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EVAPORATION IN SHELTERED AREAS AS INFLUENCED BY WINDBREAK POROSITY[1]

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SUMMARY

Evaporation was measured with atmometers located from 6 *H* (*H* is height of windbreak) windward (upwind) to 12 *H* leeward (downwind) of a 2.44 m (8 ft.) high windbreak. Evaporation, wind speed, and other associated micrometeorological measurements were made when the wind direction was perpendicular ± 25° to the windbreak.

With less porous windbreaks, minimum leeward evaporation occurred closer to the windbreak and, after reaching minimum, tended to increase more quickly than with more porous windbreaks. Minimum evaporation leeward of windbreaks 60, 40, and 0% porous occurred at about 4.5 *H*, 3.5 *H*, and immediately adjacent to the windbreak, respectively. At 4 *H* leeward of the solid windbreak, evaporation had recovered to 92% of open-field evaporation, whereas at 4 *H* leeward of 40 and 60% porous windbreaks, evaporation rates were 65 and 75% of open-field evaporation, respectively. Lowest relative evaporation over the observation region from 6 *H* windward to 12 *H* leeward was achieved with a 40% porous barrier. The windbreaks reduced evaporation in proportion to wind speed reduction. Data from measuring evaporation with atmometers agreed fairly well with data calculated with a revised combination model for instantaneous potential evaporation rate.

INTRODUCTION

Frequently, shelterbelts and windbreaks are used primarily to reduce evaporation (BATES, 1911; VAN EIMERN et al., 1964; DAVENPORT and HUDSON, 1967) and to control erosion (STAPLE, 1961; CHEPIL and WOODRUFF, 1963).

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Evaporation percentages are reduced less than wind speed percentages by shelterbelts (AL'BENSKII and NIKITIN, 1956; VAN EIMERN et al., 1964). In fact, evaporation occasionally increases in sheltered areas. BALTAXE (1967) referred to BLENK's observation (1953) that evaporation was less in the open wind than in the lee of a solid barrier, which he ascribed to greater turbulence behind the barrier. NAGELI (1965) reported increased air turbulence induced by screens as the reason for no accumulation of shelter effect by a series of windbreaks. Russian workers (AL'BENSKII and NIKITIN, 1956) report that weakly pervious shelterbelts only slightly influence turbulent exchange and have little effect on evaporation, and that reduced wind speed is offset by increased temperature in sheltered zones. Other investigators (WOODRUFF, 1954; READ, 1964) found greater evaporation reduction with dense barriers.

The effect of windbreaks on evaporation is complicated by turbulence induced by the barrier, availability of water to evaporation sites, barrier porosity, etc. This study investigated the influence of windbreaks with various porosities on evaporation from surfaces with low diffusive resistances at various distances from the windbreaks.

MATERIALS AND METHODS

The windbreaks were 2.44 m (8 ft.) high slat fences with 60, 40, or 0% porosities. The 40% porous fence was constructed from 1.3 × 3.8 × 244 cm slats, which were positioned vertically and wired together. The 60% porous fence consisted of two tiers of 1.22 m (4 ft.) snow fence constructed similarly to 40% porous fence except for wider spacing of slats. The solid barrier was created by covering the slat fence with plastic film.

A 60 m long fence was positioned perpendicular to prevailing wind direction about midway in a 100 × 200-m field of sudangrass (*Sorghum vulgare sudanense*). Fences were changed periodically, and data were obtained for several observation periods for each fence.

Evaporation from atmometers was measured at various positions relative to the windbreaks. Atmometers were positioned 30 cm above soil surface at -6, -2, -1, $+1$, $+2$, $+4$, $+6$, $+8$, and $+12$ H (H is height of barrier).

Each atmometer consisted of a 6-inch diameter, 1/4 inch thick, porous ceramic plate (bubble pressure: 3.5–4.6 p.s.i.) enclosed with a plastic ring (6-inch diameter, 1/4 inch thick, 3/4 inch wide) and connected to a 50-ml constant head buret (0.1 ml graduation). One graduation on the buret corresponded to a water film 5.5μ thick. The ratio of buret volume to surface area of evaporating surface was 3.3 mm for equivalent water thickness of the reservoir.

Atmometers were checked for variability by operating them for fourteen test periods, seven before and seven after the experiment.

To check the atmometers, we placed them on a table rotating at approximately 1 r.p.m. All were at the same height above the table as well as the same distance from the center. Burets were read to the nearest 0.05 ml after atmometers had evaporated 20 to 40 ml of water.

