Reducing Wind Erosion with Barriers

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ABSTRACT

WHEN wind shear forces on the soil surface exceed the soil's resistance to those forces, soil particles detach and are transported by the wind. Barriers obstruct the wind and reduce the wind's speed, thus, reducing wind erosion.

Application of a model, developed for evaluating effectiveness of a barrier for reducing the capacity of local wind to cause erosion, illustrated: (a) Wind erosion forces are reduced more than windspeed. (b) Properly oriented barriers give much more protection when preponderance of wind erosion forces in prevailing wind erosion direction is high than when preponderance is low. (c) When preponderance of wind erosion forces is low, barrier orientation is almost inconsequential. (d) Because of seasonal variation of wind direction and speed, need for and amount of protection also vary seasonally.

Many trees, shrubs, tall growing crops, and grasses, and slat-fences all can be used as barriers to reduce wind erosion.

INTRODUCTION

Wind erosion continues to be a serious problem in many parts of the world (Food and Agricultural Organization, 1960) and is the dominant problem on about 30 million ha of land in the United States (USDA, 1965). It lowers soil productivity, damages plants, and fills road ditches and fence rows with soil. Wind erosion is most serious in arid and semiarid regions where vegetation is sparse and soil is loose or finely divided, but is also troublesome on sandy and organic soils in more humid regions.

Several practices and procedures have been developed to prevent or reduce soil erosion by wind. They include: roughening the soil surface, increasing the percentage of nonerodible clods, reducing field length, establishing and maintaining vegetative cover, and using wind barriers (Woodruff, et al., 1972). Barriers obstruction the path of wind reduce the windspeed and momentum of air flow and thus afford wind erosion protection.

SOIL DETACHMENT AND TRANSPORT

As wind blows across a land surface, horizontal momentum is transferred vertically to the land surface causing a shear stress on the surface. The shear stress or drag force exerted on the ground surface is determined by velocity gradient or the change in velocity with height. The velocity gradient windspeed profile is given by

$$\frac{du}{dz} = \frac{u^*}{kz} \quad \ldots\ldots [1]$$

where

u = mean windspeed at height z above the mean ground surface;
k = the von Karman constant (0.4); and
u^* = friction velocity further defined as $(\tau/\varrho)^{1/2}$,

where

τ = surface shear (force per unit area) and
ϱ = fluid density.

The surface shear then is

$$\tau = \rho u^{*2}. \quad \ldots\ldots [2]$$

The eddy diffusion equation for steady-state, one-dimensional momentum transport is

$$\tau = \rho K_m \, \partial u/\partial z, \quad \ldots\ldots [3]$$

where K_m is momentum-transfer coefficient. The integrated form of equation [1] over a rough surface becomes

$$u = \frac{u^*}{k} \ln \left[\frac{z-z_d}{z_o}\right], \quad \ldots\ldots [4]$$

which is the well-known logarithmic law. The parameter z_d, the effective displacement height, is the distance from the ground surface to the plane where the momentum-transfer coefficient extrapolates to zero. The roughness parameter, z_o, is the distance from the displaced reference plane to the surface where the wind profile extrapolates to zero.

Besides surface shear, other forces and conditions that influence particle detachment include: gravity, Bernoulli effect, diameter, shape and density of soil grains, angle of repose, packing, and turbulence impulses (Chepil, 1959). When the forces tending to dislodge a particle exceed those tending to keep the particle at rest, the particle is dislodged and transported by the wind. This happens for loose grains 0.25 mm in diameter when the friction velocity u^* is about 20 cm/s (Bagnold, 1943; Chepil, 1959; Lyles et al., 1974; Zingg, 1953), which corresponds to surface drag of 0.48 dynes/cm^2.

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The windspeed at initial particle movement is from 4.0 to 5.8 m/s (9-13 mph) at 30 cm (1.0 ft) (Chepil, 1945a, 1945b; Malina, 1941).

REDUCING WIND SHEAR WITH BARRIERS

Barriers obstructing the path of the wind reduce momentum transferred to the surface and, thus, surface shear stress. That is done by deflecting the flow upwards and dissipating some of its energy in frictional losses.

The barrier exerts by its drag a force on the wind field, which is compensated by a loss of momentum of the air. In an incompressible fluid a decrease in momentum implies a decrease in velocity, thus the drag is converted into wind speed reduction desired for sheltering (Plate, 1971).

