over time attesting to the quality of the data from Bates (1924) and the other researchers referenced above. Tabler (1980), for example, reported that the drift length on the leeward side of a snow fence (at the maximum size of the drift or at the saturation point for snow storage) is approximately 30 times the height of the snow fence. These similar findings and those of other resarchers indicate that the reduction of velocities on the leeward side of barriers is a stable and reproducible phenomenon (Raine and Stevenson, 1977).

Several researchers have related wind velocity reduction with porosity of the barrier. They include Woodruff and Zingg (1952), Moysey and McPherson (1964), Hagen and Skidmore (1971a & b), and Raine and Stevenson (1977). Moysey and McPherson (1964), using the results of both wind tunnel and field experiments, found the leeward side velocities to be a function of barrier porosity. They stated that a porosity of 25% offers the best sheltering (velocity reduction) below the mid-height of the barrier. For leeward distances of one to eight barrier heights, wind barriers that have porosities in the range of 15 to 35% provide better sheltering than do solid barriers. They concluded that the fraction of reduction of leeward velocity is almost constant regardless of the change in magnitude of the approach velocity as long as the Reynold's number based on barrier height is greater than 40,000. A Reynold's number greater than 40,000 can be achieved with wind velocities of only a few kilometers per hour. They further found that the shapes of barrier openings have less effect on leeward velocities than did barrier porosity.

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Skidmore and Hagen (1976) developed a model to explain the relationship of the ratio of leeward velocity to the upstream approach velocity (U_x/U_o) and leeward distance expressed as barrier heights (X) for a 40% porous barrier. While their model generally fits wind tunnel and field data, it does not satisfy the boundary condition beyond the barrier, i.e., the value (U_x/U_o) approaches unity. This modeling procedure also necesitates separate equations for each different porosity. The authors recognized that there is a velocity reduction upwind from the barrier and presented an equation for such a reduction for a barrier with 40% porosity.

Schwab et al. (1966) used the data of Woodruff and Zingg (1952) to develop the following equation for the distance of full protection from a windbreak:

$$L = 17\ H\ (U_m/U) \cos \beta \quad \ldots\ldots\ldots\ldots [1]$$

where

- L = distance of full protection,
- H = height of the barrier in any units which are the same as L,
- U_m = minimum wind velocity at 50-ft height required to move the most erodible soil fraction,
- U = actual wind velocity at 50-ft height,
- β = the angle of deviation of prevailing wind direction from the perpendicular to the windbreak.

The above equation is typically used to design windbreaks. Its main advantage is simplicity. It, however, does not consider porosity although research has clearly shown that porosity is a factor in the distance of full protection as discussed above.

A reanalysis of the data from Woodruff and Zingg (1952) indicated that either an intercept of approximately 8 should be added to equation [1] or the value 17 should be increased to achieve a reasonable fit of the data. Furthermore, Raine and Stevenson (1977) stated that the tests by Woodruff and Zingg (1952) did not properly establish a logarithmic wind profile upstream of the test section, and the results from such tests were only a qualitative indication of full scale windbreak performance.

MODEL DEVELOPMENT

This paper will be restricted to modeling wind barriers having a top boundary that is angular in form. For a Reynold's number above 40,000, the separation point is fixed at the angular edge and does not shift with increasing Reynold's numbers (Vennard, 1961). Almost all field conditions of concern will have a Reynold's number greater than 40,000 (Greeley and Iversen, 1985).

Model Formulation

The barrier exerts, by its drag, a force on the wind field that is compensated by a loss of momentum of the air. In an incompressible fluid, a reduction in momentum implies a reduction in velocity. Thus, the drag is converted into wind speed reduction that is desired for sheltering the soil (Skidmore and Hagen, 1976). Woodruff and Zingg (1952), Hagen and Skidmore (1971a), and Raine and Stevenson (1977) have measured the wind velocity reductions on the leeward side of barriers with different porosities. Within the area of velocity reduction, the vertical velocity profile appears to be a straight line except in the immediate vicinity of the ground (Aase et al., 1976). It appears that near the ground, the profile follows the typical logarithmic shape, but above this boundary layer the profile is uniform. This information was used to develop a relationship between leeward velocity reduction, height of barrier, and porosity of the barrier.