Coefficients of variation among atmometers before and after the experiment were 3.7 and 2.8%, respectively, coefficients of variation for successive tests were 2.4 and 1.1% before and after experiment, respectively. Since the variation among atmometers was not great, standardization coefficients for individual atmometers were not evaluated. Data were not adjusted for differences among atmometers.

In addition to evaporation measurements from atmometers, concomitant micrometeorological measurements were made. The temperature of the atmometer's evaporating surface was measured during each observation with an infrared radiation thermometer. Wind speed was measured with sensitive cup-type anemometers at the same elevation and distance from the windbreaks as the atmometers. The counters used with the anemometers totalized wind travel. They were read at the end of each observation period.

Solar and net radiation were measured with Eppley pyranometers and FRITSCHEN (1963, 1965) net radiometers, respectively. Wet and dry bulb ambient air temperatures were measured at -6, $+2$, $+6$, and $+12\,H$ with radiation-shielded, ventilated thermocouples.

Each observation period was long enough for 20–30 ml of water to evaporate from the atmometers with wind perpendicular ± 25° to the barrier.

Measured evaporation from atmometers and calculated evaporation were compared. Evaporation was calculated using the revised combination model for instantaneous potential evaporation rate. The model, by VAN BAVEL (1966) is:

$$LE_0 = -\frac{\Delta/\gamma\ H + LB_\mathrm{v}d_\mathrm{a}}{\Delta/\gamma + 1}\ \text{cal./cm}^2\ \text{min} \tag{1}$$

where L is the latent heat of vaporization in cal./g; Δ is first derivative of saturated water vapor pressure versus temperature curve in mbar/°C; γ is psychrometric constant in mbar/°C; ratio of Δ/γ is a dimensionless number depending on the air temperature at elevation z_a; H as applied to the atmometers is net radiation in cal./cm^2 min; d_a is the vapor pressure deficit at elevation z_a in mbar; and B_v is a turbulent transfer coefficient for water vapor in cal./cm^2 min mbar. B_v is defined as:

$$B_\mathrm{v} = \frac{\rho\varepsilon \mathrm{k}^2}{p}\,\frac{u_\mathrm{a}}{[\ln(z_\mathrm{a}/z_0)]^2}\ \text{g/cm}^2\ \text{min mbar} \tag{2}$$

where ρ is the density of air in g/cm^3, ε the water-air molecular weight ratio, k the Von Karman constant, p the ambient pressure, u_a the wind speed at height z_a in cm/min, z_a the elevation above the surface, and z_0 the roughness parameter in cm.

The energy input H at the surface was estimated from insolation R_s by the equation:

$$H = -0.125 + 0.662\,R_s \qquad (3)$$

Eq.3 is a least squares fit of net radiation of atmometer surface as measured with Fritschen net radiometers versus insolation as measured with Eppley pyranometer. That relationship was determined from more than 100 observations between 12h00 and 18h00 for several days.

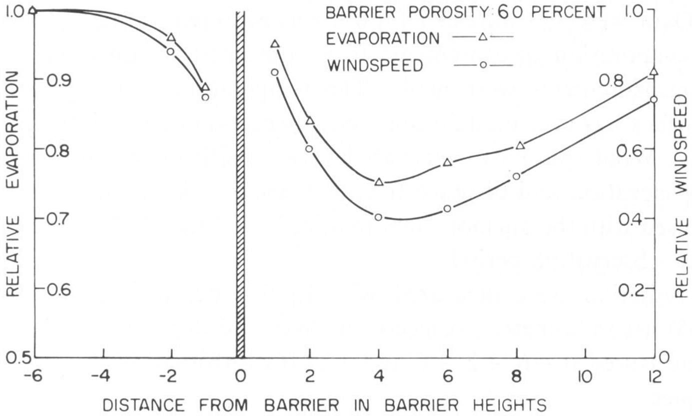

Fig.1. Relative evaporation and wind speed at various distances from 60% porous slat-fence barrier. Plotted data are averaged from five observation periods with open-field wind speeds from 6.2 to 7.1 m/sec at elevation of 1.42 m above soil surface.

RESULTS AND DISCUSSION

Relative evaporation and wind speed for each observation period were obtained by dividing by evaporation and wind speed data obtained at the 6-*H* windward site. Relative data from five runs with reference wind speeds[1] from 6.2 to 7.1 m/sec windward were averaged and are plotted in Fig.1. Fig.1 shows results for the 60% porous barrier, with evaporation scale on the left ordinate and wind speed on the right. Because wind speed percentage was reduced about twice as much as evaporation percentage, the scale for wind speed covers twice the range of the evaporation scale.