One procedure for determining barrier drag is from a momentum balance equation. The balance of horizontal forces on a control volume containing a barrier immersed in two-dimensional incompressible and turbulent flow was given by Seginer (1972) as

$$D = \int_{o}^{z_t} [\rho(u_1^2 - u_2^2) + (\sigma_1 - \sigma_2) + (p_1 - p_2)]\, dz$$

$$\int_{x_1}^{x_2} [\rho(u_t w_t) - (\tau_t - \tau_o)]\, d_x \quad \ldots\ldots\ldots\ldots\ldots\ldots [5]$$

where

χ and z	=	the horizontal and vertical distances, respectively;
u and w	=	the horizontal and vertical windspeed components;
σ and τ	=	the χ-χ and χ-z components of the Reynold's stress tensor;
ϱ	=	density of the air;
p	=	the pressure; and
D	=	the drag force per unit length.

The subscripts 1 and 2 denote, respectively, locations windward and leeward of the barrier.

Normally, $(\tau_t - \tau_o)$ and σ relative to p are neglected (Marshall, 1971; Woodruff et al., 1963a). Woodruff et al. further neglected $\varrho u_t w_t$ for a final equation for total drag of

$$D = \int_{o}^{s} [1/2\rho\,(u_1^2 - u_2^2) + (p_1 - p_2)]\, dz, \quad \ldots\ldots\ldots\ldots [6]$$

where s is depth of wake. The drag on the ground surface, D_g, in the zone immediately leeward of the barrier usually was small as compared with the drag of the barrier, D_b.

The drag coefficient for a given barrier can be computed from the relationship

$$C_d = \frac{D_b}{1/2\rho\bar{u}^2 H} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [7]$$

where

H	=	barrier height, and
$\bar{u}$	=	the mean windward windspeed over the wake depth.

Woodruff et al. (1963a) found excellent agreement between measured drag coefficients and coefficients computed with equation [7].

Hagen and Skidmore (1971) used equation [7] to estimate barrier drag as influenced by porosity. They found that drag coefficients of slat-fence barriers decreased linearly with increasing porosity until the barrier was 40 percent open. A sharp decrease in the drag coefficient for 60 percent porous barrier suggested it was not as effective in reducing leeward windspeed as the 40 percent porous windbreak, which agrees with the effect of porosity on windspeed reported by others (Baltaxe, 1967; Jensen, 1954; and van Eimern, et al., 1964).

Although the drag of the barrier decreases with increasing porosity, barriers with the greatest drag are not the most effective barriers. Woodruff et al. (1963b), who measured windspeed-reduction patterns of many shelterbelts, found that they may be either too dense or too porous to be effective barriers. For barriers with low porosities (large drag coefficients), minimum leeward windspeed occurs close to the barrier and, after reaching minimum, tends to increase more quickly than do windspeeds leeward of more porous barriers (Marshall, 1967; Skidmore and Hagen, 1970a; van Eimern et al., 1964; Woodruff et al., 1963b). Very dense barriers stimulate turbulence (Baltaxe, 1967; Marshall, 1967; Skidmore and Hagen, 1970b; van Eimern et al., 1964). At low permeabilities the area of the sheltered ground decreases, and at high permeabilities the degree of shelter provided becomes negligible.

Optimum permeability for wind erosion control would be logically the permeability that reduces the surface drag below the erodible level for the greatest distance leeward of the barrier. Surface drag necessary to initiate particle movement varies with many factors including particle size, shape, packing arrangement of surface particles, surface water content, surface roughness (Chepil, 1956, 1959; Woodruff and Siddoway, 1965).

The drag or shear exerted on the surface is difficult to evaluate. As an alternative, since rate of erosion is proportional to windspeed cubed for highly erodible surface when windspeed is above the threshold necessary to initiate particle motion (Bagnold, 1943; Chepil, 1945a; Zingg, 1953), let us use reduction of windspeed cubed as a measure of wind erosion protection from barriers. Because windspeed cubed does represent the capacity of the wind to cause erosion, it commonly is used for wind erosion evaluations (Chepil, Siddoway, and Armbrust, 1962; Hagen, 1976; Skidmore, 1965), and may in the general sense be referred to as wind erosion force. Several (Marshall, 1967; Skidmore and Hagen, 1970b; van Eimern et al., 1964) have investigated windspeed reduction patterns as influenced by barrier porosity and found that greatest overall windspeed reduction between the barrier and 30 times its height is with barrier porosity of near 40 percent.

