1577-A

Windbreak Design for Optimum Wind Erosion Control[1]

L. J. Hagen[2]/

Abstract. Planting windbreaks is a useful wind erosion control practice, but to obtain best results, three major factors must be considered in designing a windbreak system: 1) the windbreak, 2) the local winds, and 3) the field to be protected. By analyzing these factors, the optimum windbreak porosity, spacing, orientation, height, and other factors can be determined for each location.

INTRODUCTION

Windbreaks have long been used to control wind erosion, but no systematic design procedure is outlined in the literature, for three reasons: Wind and windbreak data, as compiled, are not easy to use; some effects of windbreaks are still not fully understood; and windbreak systems are generally multipurposed, with erosion control as only one of the uses.

Here, I will quantify some major direct effects of windbreaks on wind erosion and also identify some additional indirect benefits. Three major factors that must be considered in designing a windbreak system are: 1) windbreak, 2) local winds, and 3) field to be protected. Each factor will be considered individually.

THE WINDBREAK

The two main effects of windbreaks that aid in wind erosion control are: 1) they decrease surface-wind shear stress, and 2) they trap moving soil. To optimize wind-erosion control, several variables can be manipulated when designing windbreaks. These include porosity, porosity distribution, height, width, shape, resiliency, and seasonal variation in porosity.

Among these variables, windbreak porosity has the most influence on windspeed reduction and soil trapping. When surfaces are highly erodible and the windspeed is above the threshold velocity necessary to initiate particle motion, erosion rate is proportional to windspeed cubed (Bagnold 1943; Chepil 1945; Zingg 1953). Thus, even modest reductions in windspeed cause major reductions in wind erosion (figs. 1 and 2). Maximum wind and erosion reduction extends over a larger leeward area when windbreak porosity is near 40 percent as compared with a less-porous windbreak.

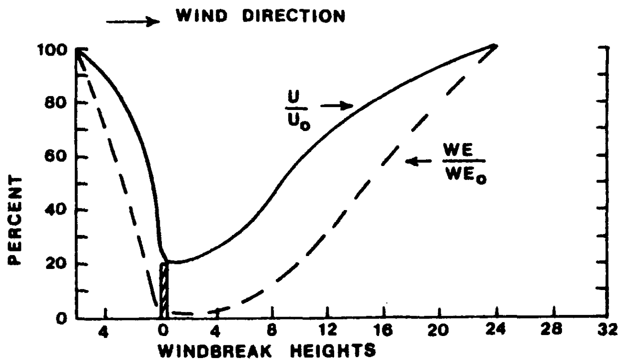

Figure 1. Ratio of shelter to open field windspeed (U/U_o) and wind erosion (WE/WE_o) with all windspeeds above threshold velocity normal to a 20-percent-porous windbreak. Windspeeds measured at 0.12H above the surface.

Skidmore and Woodruff (1968) defined preponderance as the maximum value of the ratio of parallel to perpendicular wind erosion forces obtained by calculating the ratio for every direction at a location. In locations where wind-direction preponderance is low or the windbreak is not oriented normal to the preponderant direction, wind will often pass through the windbreak at an oblique angle. Because wind then travels a longer distance through the windbreak, the effective windbreak porosity may be less

[1]/ Paper presented at the symposium: "Shelterbelts on the Great Plains", Denver, Colorado, April 20-22, 1976.
[2]/ Agricultural Engineer, USDA, ARS, NCR, Manhattan, Kansas 66506.

than that for winds normal to the windbreak, particularly in multirow windbreaks (van Eimern et al. 1964). Less land is also needed to produce a porous than a nonporous windbreak; thus, it is probably the most efficient for wind erosion control. Hagen and Skidmore (1971a) have listed probable porosities of some windbreak species, but more measurements are needed for additional species.

