

Turbulent Velocity Fluctuations and Vertical Flow as Affected by Windbreak Porosity

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THE ultimate goal of research on shelter from the wind is to delineate the most effective windbreaks and to predict their effects on crop yields, soil stabilization, and evaporation. Baltax (1)* suggested that the first step toward this goal should be to link the windbreak characteristics with the nature of the leeward airflow. Many researchers (6, 14, 15, 16) have studied windbreak windspeed reduction and made many differing assertions on how far leeward windspeed reduction extends. Most of them noted, however, that porosity is the major factor determining a windbreak's ability to reduce windspeed. Mean vertical flow and turbulent fluctuations have not been studied extensively in relation to windbreak porosity (5, 15).

Assuming that airflow over a windbreak is incompressible (i.e., Reynolds number less than 10^6), the continuity equation for steady flow indicates that a mean vertical flow exists in the lee of windbreaks. One consequence of a mean vertical flow can be demonstrated by considering a property, the measure per unit mass of which is s and the vertical transport of which can be described by the equation:

$$\overline{\rho w s} = \overline{(\rho w) s} + \overline{(\rho w) s'} \quad [1]$$

where ρ is air density, w is vertical velocity (the primes denoting instantaneous departures from the mean and the bar indicating a time average (13)). At low heights above uniform terrain, $\overline{\rho w}$ is usually zero and equation [1] represents the flux due to eddy motion alone. Leeward of a windbreak $\overline{\rho w}$ is not likely to be zero, however; and if it is large, $\overline{\rho w}$ should influence the microclimate.

Turbulent velocity fluctuations are important in the vertical transport process, as shown in equation [1]. Both the magnitude and spectral distribution of turbulent velocity fluctuations have been studied extensively in the open field (2, 4, 10, 11, 12). Knowledge is limited on how windbreak

porosity affects these turbulent-fluctuation parameters, however. Russian researchers (8, 9) have noted that vertical-velocity fluctuations decrease and small eddies form leeward of field shelterbelts. They have suggested, further, that the lee-eddy exchange coefficient (K) is proportional to the vertical velocity fluctuations (σ_w) and eddy size (L) in the lee area. Their computations and those of Brown (3) have shown that leeward K values are smaller than windward K values.

The objectives of this study were to determine the effects of windbreak porosity on mean vertical flow and turbulent velocity fluctuations under field conditions.

METHODS AND EQUIPMENT

Windbreaks 2.44 m (8 ft) high and 60 m (198 ft) long were erected in midfield and oriented so that a wind direction of 202 degrees was normal to the windbreaks. The windbreaks were constructed of vertical wooden slats. Porosities of 20, 40, and 60 percent were achieved by varying the spacing between slats. (0 porosity was achieved by covering a slat fence with polyethylene plastic film.)

Two portable towers were instrumented with sensitive cup-type anemometers (6 windward and 9 leeward) and radiation-shielded thermocouples (3 windward and 3 leeward). Profiles were measured simultaneously to a height of $4H$ (H being windbreak height) at positions $10H$ windward and 2, 6, 12, and $20H$ leeward of each windbreak. In addition, two sensitive anemometer bivanas monitored the turbulent fluctuations and vector mean wind velocities leeward and windward of each windbreak.

The anemometer bivanas, placed at a height of $0.5H$ near the leeward and windward portable towers, measured azimuth, elevation, and windspeed; analog voltages of those measurements were recorded on magnetic tape. Ten-minute runs of those data later were digitized at 0.5-second intervals. The digitized data were transformed during computer analyses from spherical to Cartesian coordinates using the method given by Kaimal and Touart (7). Power spectra were obtained directly from the analog windspeed data

with a low-frequency wave analyzer. To do this the data runs were speeded up 512 times on magnetic tape; each run was formed into a closed loop and then played back for spectra analyses. Using these procedures, 26 bivariate runs and 50 runs of temperature and windspeed profiles were analyzed.