Although reductions of evaporation and wind speed varied widely, as will be discussed later, their two curves are nearly parallel. The parallelism of wind and evaporation reductions with barriers 40 or 0% porous (Fig.2, 3) is similar to that for 60% porous barriers (Fig.1), suggesting that evaporation and wind speed are closely related regardless of barrier porosity, wind speed reduction patterns, or turbulence induced by barriers.

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[1] Reference wind speed refers to wind speed indicated by anemometer in open field at an elevation of 1.42 m above soil surface.

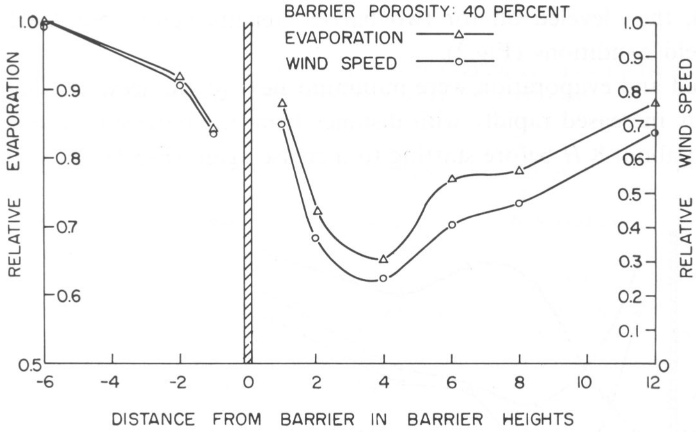

Fig.2. Relative evaporation and wind speed at indicated distances from 40% porous slat-fence barrier. Plotted data are averaged from five observation periods with open-field wind speeds from 5.6 to 6.2 m/sec at elevation 1.42 m.

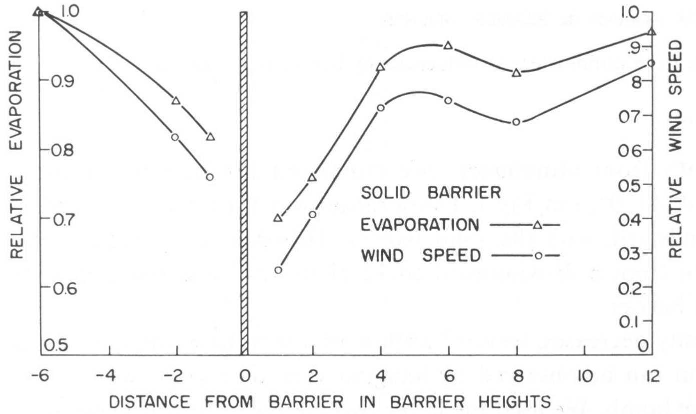

Fig.3. Relative evaporation and wind speed at indicated distances from solid-fence barrier. Plotted data are averaged from five observation periods with open-field wind speeds from 4.3 to 4.8 m/sec at elevation of 1.42 m.

As barrier porosity was reduced, minimum wind speed moved closer to the barrier. Minimum wind speed with 60% porous barrier occurred at about 5 *H*; whereas, with 40 and 0% porous barriers, it occurred at about 3.5 *H* and immediately adjacent to barrier, respectively.

After wind speed and evaporation reached a minimum leeward of the 60% porous barrier, they gradually increased to open-field conditions as distance from barrier increased. But that was not true with less porous barriers. Evaporation and wind speed lee of the 40% porous barrier tended to increase quickly after reaching a minimum, then leveled off for two barrier heights before gradually increasing to open-field conditions (Fig.2).

After wind speed and evaporation were minimum next to the leeward side of a solid barrier, they increased rapidly with distance from the barrier to about 5 *H* then decreased to about 8 *H* before starting to increase again (Fig.3).