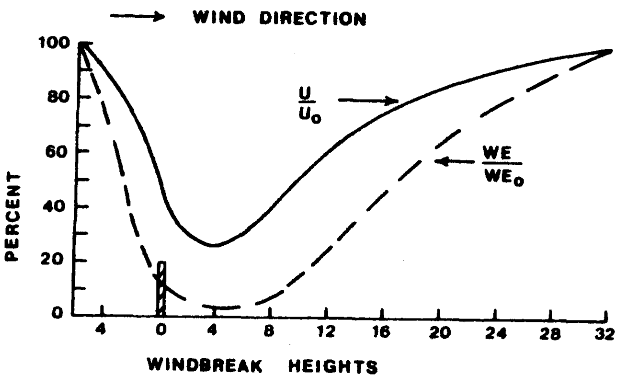

Figure 2. Ratio of shelter to open field windspeed (U/U_o) and wind erosion (WE/WE_o) with all windspeeds above threshold velocity and normal to a 40-percent-porous windbreak. Windspeeds measured at 0.12H above the surface.

The optimum porosity distribution with height is still much debated. Rosenberg (1974) suggested that porosity should decrease with height in proportion to the logarithmic increase in windspeed with height. In contrast, Raine (1974) suggested that maximum windspeed reduction with a minimum use of material should occur with a windbreak closed at the bottom and opened to nearly 100 percent porosity at the top with an overall porosity of 30 percent. He noted this design would avoid concentration of a region of high shear near the top of the windbreak, which would quickly diffuse high windspeeds back to the surface.

Experiments with uniform porosity slat-fences showed that a porosity of less than 40-percent near the fence top caused excess shear (and turbulence), while low porosity near the bottom created low pressures which induced a recirculation zone in the leeward area (Hagen and Skidmore 1971b). Either of these mechanisms can probably prevent a maximum area of shelter in the leeward area. Consequently, it is doubtful that either the top or bottom of an optimum windbreak should be of very low porosity.

The horizontal range of windspeed reduction by a windbreak is proportional to its height (H) (van Eimern et al 1964). However, measurements showed that for similitude between windbreaks, the ratio H/z_o must be similar because as H/z_o increased so did windspeed reduction at a given leeward location (Jensen 1954; Raine 1974). (z_o is open field roughness length.) Scaling the ratio of H/z_o is particularly important when wind tunnels are used to simulate field conditions.

Besides their direct effects on wind erosion, windbreaks also indirectly influence wind erosion. For example, in many areas windbreaks trap snow, which increases soil moisture and prevents freeze-drying of the surface-soil clods (Bisal and Nielson 1964). Windbreaks decrease the speed at which surface soil drys after precipitation, and also enhance vegetative growth (Skidmore et al. 1974; Rosenberg 1974). Even the windspeed reduction during rains will aid in preserving a cloddy surface near windbreaks (Lyles, Dickerson, and Schmeidler 1974).

Another useful property of windbreaks is that they trap part of the suspended dust particles blown into them. Thus, sometimes windbreaks can be used to significantly improve visibility and air quality. Honda (1974), who used industrial dusts to test the dust-trapping ability of 10 plant species, found that individual plants trapped 35 to 80 percent of the dust; most species tested trapped 50 to 60 percent. Consequently, if typically species trap 50 percent of the dust, three rows in a windbreak would presumably trap 88 percent of the dust that enters it. Honda (1974) found that trapping efficiency was inversely proportional to porosity measured by light transmission. Also, trapping efficiency depended on both leaf and dust characteristics.

A final, but important, effect of windbreaks occurs when they are numerous enough to increase the overall roughness of the landscape. Jensen (1954) measured that effect along two parallel lines extending from the North Sea to the Baltic coast. Near the North Sea coast the ratio of surface windspeed to geostrophic windspeed was 0.38; inland along the first line, with only a few windbreaks, the ratio was 0.29. Along the second line, where there were three times as many windbreaks as along the first line, the ratio was decreased to 0.21. Thus, in flat areas, adding several windbreaks over a large area can significantly decrease what we often refer to as open-field windspeed. Further studies are needed on this effect in the Great Plains, because it could be of significant value if a government-sponsored program used incentives to insure relatively continuous windbreaks over large areas.