Finally, anemometer bivariate propellers were mounted with their axes in a stationary vertical position at 0.30 and 1.22 m above the surface to measure vertical flow alone. Runs were made with the propellers at positions 1, 2, 4, 6, 8, 12, and $16H$ leeward of the 40 percent porous windbreak. Simultaneous windward temperature and windspeed profiles were measured. Two 15-minute runs were made at each leeward position, and the mean vertical flow was computed by integrating the updrafts and downdrafts, resulting in 14 additional runs of data.

The experimental field, 90 by 180 m, was covered with clipped, dormant grass. Adjacent fields upwind (southwest) of the site were free from large obstructions and were covered with sorghum stubble.

RESULTS AND DISCUSSION

The open-field windspeeds ranged from 3 to 11 m per sec at a height of $0.5H$ (1.22 m). The data were obtained during daylight hours, and bulk Richardson numbers were computed using the procedures suggested by Lettau (10). The atmospheric stabilities ranged from neutral to unstable. Using a computer program, the displacement height (d) and roughness length (z_0) were computed from the windward velocity profiles. From an average of 16 runs under neutral stability, z_0 was 0.94 cm and d was 6.08 cm.

Windspeed Reduction

The mean ratios of leeward to windward windspeeds computed from the cup anemometers are shown in Figs. 1, 2, 3 and 4. As windbreak porosity increased, the position of minimum windspeed moved leeward and the overall height of the low velocity area (wake depth) decreased. Lowest windspeeds were near positions 1, 2, 4, and $6H$ lee for the 0-, 20-, 40-, and 60-percent open windbreaks, respectively. Differences among windspeed reductions of

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* Numbers in parentheses refer to the appended references.

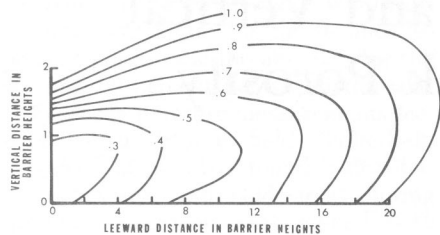


Fig. 1. Ratio of leeward to windward wind-speed in the lee of a 0 percent open (solid) windbreak

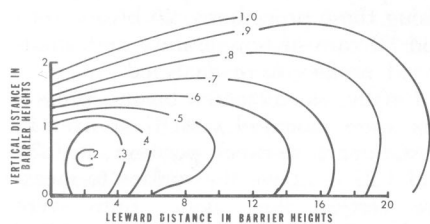


Fig. 2. Ratio of leeward to windward windspeed in the lee of a 20 percent open windbreak

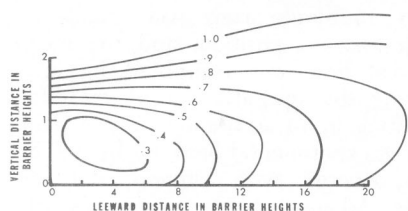


Fig. 3. Ratio of leeward to windward windspeed in the lee of a 40 percent open windbreak

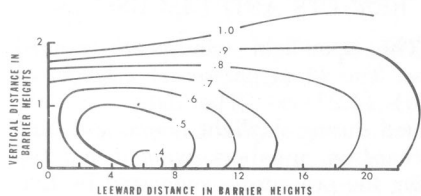


Fig. 4. Ratio of leeward to windward windspeed in the lee of a 60 percent open windbreak

the various porosity windbreaks beyond 12H lee generally were less than 10 percent of the open-field windspeed.

A comparison of the total shelter from the wind was made among the windbreaks. First, the percentage windspeed reduction (ordinate) at a height of 1/8H versus the leeward distance (abscissa) was plotted. The area under the curve for each windbreak was then integrated from 2 to 20H leeward and finally normalized by dividing by the largest area (greatest windspeed reduction). The resultant values were 0.90, 0.95, 1.0, and 0.90 for the 0-, 20-, 40-, and 60-percent open windbreaks, respectively. Thus the 40 percent porous windbreak produced the lowest windspeed over the largest leeward area in agreement with the work of Jensen (6).