MODEL

Assuming rate of wind erosion being proportional to windspeed cubed and using established windspeed reduction patterns, we developed a model to evaluate the effectiveness of a 40-percent porous barrier for reducing the capacity of wind to cause erosion. The

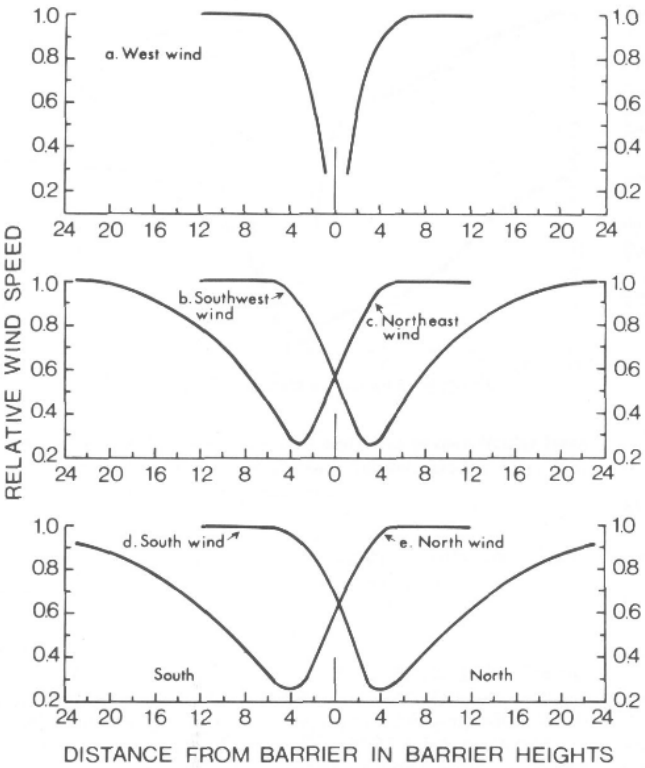

FIG. 1 Relative windspeed for wind from indicated direction with east-west oriented, 40 percent-porous barrier.

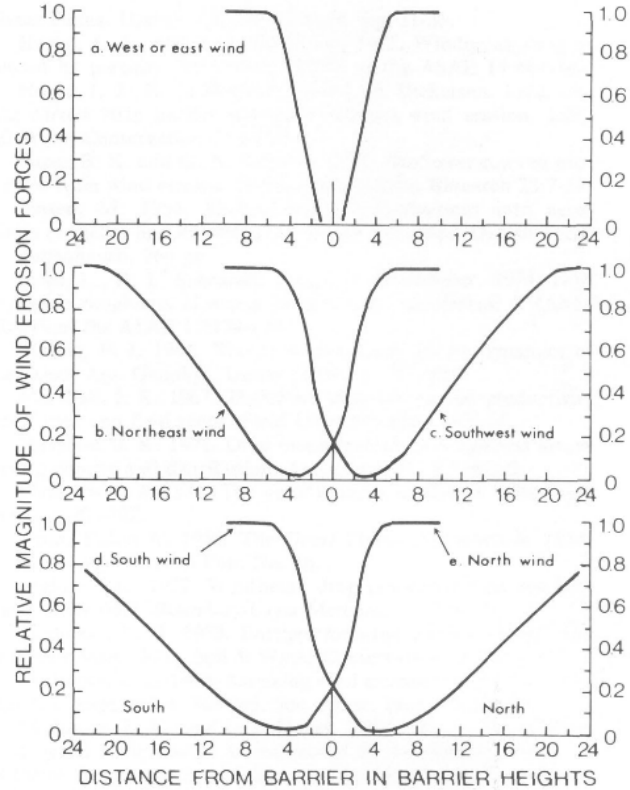

FIG. 2 Relative magnitude of wind erosion forces at various distances from east-west oriented, 40 percent-porous barrier.

functional relationship of the barrier and wind characteristics that influence windspeed most at various distances from the barrier can be expressed as windspeed reduction patterns measured leeward of a barrier of a given height and porosity distribution. We assumed that windspeed reduction is independent of open-field windspeed. The assumption seems justified (van Eimern et al., 1964) provided windspeed does not fall below about 1.5 m/s. Windspeed reduction patterns measured leeward of a 40-percent porous barrier were fitted by Skidmore and Hagen (1970a, 1973) to give this equation:

$$\frac{u_\chi}{u_o} = 0.85 - 4\exp(-0.2H') + \exp(-0.3H') + 0.0002H'^2, \quad [8]$$

H' accounted for incident wind direction not normal to the barrier and is defined as:

$$H' = \chi/\sin\Theta, \quad [9]$$

where χ and Θ are leeward distance in barrier heights and acute angle of incident wind, respectively. The terms u_χ and u_o are windspeeds at distance χ and open field, respectively. A minimum $\sin\Theta$ was set at 0.18.