THE LOCAL WINDS

Windspeeds above threshold velocity cause wind erosion at a rate proportional to windspeed cubed. To combat this force most effectively, the direction preponderance of the wind erosion forces and the distribution of the erosion forces with windspeed during critical erosion periods must be known. There are several wind-data sources, many of which are listed by Lyles (1976).

The preponderance and direction of wind erosion forces are listed in USDA Handbook No. 346 (Skidmore and Woodruff 1968). The preponderance and direction of the Great Plains wind erosion forces for March are shown in figure 3. A preponderance of one indicated no preferred direction, while a preponderance of two indicates erosion forces are twice as great parallel with the direction line as normal to it. Obviously, where preponderance is large, windbreaks should be oriented normal to the maximum erosion forces to perform efficiently.

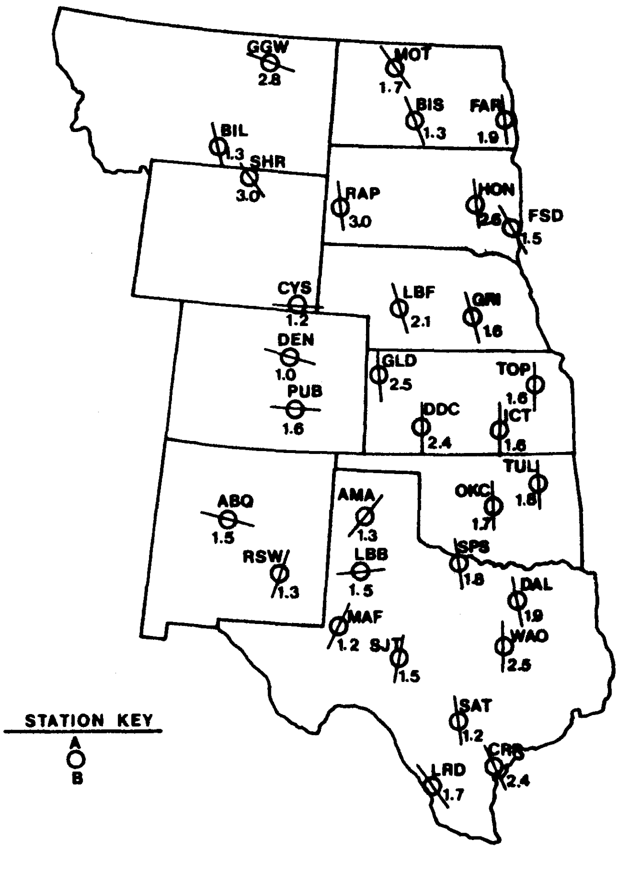

Figure 3. Map of Great Plains showing station abbreviation (A); and preponderance of average March wind erosion forces parallel to the line through each location (B).

The windspeed-probability distribution also affects windbreak performance, as illustrated in figure 4 for winds normal to a windbreak at Dodge City, Kansas. In these calculations, I used the average distribution of south winds during March and assumed an open field threshold windspeed of 19 mph. Wind erosion at each speed was assumed proportional to FU^3 where F is fraction of time at which wind was at speed U.

As shown in figure 4, windspeeds just above the threshold are most frequent, and thus on highly erodible soils, they cause the largest amount of erosion. Where shelter is sufficient, however, the windspeed is reduced below threshold at low speeds, and there is erosion only at the highest windspeeds.

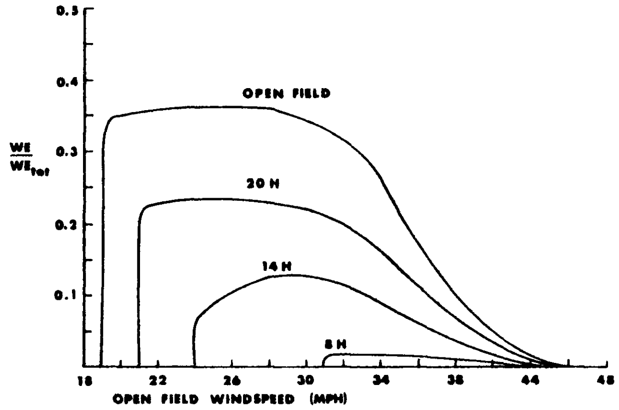

Figure 4. Calculated effects of windspeed distribution of southerly March winds at Dodge City, Kansas on amount of wind erosion (WE) in various speed ranges compared with total wind erosion over all speeds (WE_{tot}) in open field and at various distances (H) leeward of a 40 percent porous barrier.