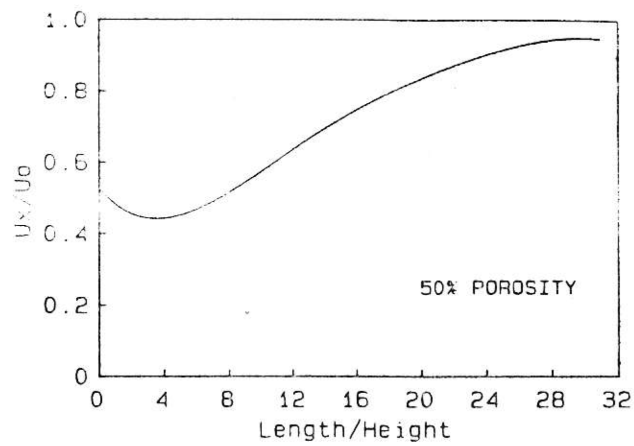

Fig. 1—Ratio of downwind to upwind velocity as a function of wind barrier heights downwind.

The region behind the barrier downwind to approximately four to six barrier heights is the vortex area where special modeling is needed to define the velocity reduction (see Fig. 1). For most applications, this area is adequately sheltered by the barrier. Using a field data set and a wind tunnel data set from Raine and Stevenson (1977), the velocity reductions for four porosities were modeled. Presented in Table 1 are wind data from the two sets of tests for porosity, velocity reduction, and downstream distance from the barrier for the winds approaching the barrier at right angles.

Reported velocities were measured or taken at a height of 1/2 H where H is the height of the barriers. Actual velocities at 1/2 were obtained for the data from Hagen and Skidmore (1971a), while the integrated average

TABLE 1. Number of barrier heights (X = L/H) below barriers for various wind velocity reductions

U_x/U_o	Porosity							
	0%		20%		34%		50%	
	F	WT	F	WT	F	WT	F	WT
1.0	44.5	43.0	60.0	50.0	44.5	43.0	45.0	44.0
0.95	34.5	31.0	37.5	37.0	37.0	34.0	36.0	33.0
0.90	28.5	25.0	32.0	30.0	27.0	25.5	28.5	25.0
0.85	25.0	21.5	27.5	25.0	21.0	19.0	24.0	20.0
0.80	20.0	18.0	21.5	21.0	19.0	17.0	16.5	16.0
0.70	16.0	15.0	16.0	16.0	13.5	13.0	10.5	11.0
0.60	13.0	12.0	12.5	12.0	9.5	9.5	7.5	7.5
0.50	10.5	10.0	10.5	10.0	6.5	6.5	–	–
0.40	8.0	7.5	7.0	7.0	–	–	–	–

Note: L = length leeward of the barrier
H = height of the barrier
U_x = the leeward wind velocity at 0.5 H
U = the upstream wind velocity at 0.5 H
F = field data from Raine and Stevenson (1977)
WT = wind tunnel data from Raine and Stevenson (1977)

velocity was used for the data from Raine and Stevenson (1977). Based on actual wind profiles measured behind barriers as measured by Tabler and Veal (1971) and Aase et al. (1976), the integrated average velocity and the velocity at 1/2 H appear to be similar.

Based on the boundary condition that the downwind velocity should asymptotically approach the upwind velocity as distance downwind increases, an exponential equation was used as a simple model. The form of the equation is

$$\frac{U_L}{U_o} = 1 - Ae^{-BX} \quad \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

where

- U_L = the leeward wind velocity at a height of 0.5 H for location L,
- U_o = the upstream wind velocity at a height of 0.5 H,
- X = L/H,
- H = the height of the barrier,
- L = the distance downstream from the barrier.

The unknown coefficients, A and B, were determined for the data given in Table 1 with MERV, a computer program designed to analyze non-linear functions (Gregory and Fedler, 1986).