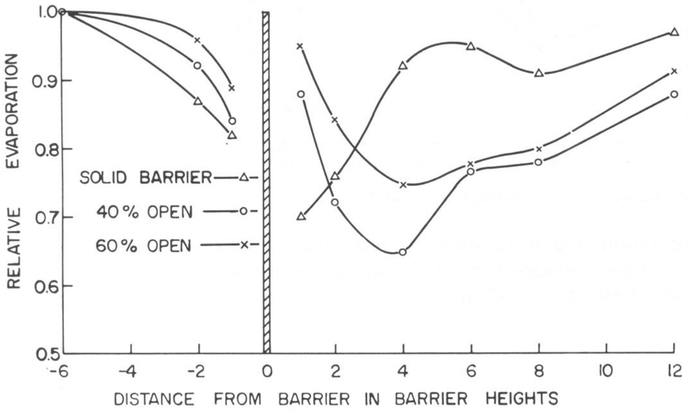

Fig.4. Evaporation from atmometers as influenced by barrier porosity and distance from barrier.

Evaporation data from atmometers are compared for barriers of three different porosities (60, 40, 0%) in Fig.4. Evaporation was least near the barrier, both leeward and windward, with the solid barrier. However, evaporation over the observation region from 6 *H* windward to 12 *H* leeward was reduced most with the 40% porous barrier.

As barrier porosity decreases, leeward airflow becomes increasingly chaotic. Chaotic wind direction can be observed by hanging yarn on a framework, with bivanes, or with smoke bomb. We used the latter two methods. At 6 *H* leeward of the 60% porous barrier, the smoke traveled in the same mean direction of the wind on the windward side of the barrier, but 6 *H* leeward of a solid barrier, it traveled in the opposite direction from windward airflow. Others (BALTAXE, 1967) have demonstrated such reverse airflow and increased turbulence.

The data have shown that although low-porosity barriers may stimulate turbulence and induce reverse airflow leeward, evaporation closely follows wind speed indicated by cup anemometers.

Ambient air temperature was higher at 2 *H* leeward than at 6 *H* windward by 0.9, 1.2, and 1.5 °C for 60, 40 and 0% porous barriers, respectively. Ambient air temperature was highest at 2 *H*, then tended towards open-field temperature farther from the barrier.

The ambient water vapor pressure was slightly higher 2 *H* leeward than 6 *H*

TABLE I

EVAPORATION RATE FROM ATMOMETERS AND ASSOCIATED MICROMETEOROLOGICAL DATA; THE DATA PRESENTED ARE AVERAGES OF SEVERAL OBSERVATION PERIODS

*Position of atmometer (H)**	*Evapor. rate (mm/h)*	*Wind speed hourly average (cm/sec)*	*Ambient air temperature (°C)*	*Ambient vapor press. (mbar)*	*Temp. evaporating surface (°C)*
Windbreak porosity: 60%; average insolation: 1.03 cal./cm² min					
− 6	0.90	393	31.9	28.5	28.0
− 2	0.87	345	—	—	28.0
− 1	0.81	293	—	—	28.3
+ 1	0.86	318	—	—	27.9
+ 2	0.76	228	32.8	30.0	28.4
+ 4	0.68	155	—	—	29.8
+ 6	0.70	165	32.7	30.1	29.8
+ 8	0.72	201	—	—	28.5
+12	0.82	287	32.6	27.8	27.9
Windbreak porosity: 40%; average insolation: 1.04 cal./cm² min					
− 6	0.96	320	32.9	27.8	28.9
− 2	0.88	260	—	—	28.9
− 1	0.81	211	—	—	29.3
+ 1	0.84	220	—	—	29.3
+ 2	0.68	113	34.1	30.9	30.1
+ 4	0.62	80	—	—	31.8
+ 6	0.73	129	33.6	28.6	30.0
+ 8	0.75	149	—	—	28.5
+12	0.84	216	33.5	25.8	28.3
Windbreak porosity: 0%; average insolation: 1.10 cal./cm² min					
− 6	0.84	223	34.2	29.9	29.9
− 2	0.73	139	—	—	30.5
− 1	0.69	117	—	—	30.8
+ 1	0.60	59	—	—	34.2
+ 2	0.63	93	35.7	32.5	32.2
+ 4	0.78	165	—	—	30.3
+ 6	0.80	168	34.7	28.8	29.9
+ 8	0.77	153	—	—	29.6
+12	0.82	192	34.5	27.4	29.4

**H* = barrier height

windward of the barrier. The differences were 1.5, 3.1, and 2.6 mbar, respectively, for 60, 40, and 0% porous barriers. But at 12 *H* leeward, vapor pressure was less than windward by 0.7, 2.0, and 2.5 mbar, respectively, for barriers of 60, 40, and 0% porosity.

Evaporation rate is reflected in temperature of evaporating surface of atmometers. As evaporation rate decreased with reduced wind speed, temperature of the evaporating surface rose. Data from Table I show that the temperature of the atmometer surface evaporating slowest was 1.8, 2.9 and 4.3 °C higher than the temperature of the atmometer at 6 *H* windward of 60, 40, and 0% porous barriers, respectively.