Turbulence

According to Lumley and Panofsky (11), the standard deviation of the longitudinal velocity (σ_{u_1}) is proportional to the friction velocity (u_*) under neutral stability.

$$\sigma_{u_1} = Cu_* \quad [2]$$

where C is a constant that increases in unstable conditions but is not sensitive to stability at low heights. Reported values of C range from 2.1 to 2.9. In this study the average windward value of C was 2.27. The linear correlation coefficient of determination (r^2) between the windward C values and the bulk Richardson numbers was 0.03, indicating that windward C values were independent of stability. The effect of the various porosity windbreaks on σ_{u_1}/u_* is shown in Fig. 5. In each

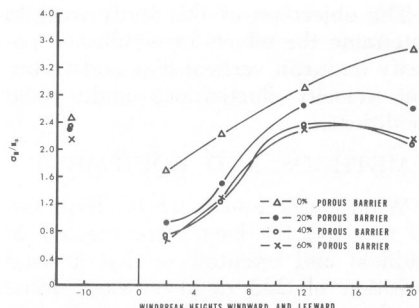


Fig. 5. Longitudinal velocity fluctuations for various porosity barriers at a height of 1.22 m

case, u_* was derived from the windward-velocity profiles. Although mean windspeeds were lower near the low-porosity windbreaks, they still produced larger longitudinal velocity fluctuations than the more open windbreaks produced. Beyond 12H lee, the low porosity windbreaks produced longitudinal velocity fluctuations that were larger than those in the open field.

For neutral conditions the lateral standard deviations (σ_v) are also proportional to windspeed (see equation 2), and the reported C values range from 1.3 to 2.6 for various locations (11). The value of C for the lateral fluctuations is sensitive to atmospheric stability. For the windward bivane in our study, the linear correlation coefficient (r^2) between the σ_v/u_* values and the bulk Richardson numbers (Ri') was 0.79. The mean windward σ_v/u_* was 1.71 when adjusted to neutral stability using the equation

$$\sigma_v/u_* = 1.71 - 22.65 (Ri') \quad [3]$$

where (Ri') had units of m^{-1} . The σ_v/u_* values for the leeward bivane also were adjusted to neutral stability; curves of σ_v/u_* are shown in Fig. 6. Near 6H lee the more open windbreaks had smaller lateral fluctuations than the low-porosity windbreaks had. Beyond 12H lee, all windbreaks produced lat-

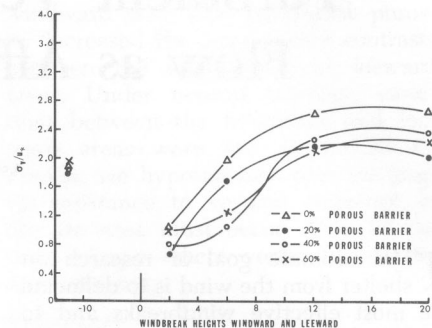


Fig. 6. Lateral velocity fluctuations for various porosity barriers at a height of 1.22 m

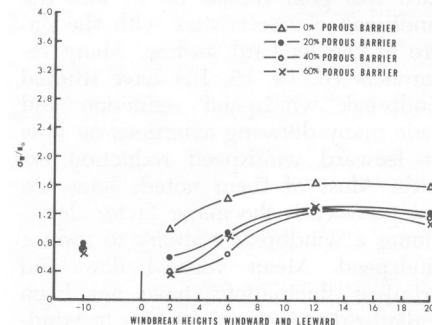


Fig. 7. Vertical velocity fluctuations for various porosity barriers at a height of 1.22 m

eral fluctuations larger than the open-field fluctuations.

