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Potential Evaporation as Influenced by Barrier-Induced Microclimate

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In many agricultural regions, especially where evaporation is high, windbreaks are used to reduce evaporation and provide a more favorable environment for plants. Shelterbelts planted extensively on the Steppes in Russia and on the Great Plains in the United States are examples.

The extent to which windbreaks will lower potential evaporation, \( E_p \), (see Notation, p. 243) depends on the climate and on the relationships of windbreak characteristics-leeward airflow and leeward airflow-barrier-induced microclimate. For windbreaks to lower the \( E_p \), \( E_p \) must be caused by elements that windbreaks modify. That implies wind with relatively high temperature and low humidity. A change in windspeed when air temperature is low or humidity is high (\( e_x - e_a \) is small) only slightly affects evaporation rate (SKIDMORE et al., 1969). Windbreaks affect net radiation, the principal source of energy, only in the immediate vicinity of the windbreak, and then only slightly.

Leeward airflow is the primary factor affected by a windbreak. Horizontal windspeed is reduced; vertical flow is modified; and turbulence is stimulated. Horizontal windspeed at some position leeward of the barrier is a function of the nature of incident wind (open-field windspeed, angle of incident wind, and to some extent, thermal stability and turbulence) and of the barrier characteristics, which include permeability, height, shape, width, and resilience. Of those windbreak characteristics, permeability (porosity or density) and height are most important.

Wind direction varies widely in most areas, thus barriers often are not oriented normal to wind direction. The distance a barrier protects from blowing wind and angle of incidence less than 90° go down together. However, even a wind parallel to a barrier is reduced as much as 5H behind the barrier (VAN EIMERN et al., 1964). Reduction then results from inevitable variation in wind direction and friction at and above the barrier.

Model

The 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 given height and porosity distribution. In so doing, it is assumed that windspeed reduction is independent of open-field windspeed. The assumption appears justified (VAN EIMERN et al., 1964) provided windspeed does not fall below about 1.5 m/sec. Windspeed reduction pattern measured leeward of a 40%-porous barrier were fitted by SKIDMORE and HAGEN (1970) to give an equation:

\[
\frac{u_x}{u_o} = 0.85 - 4\exp(-0.2H') + 4\exp(-3H') + 0.0002H'^2
\]  

(1)
H' accounted for incident wind directions not normal to the barrier and was defined as:

\[ H' = \frac{x}{\sin \theta} \]  

(2)

where \( x \) and \( \theta \) are leeward distance in barrier heights and acute angle of incident wind, respectively.

Eq. (1) approximates the windspeed distribution for a particular wind barrier; the coefficients and the form of the equation may differ for wind barriers whose properties for influencing windspeed distribution differ from those of a 40%-porous slat fence.

To account for windspeed reductions near windbreaks because of barrier roughness and wind direction fluctuation when the mean wind direction is parallel to the barrier, a minimum value of 0.18 was set on \( \sin \theta \), which corresponds to about 10°.

Windspeed is also reduced on the windward side of a barrier, but to a much lesser extent. An equation for windward windspeed reduction was fitted to data for a 40%-porous, slat-fence barrier as:

\[ \frac{u_x}{u_0} = 0.502 - 0.0197x - 0.019x^2 \]  

(3)

No effort was made to account for change in wind direction for the windward side.

The barrier-induced change in temperature and humidity only slightly influenced evaporation rate in the shelter. Barriers raise daytime ambient air temperature. They also raise ambient water vapor pressure from the windbreak out to about 10H. At 12H leeward, SKIDMORE and HAGEN (1970) found that vapor pressure was less than windward pressure by 0.7, 2.0, and 2.5 mb, respectively, for barriers of 60, 40, and 0% porosity.

The higher temperature and humidity in the sheltered region tended to offset each other in changing evaporative demand. However, in the region where vapor pressure and temperature were lower and higher, respectively, than in open-field the vapor pressure deficit was greater.

We compared calculated \( E_p \) using both actual and open-field \( T \) and \( e \) at 2, 6, and 12H leeward of 60, 40, and 0% porous slat-fence barriers. Neglecting the barrier-induced change in temperature and water vapor pressure at 2 and 6H leeward of windbreak made an average difference in \( E_p \) of about 1 percent, whereas neglecting the barrier-induced change of \( T \) and \( e \) at 12H leeward reduced calculated \( E_p \) an average 5%. Based on the data used, neglecting barrier-induced changes in temperature and humidity is of small consequence in regulating evaporation, so the influence of a wind barrier on \( E_p \) can be approximated with an appropriate model by accounting for effects of reduced windspeed on \( E_p \).