Although surface temperatures were higher for atmometers evaporating more slowly, they were always below air temperature. DESJARDINS and HANSEN (1967) reported that the temperature of an evaporating surface of black porous disc atmometers approached air temperature under high insolation but under low insolation, approached wet bulb temperature of the air.

If wind speed and evaporation from wet surface of atmometers are reduced proportionally, regardless of barrier characteristics, one should be able to compute evaporation reduction based on some model. That would permit predictions regarding potential evaporation that include a wind function.

Various methods have been proposed to use meteorological data to estimate potential evaporation. TANNER and PELTON (1960) tested the energy balance approximation of Penman and found that although his estimates correlated highly with detailed energy balance measurements, his absolute values of estimates were much too small, which others (THOMPSON and BOYCE, 1967) have confirmed.

A revised Penman version including surface roughness and a wind function for water vapor transfer was tested by VAN BAVEL (1966) and is presented here as eq.1 and 2. Van Bavel found excellent agreement of calculated and measured values for a variety of conditions including strongly advective. The model is not completely applicable to our problem because the transfer coefficients were computed for a crop boundary layer surface. Despite that, however, the model should give reasonable results and compare effects of barriers of various porosities on evaporation.

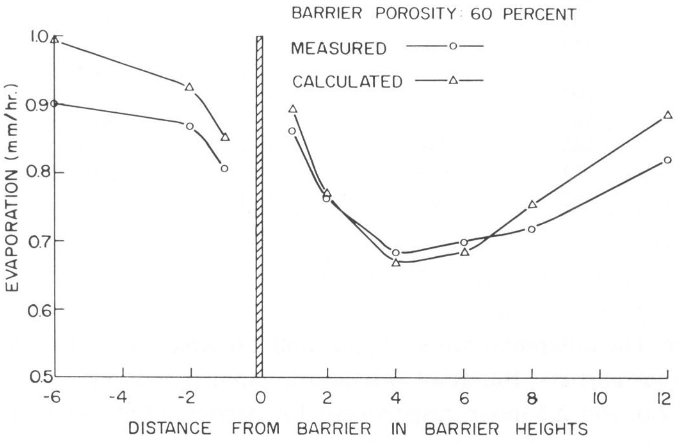

Fig.5. Evaporation from atmometers compared with calculated evaporation in sheltered area of 60% porous slat-fence barrier. Data are averaged from six observation periods with open-field wind speeds from 5.0 to 7.1 m/sec at 1.42 m above soil surface.

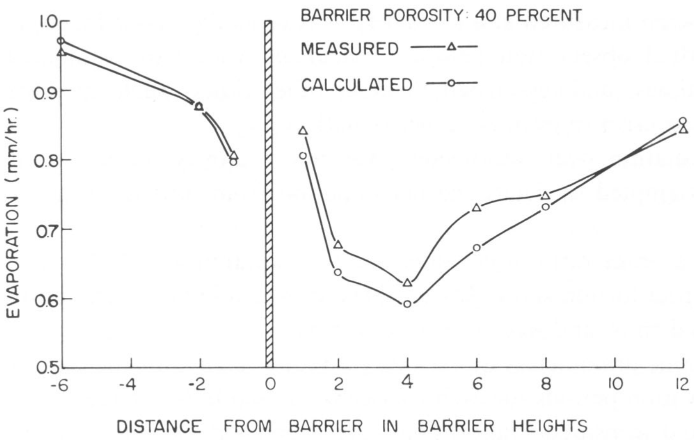

Fig.6. Evaporation from atmometers compared with calculated evaporation in sheltered area of 40% porous slat-fence barrier. Data are averaged from four observation periods with open-field wind speeds from 4.6 to 6.0 m/sec at 1.42 m above soil surface.