The value of σ_w , determined chiefly by mean windspeed and local roughness, is not sensitive to stability at low heights (11), but is proportional to u_* . Reported values of the constant of proportionality C range from 0.7 to 1.3 with 1.05 suggested as the "best" value by Lumley and Panofsky (11). In this study the mean value of C from the windward bivane was 0.74. This is probably a slight underestimate of the true value, however, since the bivanes are not sensitive to the higher frequencies in the vertical-velocity fluctuations. The windbreaks produced a marked increase in the leeward vertical fluctuations and these exceeded the windward fluctuations at positions beyond 6H lee (Fig. 7). The solid windbreak produced the largest leeward vertical fluctuations; the other three windbreaks, behaving similarly to each other, produced smaller vertical fluctuations.

The windward and leeward voltage analogs of the bivane windspeed signals were examined using a wave analyzer to determine the fraction of windspeed variance ($F(n)$) between the frequencies n and $n + dn$. Let f denote the dimensionless frequency with

$$f = nz/\bar{u} \quad [4]$$

where \bar{u} is mean windspeed and z is the measurement height. An analysis of variance indicated that leeward position had a statistically significant influence on peak f (i.e., f where $nF(n)$

was maximum) (Fig. 8). Because of considerable scatter among the runs, peak f differences caused by barrier porosity were not statistically significant. The peak f was highest at 6H lee and decreased toward open-field values of f in the leeward direction. For the range of leeward windspeeds encountered, the peak f values suggested that most of the variation in windspeed was associated with gusts ranging from about 5 m in wavelength at 6H to about 25 m in wavelength at 20H lee.

The windward ratio of $nF(n)/nF(n)_{\max}$ were nearly constant for values of f less than 0.03, but the peak f was about 0.007, which agreed with Berman's (2) estimates at 1.22 m above the surface. In contrast, the leeward ratios of $nF(n)/nF(n)_{\max}$ dropped sharply on either side of the peak f ; at equal 0.03, the ratio was always less than 0.5. That suggested windbreaks destroy eddies having large wavelengths, while they create eddies about the size scale of the windbreak height.

Because K is proportional to σ_w and L (8, 9), it follows that eddy exchange should be least close to the windbreak where σ_w and L are small. Farther leeward, σ_w exceeded the windward value, but L remained smaller than the windward value of L . Hence, K should be less than the windward value near the windbreak, but it should increase leeward. Because the high-porosity windbreaks produced the smallest σ_w , they also should have produced the lowest values of K .

Vertical Flow

Moving away from the soil surface, the magnitude of the mean vertical flow leeward of a windbreak must be evaluated to determine vertical transfer (see equation [1]). Using the continuity equation for an incompressible fluid and the boundary condition of zero velocity at the surface, the vertical velocity (w) may be estimated at height z by

$$w = -\int_{z_0}^z \frac{du}{dx} dz \quad [5]$$

where u is horizontal velocity, x is in the downstream direction, and a positive w is upward. Equation [5] was evaluated between the leeward positions to a height of $0.5H$ using the bivariate wind velocities and the profile shape derived from the cup anemometers (Table 1).

TABLE 1. MEAN VALUES OF THE VERTICAL COMPONENT OF VELOCITY w , EXPRESSED AS PERCENTAGE OF THE WINDWARD HORIZONTAL VELOCITY AT A HEIGHT OF $0.5H$ (1.22 m)

Percent open barrier	Mean vertical velocity component at $0.5H$ height		
	2 to 6H	6 to 12H	12 to 20H
0	0.82	-3.01	-2.12
20	1.24	-2.51	-1.70
40	1.77	-2.07	-1.22
60	1.48	-1.21	-0.86

Vertical flow was upward near the windbreaks but shifted to downward flow near the 6H lee position. Beyond 6H lee the vertical flow was larger for the less porous barriers. From 2 to 6H lee the vertical flow was largest leeward of the high-porosity windbreaks because they had the largest vector, mean wind velocities. An increase in terrain roughness or atmospheric instability would decrease windbreak effectiveness, probably resulting in a decrease in mean vertical flow.