The equation fitted to data to account for windspeed reductions on the windward side of a barrier was:

$$\frac{u_\chi}{u_o} = 0.502 + 0.197\chi - 0.019\chi^2 \quad [10]$$

Windspeed reduction patterns calculated by equation [8] and [10] are shown in Fig. 1 for wind parallel, 45 deg from parallel, and perpendicular to barrier. The corresponding windspeed cubed reduction patterns are shown in Fig. 2. As was demonstrated by Hagen (1976), the decrease in erosion forces is much greater than windspeed reductions when wind is normal to barrier. The windspeed at 12H leeward of barrier is 62 percent of open field; whereas windspeed cubed is only 25 percent.

Wind erosion forces at various distances from the barrier can be estimated from wind data reported in climatological records. Skidmore (1965) obtained a wind erosion force vector by summing, for all speed groups with windspeeds greater than a threshold windspeed, the product of mean windspeed cubed and a duration factor for a specified direction as expressed by

$$r_j = \sum_{i=1}^{n} \bar{u}_i^3 f_i, \quad [11]$$

where

$\bar{u}_i$ = the mean windspeed within the ith speed group;

f_i = a duration factor expressed as the percentage of the total observations in jth direction with the ith speed group.

By using the mean windspeed in each speed group, as reported in the climatological records as u_o in equations [8] and [10], we can estimate what the windspeed would be at various distances from the barrier, then use that calculated windspeed in equation [11] and calculate a wind erosion force vector at various distances from the barrier.

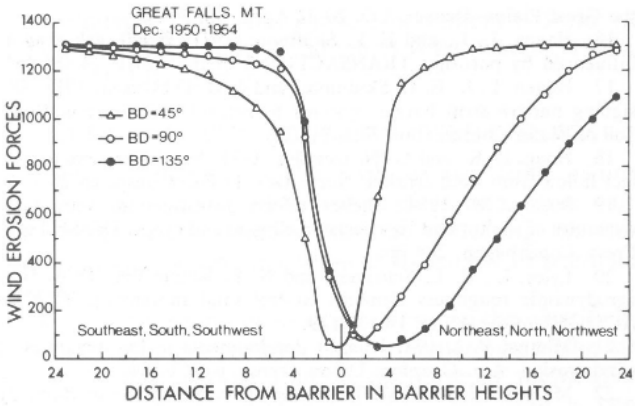

FIG. 3 Wind erosion forces at indicated distances perpendicular from 40 percent-porous barrier when the barrier direction [BD] is 45, 90 (east-west), and 135 deg, respectively. Wind data are for Great Falls, MT.

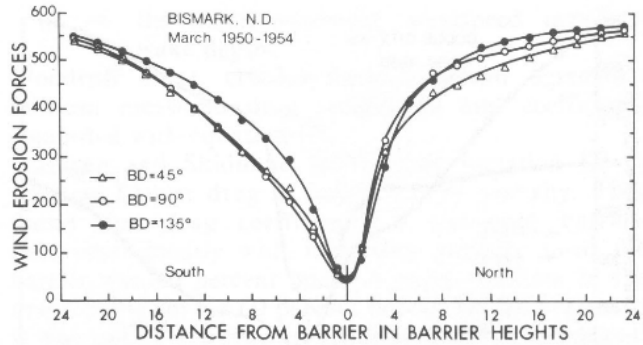

FIG. 4 Wind erosion forces at indicated distances perpendicular from 40 percent-porous barrier when the barrier direction [BD] is 45, 90 (east-west), and 135 deg, respectively. Wind data are for Bismark, ND.

The sum of the wind erosion force vectors for all directions gives the total wind erosion forces for specified distance from the barrier and is expressed by:

$$F_\chi = \sum_{j=1}^{16} \sum_{i=1}^{n} \bar{u}^3_{\chi\,ij} f_{ij}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [12]$$

where $u_{\chi ij}$ is calculated from equations [8] and [10] for n speed groups, and 16 cardinal directions at distance χ from the barrier.

APPLICATION

In an experiment using wind data for Dodge City, Kansas; Bismark, ND; and Great Falls, MT, and equation [12], we calculated the influence of a 40-percent porous barrier on wind erosion forces at various distances from the barrier. For Great Falls and Bismark, we calculated for three different orientations of the barrier: northeast-southwest, east-west, and southeast-northwest. For Dodge City, we used east-west orientation of barrier and calculated for March and August.