Various models as well as definitions have been proposed for estimating \( E_p \), including the combination concept, which can be used to calculate \( E_p \) using climatological observations. VAN BAVEL'S (1966) combination equation for \( E_p \) in energy equivalents is:

\[ E_p = \frac{\frac{\Delta}{\gamma} (R_g - G) + \lambda B_x (e^*_x - e_x)}{\frac{\Delta}{\gamma} + 1} \]  

(4)

where \( \lambda \) is the latent heat of vaporization in cal g\(^{-1}\), \( \Delta \) is the first derivative of saturated water vapor pressure-temperature curve in mb C\(^{-1}\), \( \gamma \) is the psychrometric constant in mb C\(^{-1}\), the ratio of \( \Delta/\gamma \) is a dimensionless number depending on the air temperature,
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$R_n$ and $G$ are net radiation and soil heat flux densities, $e_s$ is the saturated water vapor pressure at ambient air temperature, $e$ is the water vapor pressure in mb, and $B_v$ is the turbulent transfer coefficient for water vapor defined as:

$$B_v = \frac{\varrho e k^2 u_z}{P \left[ \ln(ze_0) \right]^2}$$  \hspace{1cm} (5)

where $\varrho$ is the density of air in g cm$^{-3}$, $e$ the water-air molecular weight ratio, $k$ the von KARMAN constant, $P$ the ambient pressure, $u_z$ the windspeed as height $z$, $z$ the elevation above the surface, and $z_0$ the roughness parameter in cm.

In the derivation of Eq. (4), it is assumed that water vapor pressure at the surface is equal to vapor pressure of water at surface temperature, which is the defining condition for $E_p$.

This theoretical form of the transfer coefficient (Eq. 5), first recommended by BUSINGER (1956) was derived from an aerodynamic profile equation for evaporation and a vapor-pressure, gradient type equation for latent heat transfer. VAN BAVEL (1966), using Eqs. (4) and (5), found excellent agreement between calculated and measured values of $E_p$ on an hourly and daily basis. TANNER and PELTON (1960) also found that the combination method was satisfactory when $B_v$ was determined as suggested by BUSINGER (1956), assuming neutral conditions. Others have noted an overestimation of evapotranspiration with well-watered crops at high windspeed and underestimation at low windspeeds. Pan evaporation at Yuma, Arizona, (SELLERS, 1964) for May, June, July, Aug., and Sept. was 50% greater than $E_p$, as estimated by PENMAN'S method (1956). On the other hand, values for the diffusion coefficient obtained by the BUSINGER method seemed too large when windspeed was greater than 2.0 m/sec. JENSEN et al. (1969) found that a local calibration of the transfer term improved agreement between calculated $E_p$ and observed evaporation from well-watered crops.

**Experimental Procedure**

$E_p$ as influenced by barrier-reduced windspeed was calculated by Eq. (4), with the transfer coefficient defined by Eq. (5) and the windspeed term evaluated by Eq. (1–3). Calculations were first made from assumed data of air temperature, dewpoint temperature, windspeed, wind direction relative to windbreak, and net radiation. The calculations illustrate some principles of using barriers to reduce evaporation as well as possible influences of windbreaks on $E_p$ for various combinations of climatic variables that might exist in the Great Plains climate.

Next, using climatological data from two sample locations in the Great Plains, $E_p$ was calculated. Records of daily mean air temperature, dewpoint temperature, average daily windspeed, prevailing or resultant wind direction, and solar radiation were obtained for Bismarck, North Dakota, and Dodge City, Kansas, from Local Climatological Data, National Climatic Center, Asheville, North Carolina. Bismarck is at 100° 45' W. longitude and 46° 46' N. latitude. Dodge City is about the same longitude (99° 58') but it is 9° farther south (37° 46' N.). Average station barometric pressures were 955 and 924 mb for Bismarck and Dodge City, respectively.

$E_p$ was calculated from the climatological data each day, May through September,
1960–1969, for both Bismarck and Dodge City. Net radiation was estimated from solar radiation by:

$$R_n = 0.8R_s - 120$$  \hfill (6)

Calculations of $E_n$ were made at 13 positions from $-6H$ to $28H$ from the barrier.