To check the computed vertical velocities in Table 1, the mean vertical velocities leeward of the 40 percent porous windbreak were measured (Fig. 9). The measured values at the 1.22-m height agreed with the computed values, but showed that the vertical flow varied sharply between closely spaced leeward positions. The vertical flow at 30 cm was in the same direction as the flow at 1.22 m but was smaller in magnitude because of the restricting influence of the surface.

To illustrate the importance of vertical velocity, let s equal windward windspeed (u_0) in equation [1] and consider momentum transport. At a height of 1.22 m, using the displacement height and roughness of the experimental site, the two terms on the right of equation [1] become equal

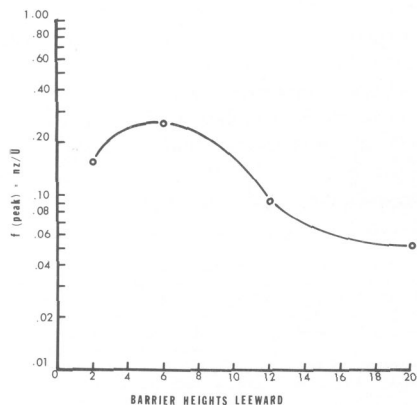


Fig. 8 Frequency (F) where the power spectra peak ($NF(N)_{\max}$) occurred compared with leeward distance

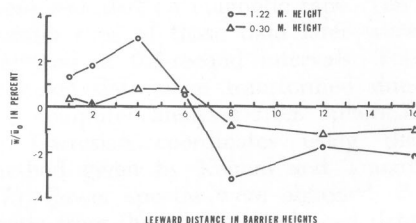


Fig. 9 Vertical flow leeward of a 40 percent open barrier

when $\overline{w/u_0}$ equals 0.7 percent. Recent research has suggested that leeward eddy exchange is usually less than windward eddy exchange (3). The turbulent fluctuation measurements made in this study also support that view. Hence, at 1.22 m above the surface, the mean vertical velocities dominate the leeward vertical exchange process. At lee positions where the vertical flow is downward, the two transfer processes denoted in equation [1] could be opposite in sign, thus decreasing the net vertical transfer. Closer to the surface the vertical velocity is restricted, and below 30 cm eddy exchange probably dominates the vertical exchange process. Because the vertical exchange is large above 30 cm, the air layer close to the crop canopy probably provides the largest resistance to vertical transfer in the sheltered area.

Temperature Effects

Because they are large, vertical velocities apparently affect the leeward temperature distributions during unstable atmospheric conditions. Measured leeward temperatures suggested that downdrafts brought cool air to the surface while updrafts moved the heated surface air upward (Figs. 10 and 11). In addition, because of horizontal flow toward the low-porosity windbreaks, cool air was positioned closer to them than the high-porosity windbreaks. Evaporation effects on the lee temperature distribution were absent in this study, but for a well-watered crop, differences in evaporation rates in the leeward direction probably would affect the temperature distribution also. An analysis of variance revealed that the absolute values of the mean temperature differences

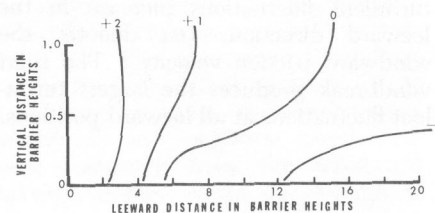


Fig. 10 Average leeward temperatures minus windward temperatures at corresponding height in degrees Centigrade for unstable conditions leeward of the 0- and 20-percent porous barriers

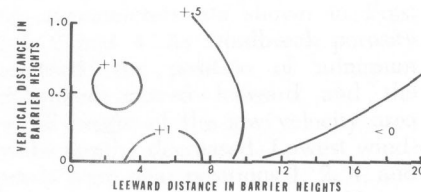


Fig. 11 Average leeward temperatures minus windward temperatures at corresponding height in degrees Centigrade for unstable conditions leeward of the 40- and 60-percent porous barriers

between the leeward and windward profiles were larger for the 0- and 20-percent porous windbreaks than for the 40- and 60-percent porous windbreaks.