The results for Great Falls (Fig. 3) illustrate importance of barrier orientation when the wind is predominately from the prevailing direction of 225 deg (southwest). When the barrier was normal to prevailing wind erosion direction, the wind erosion forces were less than 25-percent open field at 10H leeward, and at 15H they still were less than 50-percent of open field. With the barrier at 90 and 45 deg, the wind erosion forces at 10H were about 50 and 95 percent, respectively. The average value for wind erosion forces in the 0-8H range was only about one eight as much with optimum barrier orientation as with minimum barrier orientation (Table 1).

When the preponderance of wind erosion forces is low, like at Bismark, barrier orientation is almost inconsequential. The curves of Fig. 4 for barrier orientations of 45, 90, and 135 deg are nearly the same. Also, the protection afforded is much less than for a correctly oriented barrier where preponderance is high (Table 1).

Because of seasonal variation in wind direction and speed, the need and degree of protection also vary seasonally. At Dodge City, KS, for example (Fig. 5, Table 1), the winds are stronger in March than in August, and an east-west oriented barrier affords greater protection on the south side. Whereas, in August the winds are more southerly, and the barrier reduces wind erosion forces more on its north side.

Barriers' ability to reduce wind erosion combined with benefits from water conservation, snow catch, farmstead protection, and wildlife habitat have prompted extensive use of barriers — not only in the Great Plains but other areas also. Besides the more conventional tree windbreak used extensively (Ferber, 1969; Read, 1958; Woodruff, Dickerson, Banbury, Erhart, and Lundquist, 1976), many other barrier systems now are used to control wind erosion, including annual crops, like small grains, corn, sorghum, sudangrass, sunflowers (Carreker, 1966; Fryrear, 1963, 1969; Hagen et al., 1972; Hoag and Geiszler, 1971; Siddoway, 1970), tall wheatgrass (Aase et al., 1976; Black and Siddoway, 1971), sugarcane and rye strips on the sands in Florida (Griffin

TABLE 1. RELATIVE CAPACITIES OF THE WIND TO CAUSE SOIL BLOWING NEAR A 40 PERCENT WIND BARRIER FOR INDICATED CONDITIONS

Location	Month	Preponderance	Prevailing wind erosion direction	Barrier orientation	0-8 HN*	8-16 HN	16-24 HN	0-8 HS	8-16 HS	16-24 HS
			degree	degree						
Great Falls, MT	DEC	3.6	225 (SW)	45 (NESW)	791	1284	1306	641	1184	1273
Great Falls, MT	DEC	3.6	225 (SW)	90 (EW)	219	800	1212	924	1265	1298
Great Falls, MT	DEC	3.6	225 (SW)	135 (SENW)	100	433	943	982	1302	1308
Bismark, ND	MAR	1.3	325 (NNW)	45 (NESW)	318	479	542	180	372	508
Bismark, ND	MAR	1.3	325 (NNW)	90 (EW)	345	513	554	167	381	515
Bismark, ND	MAR	1.3	325 (NNW)	135 (SENW)	311	530	567	224	431	527
Dodge City, KS	MAR	2.4	0 (N)	90 (EW)	400	583	681	201	401	609
Dodge City, KS	AUG	2.5	180 (S)	90 (EW)	64	164	323	259	368	398

*H is perpendicular distance from barrier in barrier heights; N and S are northerly or southerly directions, respectively.

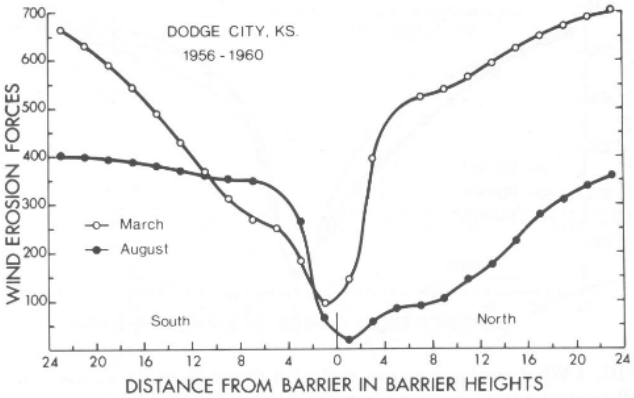

FIG. 5 Wind erosion forces at indicated distances perpendicular from 40 percent-porous barrier in March and August, Dodge City, KS, when barrier direction is 90 deg (east-west).

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