The exponent B was found to be approximately constant with an average value of 0.0876. Next, this average value of 0.0876 for B was used with equation [2] and the data in Table 1 to determine new values for A. The equations for the different porosities are as follows:

Porosity of Barrier	Fitted Equation	R^2	
0% (Solid)	$U_L/U_o = 1.0 - 1.190\ e{-0.0876X}$	0.99	[3]
20%	$U_L/U_o = 1.0 - 1.172\ e{-0.0876X}$	0.99	[4]
34%	$U_L/U_o = 1.0 - 0.909\ e{-0.0876X}$	0.99	[5]
50%	$U_L/U_o = 1.0 - 0.792\ e{-0.0876X}$	0.99	[6]
100%	$U_L/U_o = 1.0 - 0.0\ e{-0.0876X}$	Boundary Condition	[7]

All equations fit the measured data well with an R^2 of 0.99, which was highly significant ($\alpha = 0.001$). Equation [7] was obtained by the boundary condition that zero porosity is equal to no barrier and Ux is equal to Uo. Results are shown in Fig. 2.

Note that U_x/U_L automatically approaches one as X becomes large. This is a correct boundary condition not achieved by equation [1]. At this point, it was concluded that equation [2] with a constant value for B and a variable A as a function of porosity was both a simple and accurate model for the given data and should be an appropriate equation for modeling downwind effects behind barriers.

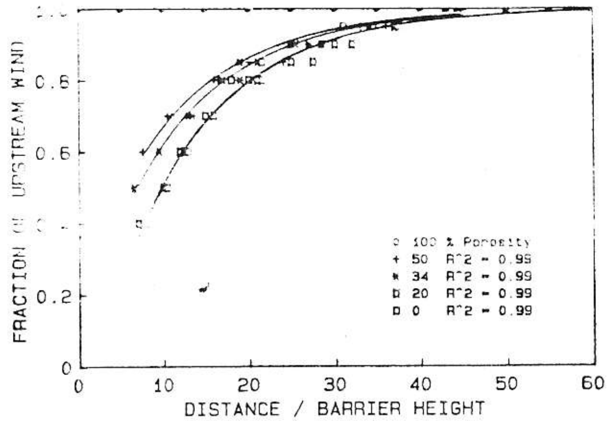

Fig. 2—Relationship between wind barrier porosity and the coefficient A.

Porosity Effects

Porosity effects are considered by variations in the coefficient A. The zero value for coefficient A for 100% porosity is a theoretical boundary condition. One would expect the magnitude of velocity reduction to be inversely proportional to porosity. Both Raine and Stevenson (1977) and Moysey and McPherson (1964) reported that the velocity reduction was greater for 20% porosity than for zero percent. This result does not match our equation, but was probably due to back flow in the core area behind solid barries. Values for A are plotted as a function of porosity in Fig. 3. The following nonlinear function gave a reasonable fit ($R^2 = 0.995$ and $\alpha = 0.01$):

$$A = 1.217 - 4.81 \times 10^{-3}\ P - 7.39 \times 10^{-5}\ P^2 \quad \ldots\ldots [8]$$

where P is porosity in percent.

Because a barrier exerts a drag on the wind as it flows over the barrier, the coefficient A should be a function of the drag coefficient. If this hypothesis is true, knowledge relating drag coefficients to shape could be used to estimate A for shapes not considered in our analysis.

The hypothesis that A was a function of drag coefficient was tested with measured drag coefficients reported by Hagen and Skidmore (1971b). Equation [8] was used to calculate values for A for porosities given by Hagen and Skidmore (1971b). These values were then related to the measured drag coefficients for the same prorosities (Fig. 4). A simple linear equation with an

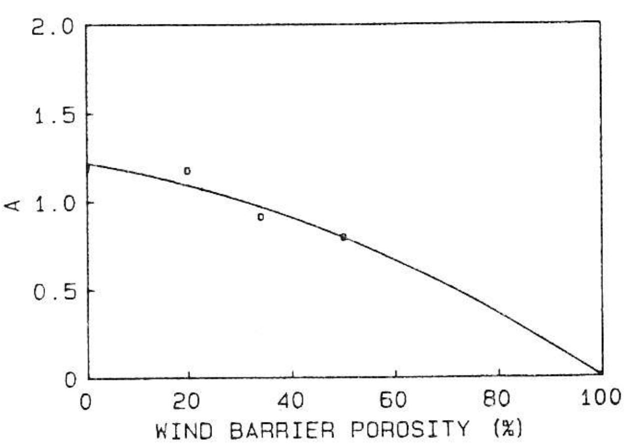

Fig. 3—Relationship between drag coefficient and the coefficient A.