From temperature measurements leeward of a 10-row field shelterbelt, Woodruff et al. (16) found a distribution of warm and cold areas during unstable conditions that agreed with the present study. They also noted that the air temperatures at 32H lee were 0.5 to 1.5 C cooler than the open-field temperatures but that they nearly equalled the open-field temperatures at 43H lee.

In runs under neutral stability, the leeward area became cooler than the windward area, but the differences were less than 0.25 C. The shift to cooler leeward temperatures occurred rapidly when the windward temperature profiles became neutral.

SUMMARY AND CONCLUSIONS

Windspeed and temperature profiles were measured leeward and windward of 0-, 20-, 40-, and 60-percent porous, slat-fence windbreaks. Simultaneously, turbulent fluctuations and vector mean-wind velocities were measured using anemometer bivanes.

The largest windspeed reductions, which occur close to the slat-fence windbreaks, ranged from 70 percent for the solid windbreak to about 50 percent for the 60-percent porous windbreak. However, average windspeed reduction over the leeward area was 5 to 10 percent larger for the 40-percent porous windbreak than that for any other windbreak.

Windbreaks reduce the leeward turbulent velocity fluctuations (σ_{u_i}/u_* , σ_v/u_* , σ_w/u_*) below the windward values close to the windbreaks, but the turbulent fluctuations increase in the leeward direction. (u_* denotes the windward friction velocity.) The solid windbreak produces the largest turbulent fluctuations at all leeward positions.

In this study σ_{u_i}/u_* ranged from 1.68 at 2H to 3.48 at 20H leeward of the solid windbreak; σ_{u_i}/u_* ranged from 0.73 at 2H to 2.34 at 12H leeward of the 60-percent porous windbreak. The mean windward σ_{u_i}/u_* was 2.27. The σ_v/u_* values were sensitive to atmospheric stability, but for neutral stability the mean windward σ_v/u_* was 1.71. Beyond about 10H lee, the leeward σ_v/u_* exceeded the windward values for all porosity barriers. The mean windward σ_w/u_* was 0.74; σ_w/u_* ranged from 0.95 at 2H to 1.67 at 12H leeward of the solid windbreak. Leeward of the 60-percent porous windbreak, σ_w/u_* ranged from 0.39 at 2H to 1.27 at 12H.

The power spectra peak had the highest frequencies at 6H lee, but the peak shifted toward lower, open-field frequencies in the leeward direction. The power spectra peaks were associated with eddies ranging from about 5 m in wavelength at 6H lee to about 25 m in wavelength at 20H lee. Further, the power spectra magnitude dropped sharply on either side of the peak in the leeward flow, indicating windbreaks destroy eddies with large wavelengths and create eddies about the size scale of the windbreak height.

At $\frac{1}{2}H$ (1.22 m) above the surface in the lee flow, the vertical velocities were large and probably dominated the vertical-exchange process. From 2 to 6H lee the mean flow was upward, ranging from 0.82 to 1.77 percent of the windward windspeed for the 0 and 40-percent porous windbreaks, respectively. From 6 to 20H lee the mean flow was downward, ranging from 2.12 to 0.86 percent of the windward windspeed for the 0 and 60-percent porous windbreaks, respectively. The vertical flow impressed a temperature distribution on the leeward area when the atmospheric stability was not neutral. During unstable conditions the leeward area was warmer to about 8H lee but

cooler beyond 8 to 10H lee than the windward area. Low windbreak porosity increased the temperature contrasts between the windward and leeward areas. Under neutral stability, variations between the windward and leeward areas were less than 0.25 C. Finally, we hypothesized that the largest resistance to vertical exchange in the lee area must occur close to the crop canopy where vertical velocities are restricted.

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