To evaluate windbreak effects on wind erosion at a location, both the windspeed and direction distributions must be considered simultaneously. To illustrate this, I calculated the effects of windbreaks oriented east-west and northeast-southwest during March at Dodge City, Kansas (fig. 5). We assumed a 40 percent porous windbreak and used an empirical formula derived earlier (Skidmore and Hagen 1970) to describe windspeed reduction by the windbreak as follows: $U/U_o = 0.85 - 4EXP(-0.2H') + 4EXP(-0.3H') + 0.0002H'^2$ where H' equals H/sin θ, and U/U_o is the ratio of shelter to open field windspeed. (θ is the acute angle between the windbreak and wind directions, and sin θ is given a lower limit of 0.18 as θ approaches zero.)

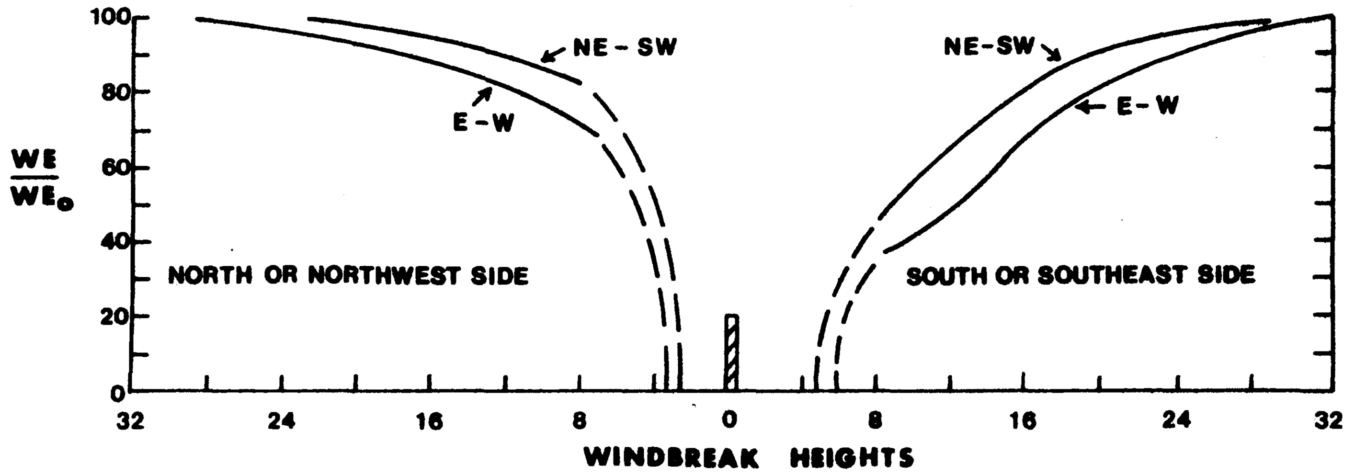

Figure 5. Calculated ratio of shelter to open-field wind erosion for average distributions of windspeed and wind direction at Dodge City, Kansas, in March. Calculations are for two, 40 percent porous windbreaks - one oriented east-west and the other northeast-southwest. A threshold velocity of 19 mph was assumed at anemometer height; the dashed lines indicate estimated values.

We did not calculate erosion within 8 h of the windbreak because in that region where turbulence intensity is high, surface shear stress and windspeed measurements by cup anemometers are not related by a constant drag coefficient[3]. However, wind erosion approaches zero in the sheltered area where windspeed is lowest.

Calculated results in figure 5 show that most of the wind-erosion forces were from the north at Dodge City. Figure 3 also shows that the east-west windbreak is normal to the preponderant wind erosion forces and, thus, should be most effective. Orienting the windbreak northeast-southwest increases WE/WE_o about 10 percent at most locations within the shelter or, conversely, reduces windbreak influence by 3 to 4 H. This sharply illustrates the value of proper windbreak orientation for wind erosion control.