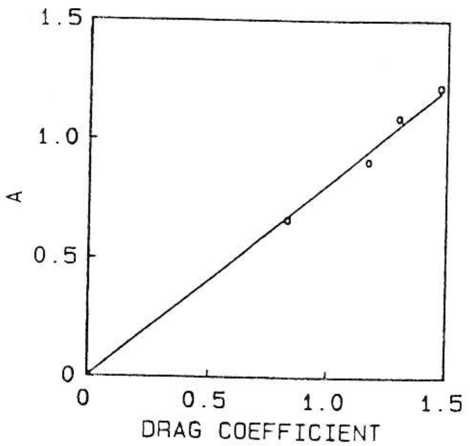

Fig. 4—A typical fit between predicted (solid line) and measured (circles) velocities downwind of wind breaks.

intercept of zero and a slope of 0.81 gave an R^2 of 0.996 that was highly significant ($\alpha = 0.001$). Based on this result, the hypothesis was accepted, and it was concluded that A can be replaced with 0.81 times the known drag coefficient.

Length of Protection

With X expressed as L/H, equation [2] can now be written as

$$U_L/U_o = 1 - Ae^{-0.0876L/H} \quad \ldots\ldots\ldots\ldots\ldots\ldots [9]$$

with A being determined using equation [8]. Furthermore, the wind profile downwind from the barrier near the end of the length of protection can be assumed to follow the typical logarithmic profile (Abtew et al., 1980) described as follows:

$$U = (U^*/0.4)\ln((Z-D)/Zo) \quad \ldots\ldots\ldots\ldots\ldots\ldots [10]$$

where

U = wind velocity at height Z,
U* = friction velocity,
Z = height above land surface,
D = displacement height,
Zo = aerodynamic roughness.

Equation [10] can be applied twice, once for location 0, upwind to the barrier, and once for location L, downward, and the results can be used with the relationship expressed in equation [9] to obtain the following:

$$U^*_L = U^*_o\,(1 - A\,e^{-0.0876(L/H)})\left[\frac{\ln((H/2-D_o)/Zo_o)}{\ln((H/2-D_L)/Zo_L)}\right] \quad \ldots\ldots\ldots\ldots [11]$$

The term in square brackets will be defined as the roughness adjustment factor R_a. If the surface conditions downwind are equal to the surface conditions upwind, D_L will equal D_o and Zo_L will equal Zo_o causing R_a to be equal to unity. The elevations of the two land surfaces are assumed equal. If the land elevations differ, then the H terms in equation [11] would also be different. Raine and Stevenson (1977) have pointed out that some of the data in the literature such as those reported by Woodruff and Zingg (1952) may not be accurate because the wind profile upwind was not considered and controlled to simulate true field conditions.

Equation [11] has the advantage that it expresses the effects of the barrier on the friction velocity, U*, which is the term often used to predict wind erosion (Greeley and Iversen, 1985; Gregory et al., 1988). It is also in a form that can be used directly in wind erosion models that consider changes in surface roughness. As discussed earlier, the velocity reductions in the vortex zone from the barrier downwind 4 to 6 barrier heights are not considered with equation [11]. The results obtained from equation [11] may, however, be adequate in the vortex zone for most modeling objectives. For example, if the porosity is 30% or higher, the vortex zone of reverse flow near the back side of the barrier may not form and equation [11] will be a satisfactory model for all lengths behind the barrier. In the case of a solid barrier where moving soil cannot pass through the barrier, equation [11] would yield a U* that goes to zero (in fact a small negative number), indicating no potential to move sediment downwind. While some velocity may truly exist behind the barrier, no sediment movement will continue because the barrier is solid. This result matches the result predicted with equation [11]. Finally, since U* must exceed the threshold or critical value, U*c, for soil movement to occur, errors in the prediction of U* in the vortex zone where U* is small will not have an effect on the predicted soil movement because the U* does not exceed the threshold value, U^*_c. Equation [11] therefore appears adequate for use in modeling soil movement behind barriers.