**Results and Discussion**

The influence of decreasing the angle of incident wind from perpendicular to parallel on relative calculated $E_n$ at indicated distances from a barrier is shown in Fig. 1. Computations were made for windspeed, air temperature, and dewpoint temperature of 4 m/sec., 25°C, and 10°C, respectively, at a height of 2 meters. Net radiation was assumed to be 375 ly/day. The shape of the family of curves (Fig. 1) is similar to what one would get by plotting windspeed reduction data generated by Eq. (1). As the angle of incident wind decreases from 90°, the leeward sheltered distance shortens and the influence of the barrier on reducing evaporation lessens. However, the influence of the acute angle of incident wind on evaporation is less between 45° and 90° than between 0° and 45°. If the barrier were oriented perpendicular to the prevailing wind direction, the

![Fig. 1.](image)

wind direction relative to barrier would be 45° to 90° most of the time. Even at 45°, most barriers significantly reduce windspeed 10 to 12 times their heights.

Reducing windspeed reduces $E_n$ more at larger water-vapor-pressure deficits. Even at relatively low windspeed of 2 m/sec. and large water-vapor-pressure deficits (conditions of Fig. 2, curve d), wind barriers may greatly reduce $E_n$—even more than with relatively low vapor-pressure deficit and much higher windspeeds of 6 m/sec. (Fig. 2, curve c).

Fig. 2 compares shelter effects when radiation is large or small in relation to wind. When radiation dominates (Fig. 2, curve a), that is, when both the water-vapor-pressure deficit of the atmosphere and the windspeed are low, a windbreak influenced $E_n$ only slightly. But when vapor-pressure deficit and windspeed are high, a windbreak reducing windspeed greatly reduces $E_n$ (Fig. 2, curve f).
Fig. 2. Relative calculated potential evaporation at indicated distances from the barrier as influenced by windspeed and other climatological variables. $T$, $T_d$, and $R_e$ were 20°C, 15°C, and 450 ly/day, respectively, for curves a, b, and c. For curves d, e, and f, $T$, $T_d$, and $R_e$ were 30°C, 5°C, and 300 ly/day, respectively.

Synthetic data were used in the last example to illustrate how wind barriers may reduce $E_p$. Real data from Bismarck and Dodge City are used now to show the influence of wind barriers on $E_p$. Each month, May through September, was analyzed separately; relationships were similar from month to month, so the average of the five months is presented in Fig. 3 and 4 for Bismarck and Dodge City, respectively.

Data for all days as well as for leeward days are shown. When wind direction was from 90° to 270°, the north side of an E–W oriented barrier was leeward. When wind direction was less than 90° or greater than 270°, the north side of the barrier was windward. Therefore, data were obtained on the north side of an E–W barrier when the wind was from the south and on the south side, when the wind was from the north.

At Dodge City, the data for leeward days only show that $E_p$ was 38% greater when winds were southerly. Temperatures then were higher and winds were stronger. At Bismarck, only 5% difference occurred in $E_p$ between days of southerly or northerly winds.

Fig. 3. Average calculated potential evaporation at indicated distances from wind barrier for Bismarck, North Dakota, May through Sept., 1960–1969. The wind was southerly 52% of the days.
Fig. 4. Average calculated potential evaporation at indicated distances from wind barrier for Dodge City, Kansas, May through Sept., 1960–1969. The wind was southerly 73% of the days.

To obtain a complete picture of barrier influence, we must consider both sides of the windbreak for all days. The leeward side of a barrier is, of course, protected more than the windward side regardless of the wind direction. See Fig. 4 for all days in Dodge City (May through Sept.) when southerly winds predominated. The south side received much less protection than did the north side, where $E_p$ was reduced more.

Table 1. Average monthly reduction in calculated potential evaporation for areas north of east-west oriented barriers near Dodge City, Kansas and Bismarck, North Dakota, 1960–1969. The north side was the leeward side 73 and 52% of the time, respectively, for Dodge City and Bismarck.

<table>
<thead>
<tr>
<th>Month</th>
<th>Area</th>
<th>Dodge City</th>
<th>Bismarck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrier heights</td>
<td>Percent</td>
<td>All days</td>
</tr>
<tr>
<td></td>
<td>0–10</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>June</td>
<td>0–10</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>July</td>
<td>0–10</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>August</td>
<td>0–10</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>September</td>
<td>0–10</td>
<td></td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>0–10</td>
<td></td>
<td>30.6</td>
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<tr>
<td></td>
<td>10–20</td>
<td></td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>
At Bismarck where a prevailing wind direction is less predominant and $E_p$ is less, protection was apparently about equal on both sides.