Field, wind-erosion control practices are often designed using the "wind erosion equation" (Woodruff and Siddoway, 1965). In this equation, field width is usually reduced by 10 H to account for the effect of a windbreak when computing the potential soil loss. A better design criteria than the present "10 H-rule" would be to reduce the field width by the number of windbreak heights over which open field wind erosion is reduced at least 50 percent. Such a criterion, by accounting for differences in windbreak porosity and orientation in erosion control designs, would permit wider windbreak spacing in good designs. For example, at Dodge City, erosion was reduced 50 percent at 12 H leeward for the east-west windbreak (fig. 5). If these windbreaks were in a series with some shelter on both sides, then 17 H could be subtracted from the field width. In contrast, only 13 H could be subtracted from the field width, if the series of windbreaks were oriented northeast-southwest.

[3]/ Unpublished data of Hagen.

THE FIELD

The final factor in windbreak design is the field, on which control practices are generally designed to reduce field erosion to some tolerable level. The field erosion tolerance depends on such factors as the crop, depth of productive soil, laws, and downwind effects on air quality or drainage ditches. In the absence of more restrictive constraints, the Soil Conservation Service often applies a soil-loss tolerance of 5 T/AC/YR to wind and water erosion combined. Conservationists usually use a combination of control practices to control wind erosion. Here, I will only consider some general principles applicable to using windbreaks on fields with various potentials for erosion.

I used the wind-erosion equation to calculate both the effects of low windbreaks (which only trap the saltating soil) and of 20 ft-tall windbreaks (which trap soil and provide a sheltered area of 10 H). The results are shown in figure 6 for four wide fields in western

Kansas (i.e., climatic factor equal 100) where the potential erosion ranged from 20 to 200 T/AC/YR.

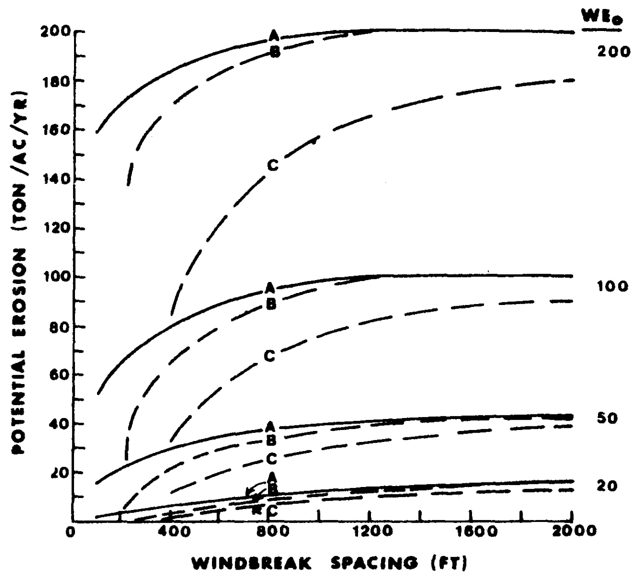

Figure 6. Effect of windbreak spacing on potential annual wind erosion (WE) on four fields using: (A) very low windbreaks, (B) 20-ft-tall windbreaks with erosion averaged over unsheltered part of field, and (C) 20-ft-tall windbreaks with erosion averaged over entire field width. WE_o is the potential wind erosion without windbreaks on four wide fields.

If the erosion potential is high, say 200 T/AC/YR, then windbreaks must be spaced less than 1000 ft apart to trap enough moving soil to begin reducing erosion. If windbreaks alone must reduce the erosion potential to low levels in the unsheltered area, they must be spaced 15 to 20 H. Although curve B (fig. 6) is used in design procedures to insure a tolerable erosion level in the unsheltered area, it tends to hide the fact that when erosion is averaged over the entire area, sheltered and unsheltered, soil loss is reduced substantially, as shown by curve C. For example, 20-ft-tall windbreaks spaced 600 ft apart reduced soil loss to 60 percent of the total lost from an open field.