If the length of protection needs to be predicted, equation [11] can be arranged in the following form:

$$L = 11.4\,H\ln\left[\left(\frac{A}{1 - U^*_c/(U^*_o\,R_a)}\right)\right]\cos\beta \quad \ldots\ldots [12]$$

where U^*_c is the threshold velocity for soil conditions downwind from the barrier, and $\cos\beta$ is the length adjustment added for the condition of nonperpendicular wind to the barrier.

A barrier also provides some protection upwind. Woodruff and Zingg (1952) and Pelton (1976) reported a limited amount of such data. Plate (1971) graphically presented measured results from Nageli (1941). All of these reports considered indicated that the shape of the upwind protection was similar to the downwind protection except for a distortion in the length scale. Skidmore and Hagen (1976) used a second order polynomial equation to fit the upwind effect on wind velocity. Their equation was for a 40% porosity and is not valid for a distance upto five times the windbreak height.

Since insufficient data were found in the literature to directly evaluate the protection upwind, the equation by Skidmore and Hagen (1976) was used to generate velocity values for lengths between 0 and 5H. Equation [2] was then fit to this generated data for determination of the B value. Equation [2], after calibration, matched the generated data except for the first 0 to 1H. Since modeling the inter-core section of windbreaks was not part of the objectives of this article, data for lengths less than one windbreak height were discarded from further analysis. The remaining data were refit to determine a more precise value for B. This resulted in a value of 0.0877 for B. Equation [2] fit this data with an R^2 of 0.951 and was significant ($\alpha = 0.001$). Between the length limits of 1 to 5H, both equations produced about the same results.

Equation [2] provides three advantages over the polynomial equation of Skidmore and Hagen (1976). First, it is stable at the upper boundary condition for lengths greater than 5H. Second, it includes the variable A which includes the effect of porosity. Changes in porosity can be considered by changing A with equation [8]. This consideration fits the graphs presented by Plate (1971), which provides some verification of equation [2]. The final advantage is both the upwind and downwind effects are modeled by the same form of equation. This easily allows the total length of protection to be considered by changing the numeric value in front of H in equation [12]. Instead of being the inverse of the B coefficient for downwind conditions, it is the sum of the inverse of both the upwind and downwind B values (1/0.0876 + 1/0.0877). This provides the following final equation for predicting the total length of protection:

$$L = 12.6\ H \ln\left[\left(\frac{A}{1 - U_c/(U_o R_a)}\right)\right] \cos\beta \quad \ldots\ldots\ldots [13]$$

VERIFICATION WITH FIELD DATA

Equation [11] was tested with $R_a = 1.0$ and $\beta = 0$ using each of the data sets given in Table 1. Equation [11] fit all data sets with an R^2 value of 0.97 or better. Since all data sets were used in development, three degrees of freedom were lost due to determination of coefficients. Nevertheless, the relationship was highly significant.

An independent check was made using data reported by Tabler and Veal (1971). They reported that their barriers had a porosity of approximately 50%. They also reported that all barriers were open for the bottom two feet. This information was used with the total height to estimate a total barrier porosity using 100% porosity for the bottom two feet and 50% for the rest of the barrier. Measured velocity reductions were compared to predicted velocity reductions using the estimated porosities and equation [11]. Values of $R_a = 1$ and $\beta = 0$ were assumed for this data set. Average values for velocity reductions were reported by Tabler and Veal (1971) and were used in the analysis. There was one point where one of the replications was less than one-third the magnitude of the other two or more than three standard deviations away from the other two. This point was treated as an outlier and the average recomputed using only the two closest values. The equation had an R^2 of 0.703 and was significant ($\alpha = 0.001$) for this set of data.

SUMMARY

Literature reporting windbreak data was reviewed. The equation often used to evaluate protection from windbreaks does not consistently fit the majority of published data. Furthermore, the equation also does not predict correct values for leeside velocity reductions at boundary conditions. The literature review also revealed that windbreak porosity is an important variable that needs to be considered in the evaluation.

An alternative equation was developed to predict the relationship between leeward and upwind velocities as a function of the ratio of distance leeward to barrier height. The new equation gives correct predictions at boundary conditions and includes the variable of porosity. The equation fits published data sets well. Based on this good fit and the problems with the present equation for wind barriers, this new equation should be an improvement over current procedures for evaluating wind barriers with an angular top boundary.

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