The E–W barrier reduced average calculated $E_p$ for areas north of it more at Dodge City than at Bismarck (Table 1). From the barrier out to 10 times its height, $E_p$ was reduced 37 and 26%, respectively, at Dodge City and Bismarck when wind was southerly. For all days, the barriers reduced $E_p$ 31 and 16% for Dodge City and Bismarck, respectively.

Open-field $E_p$ was considerably less at Bismarck than at Dodge City. $E_p$ was usually higher in the sheltered area at Dodge City than in the open field at Bismarck. For the 60 months studied, we compared estimated $E_p$ and pan evaporation data from Garden City, Kansas, location nearest Dodge City (85 km) that had evaporation data. Pan evaporation was approximately 10% less than calculated $E_p$.

$E_p$ would be reduced more by wind barriers in a climate typified by Dodge City's than by Bismarck's. However, Dodge City might not benefit more from wind barriers. At more northern latitudes, such as Bismarck, conserving water in winter months by catching and distributing snow across the field could be more beneficial than reducing $E_p$ during summer months.

A primary reason for greater reduction in $E_p$ at Dodge City was that winds there were dominantly southerly, 73% to Bismarck's 52%. We also calculated for a N–S oriented barrier and found essentially no difference in $E_p$ at Bismarck. But from 0 to 10H at Dodge City, $E_p$ was reduced 20 and 13% for leeward and all days, respectively, compared with 37 and 31%, respectively, for the E–W barrier.

The greatest benefit from reducing $E_p$ usually is not from reducing use of water but by increasing water-use efficiency (BOUCHET, 1963; BOUCHET et al., 1963, 1968; ROSENBERG, 1966). DENMEAD and SHAW (1962) reported that on days when $E_p$ was lower, corn plants could be maintained in soil with lower soil-water potential without losing turgor. Each day below an estimated turgor-loss point, dry weight was reduced approximately equal to the mean growth rate of control plants.

SKIDMORE (1969) used a hypothetical example to show how reducing $E_p$ with wind barriers may benefit crop yield. The relative yield curve generated from the example, based on lowering $E_p$ relative to soil-water potential, was similar to yields observed by others (MARSHAL, 1957; STOECKELER, 1962) leeward of wind barriers.

### Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s$</td>
<td>Transfer coefficient</td>
<td>g cm$^{-2}$t$^{-1}$mb$^{-1}$</td>
</tr>
<tr>
<td>$E_p$</td>
<td>Potential evaporation</td>
<td>cal cm$^{-2}$t$^{-1}$</td>
</tr>
<tr>
<td>$G$</td>
<td>Heat flux density into ground</td>
<td>cal cm$^{-2}$</td>
</tr>
<tr>
<td>$H$</td>
<td>Barrier height</td>
<td>length</td>
</tr>
<tr>
<td>$H'$</td>
<td>$x/sin \theta$</td>
<td>length</td>
</tr>
<tr>
<td>$P$</td>
<td>Ambient air pressure</td>
<td>mb</td>
</tr>
<tr>
<td>$R_n$</td>
<td>Net radiation flux density</td>
<td>cal cm$^{-2}$t$^{-1}$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Solar radiation flux density</td>
<td>cal cm$^{-2}$t$^{-1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>Air temperature</td>
<td>C</td>
</tr>
<tr>
<td>$T_d$</td>
<td>Dewpoint temperature</td>
<td>C</td>
</tr>
<tr>
<td>$e_p$</td>
<td>Specific heat at constant pressure</td>
<td>cal g$^{-1}$C$^{-1}$</td>
</tr>
<tr>
<td>$e$</td>
<td>Vapor pressure</td>
<td>mb</td>
</tr>
<tr>
<td>$e^*$</td>
<td>Saturation vapor pressure</td>
<td>mb</td>
</tr>
</tbody>
</table>
Vapor pressure at height \( z \)

von Karman's constant, \( k = 0.4 \)

Langley

time-units consistent with application

Horizontal windspeed

Open-field windspeed

Horizontal windspeed at \( x \) for corresponding height at \( u \)

Horizontal distance from barrier

Height

Roughness length

Slope of saturation vapor pressure curve, \( A = \frac{de}{dT} \)

Psychrometer constant, \( y = \frac{c_p}{c_m} \)

Ratio molecular weight water vapor to air = 0.622

Acute angle between wind directions & barrier

Latent heat of vaporization

Density of air

mb

1 cal cm\(^{-2}\) sec, min, day

cm sec\(^{-1}\)

cm sec\(^{-1}\)

barrier height

cm

mb C\(^{-1}\)

mb C\(^{-1}\)

1 degrees

cal g\(^{-1}\)

g cm\(^{-3}\)

References