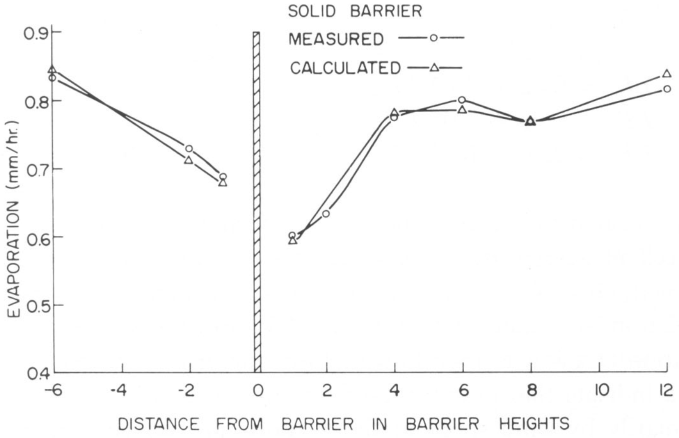

Fig.7. Evaporation from atmometers compared with calculated evaporation in sheltered area of solid barrier. Data are averaged from five observation periods with open-field wind speeds from 3.0 to 4.5 m/sec at 1.42 m above soil surface.

Evaporation from atmometers was compared with evaporation calculated from eq.1. Results for the 60% porous barrier are shown in Fig.5. Data were averaged from six observation periods with open-field wind speeds from 5.0 to 7.1 m/sec at 1.42 m above soil surface. Calculated values overestimated measured values where barrier influence was small. The overestimation was about 10% at 6 *H* windward.

Agreement between calculated and measured evaporation rates was excellent for the other two barriers, as shown in Fig.6 and Fig.7.

Agreement between measured and calculated was generally better for averages than for individual observation periods. Calculated values overestimated measured values at times, underestimated them at other times. Such an error easily could be from an error in estimating net radiation.

Because net radiation over atmometers was not routinely measured, as insolation was, we attempted to determine net radiation from insolation, hence eq.3.

With our data, average ratio of net radiation to insolation was 0.54, which is what one would expect for old snow (LIST, 1951) and which indicates similarity of the two surfaces, old snow and wet, near-white ceramic.

Data from all nine atmometers at various positions relative to the barrier and for several observation periods for each barrier were used in linear regression analysis; calculated and measured evaporation were dependent and independent variables, respectively. Resulting regression equations and correlation coefficients follow:

Barrier porosity (%)	*Regression equation*	*Correlation coefficients*
60	$LE_c = 0.02 + 1.02\ LE_m$	0.91
40	$LE_c = 0.06 + 1.05\ LE_m$	0.99
0	$LE_c = 0.19 + 0.74\ LE_m$	0.93

The equations with near zero intercept and unity slope and high correlation coefficients indicate excellent agreement between calculated and measured evaporation. Near barriers with 60 or 40% porosity, slope was near unity with near zero intercept. The deviation from unity slope for the solid barrier was caused by overestimating evaporation at a low evaporation rate for one of the observation periods. Again the data indicate that evaporation from atmometers in sheltered areas is influenced primarily by wind speed at the evaporating surface, not by porosity characteristics of barriers except as they affect wind speed. However, more nearly accurate measurements of energy input (net radiation) and other micrometeorological parameters might show that modification of flow structure is affecting exchange.

It was noted earlier that barriers reduce wind speed much more than evaporation. This is easily explained by eq.1, the model for predicting potential evaporation.

By separating two terms on the right side of eq.1, we obtain:

$$LE_0 = -\left(\frac{\Delta/\gamma\ H}{\Delta/\gamma + 1} + \frac{LB_v d_a}{\Delta/\gamma + 1}\right) \tag{4}$$

which shows potential evaporation as the sum of energy input and turbulent transfer terms. The energy input term is not affected by wind. It is the term that MONTEITH (1965) gave as an expression for the rate at which latent heat must be taken up when water evaporates into saturated air. The condition existing when all evaporation is accounted for by energy input term has been referred to as an equilibrium evaporation case (PRUITT et al., 1968). However, under advection, the turbulent transfer term may be as large as or larger than the energy input term (SKIDMORE et al., 1969). If the two terms were equal and a barrier reduced wind speed 50%, evaporation would not be affected by the contribution of energy input term and the contribution of the second term would be reduced 50%; therefore, overall evaporation would be reduced 25%. That is one reason wind barriers reduce wind speed more than evaporation. Also, the turbulent transfer term of eq.1, and expressed by eq.2, is applicable only to wet surfaces. The assumption is made in deriving eq.1 that water vapor pressure at the evaporating surface equals water vapor pressure of pure free water at the temperature of the surface. If the evaporating surface is not wet or if diffusive resistances are high, evaporation may not decrease when wind speed decreases. VAN BAVEL et al. (1967) have shown, using MONTEITH's (1965) procedure, that a critical value for canopy resistance exists. Below this value evaporation increases with increasing wind speed; above it evaporation decreases with increasing wind speed.

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