When potential erosion on a field is low because of adequate vegetation and clods, then tall windbreaks are not as important because little soil is usually saved in the sheltered area. This is illustrated by the 20 T/AC/YR field in figure 6; low windbreaks, at 1000-ft spacings reduced erosion 45 percent while a 20-ft-tall windbreak reduced erosion only an additional 11 percent. Before the designer chooses low windbreaks for a field, however, he should consider two additional factors. If the area has some tall windbreaks, then additional ones may contribute to roughening the landscape. Second, a windbreak may be the major wind-erosion -control method when climatic extremes cause vegetation and other control methods to fail.

A final step in designing a windbreak system should be to calculate the amount of soil which will be trapped by the system. This should be done to insure that the trapped soil will not exceed the capacity of small windbreaks or be incompatible with farming operations near the windbreak (Hagen, Skidmore, and Dickerson, 1972).

LITERATURE CITED

Bagnold, R. A.
1943. The physics of blown sand and desert dunes. William Morrow & Co., New York, 265 pp.

Bisal, F., and K. F. Nielsen.
1964. Soil aggregates do not necessarily break down over winter. Soil Science 98(5):345-346.

Chepil, W. S.
1945. Dynamics of wind erosion: III. The transport capacity of the wind. Soil Science 60(6):475-480.

Hagen, L. J., and E. L. Skidmore.
1971a. Windbreak drag as influenced by porosity. Trans. ASAE 14(3):464-465.

Hagen, L. J., and E. L. Skidmore.
1971b. Turbulent velocity fluctuations and vertical flow as affected by windbreak porosity. Trans. ASAE 14(4):634-637.

Hagen, L. J., E. L. Skidmore, and J. D. Dickerson.
1972. Designing narrow strip barrier systems to control wind erosion. Jour. Soil and Water Conserv. 27(6):269-272.

Honda, Hitoshi.
1974. Fundamental study on the planting and space effects in public nuisance prevention in the city: III. Dust catching ability of plant foliage. Tech. Bul. Fac. Hort. Chiba Univ. 22:81-88.

Jensen, M.
1954. Shelter effect. Danish Techn. Press, Copenhagen, 266 pp.

Lyles, Leon.
1976. Wind patterns and soil erosion on the Great Plains. Symposium on Shelterbelts on the Great Plains, Denver, Colo. Apr. 20-22.

Lyles, Leon, J. D. Dickerson, and N. F. Schmeidler.
1974. Soil detachment from clods by rainfall: Effects of wind, mulch cover, and initial soil moisture. Trans. ASAE 17(4):697-700.

Raine, J. K.
1974. Wind protection by model fences in a simulated atmospheric boundary layer. Fifth Australasian Conference on Hydraulics and Fluid Mechanics, Univ. of Canterbury, Christchurch, New Zealand, pp. 200-210.

Rosenberg, N. J.
1974. Microclimate: the biological environment. John Wiley & Sons, New York, 315 pp.

Skidmore, E. L., and L. J. Hagen.
1970. Evapotranspiration and the aerial environment as influenced by windbreaks. Proc. of Great Plains Evapotranspiration Seminar, Bushland, Texas, pp. 339-368.

Skidmore, E. L., L. J. Hagen, D. G. Naylor, and I. D. Teare.
1974. Winter wheat response to barrier-induced microclimate. Agron. Jour. 66:501-505.

Skidmore, E. L., and N. P. Woodruff.
1968. Wind erosion forces in the United States and their use in predicting soil loss. USDA Agriculture Handbook No. 346, 42 pp.

van Eimern, J., R. Karschon, L. A. Razumova, and G. W. Robertson.
1964. Windbreaks and shelterbelts. WMO Tech. Note No. 59, 188 pp.

Woodruff, N. P., and F. H. Siddoway.
1965. A wind erosion equation. Soil Sci. Soc. Amer. Proc. 29(5):602-608.

Zingg, A. W.
1953. Wind-tunnel studies of the movement of sedimentary material. 5th Hydraul. Conf. Proc., Iowa Inst. Hydraul. Bul. 34, pp. 111-135.