1160

Reprint from

Ecological Studies. Analysis and Synthesis, Vol. 4

Edited by A. Hadas et al.

Springer-Verlag Berlin · Heidelberg · New York 1973

Printed in Germany. Not for Sale

4

Potential Evaporation as Influenced by Barrier-Induced Microclimate

E. L. SKIDMORE and L. J. HAGEN

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 ($e_z^*-e_z$ 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 5 H 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:

$$\frac{u_x}{u_o} = 0.85 - 4\exp(-0.2H') + 4\exp(-3H') + 0.0002H'^2 \qquad (1)$$

H′ accounted for incident wind directions not normal to the barrier and was defined as:

$$H' = x/\sin\theta \tag{2}$$

where x and θ 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 θ, 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:

$$\frac{u_x}{u_o} = 0.502 - 0.0197x - 0.019x^2 \tag{3}$$

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:

$$E_p = -\frac{\frac{\Delta}{\gamma}(R_n - G) + \lambda B_v(e_z^* - e_z)}{\frac{\Delta}{\gamma} + 1} \tag{4}$$

where λ is the latent heat of vaporization in cal g^{-1}, Δ is the first derivative of saturated water vapor pressure-temperature curve in mb C^{-1}, γ is the psychrometric constant in mb C^{-1}, the ratio of Δ/γ is a dimensionless number depending on the air temperature,

R_n and G are net radiation and soil heat flux densities, e_z is the saturated water vapor pressure at ambient air temperature, e_z is the water vapor pressure in mb, and B_v is the turbulent transfer coefficient for water vapor defined as:

$$B_v = \frac{\varrho \, \varepsilon \, k^2 \, u_z}{P \, [\ln(z/z_o)]^2} \tag{5}$$

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_z the windspeed as height z, z the elevation above the surface, and z_o 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:

$$R_n = 0.8\,R_s - 120 \tag{6}$$

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

Results and Discussion

The influence of decreasing the angle of incident wind from perpendicular to parallel on relative calculated E_p 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

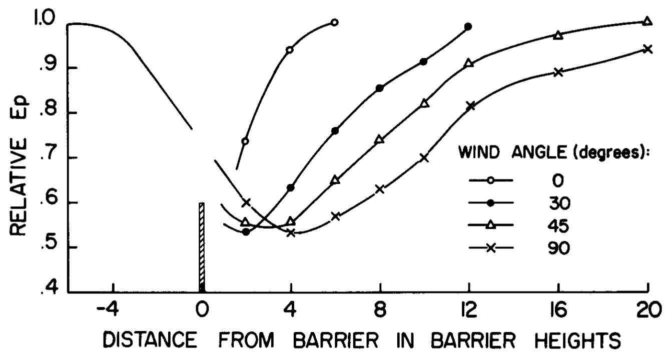

Fig. 1. Relative calculated potential evaporation at various distances from the barrier as influenced by angle of incident wind. Computations were made for u_o, T, T_d, and R_n of 4 m/sec., 25 °C, 10 °C, and 375 ly/day, respectively

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_p 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_p-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_p only slightly. But when vapor-pressure deficit and windspeed are high, a windbreak reducing windspeed greatly reduces E_p (Fig. 2, curve f).

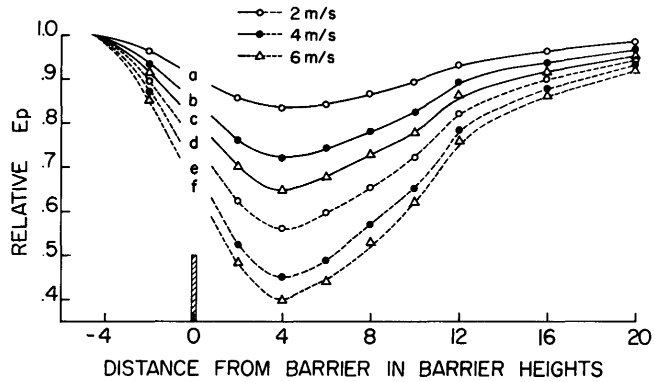

Fig. 2. Relative calculated potential evaporation at indicated distances from the barrier as influenced by windspeed and other climatological variables. T, T_d, and R_n were 20° C, 15° C, and 450 ly/day, respectively, for curves a, b, and c. For curves d, e, and f, T, T_d, and R_n were 30° C, 5° C, and 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.

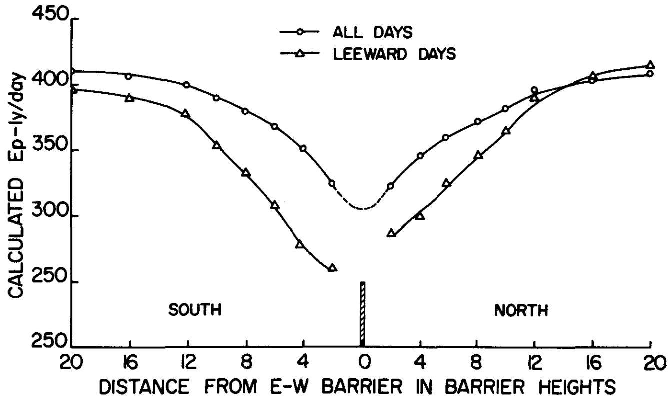

Fig. 3. Average calculated potential evaporation at indicated distances from wind barrier for Bismarck, North Dakota, May through Sept., 1960–1969. The wind was southerly 52% of the days

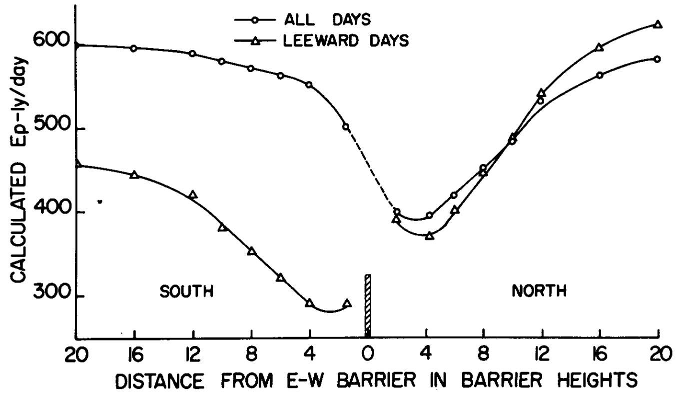

Fig. 4. Average calculated potential evaporation at indicated distances from wind barrier for Dodge City, Kansas, May through Sept., 1960–1969. The wind was southerly 73% of the days

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

Month	Area	Dodge City		Bismarck	
		All days	Leeward days only	All days	Leeward days only
	Barrier heights	Percent			
May	0–10	29	39	16	27
	10–20	9	12	3	6
	20–30	1	1	1	1
June	0–10	29	36	13	22
	10–20	9	11	3	6
	20–30	1	1	1	1
July	0–10	32	36	13	23
	10–20	10	11	3	6
	20–30	1	1	1	1
August	0–10	32	37	17	27
	10–20	9	11	4	6
	20–30	1	1	1	1
September	0–10	31	39	21	31
	10–20	9	12	5	8
	20–30	1	1	1	1
Average	0–10	30.6	37.4	16.0	26.0
	10–20	9.2	11.4	3.6	6.4
	20–30	1.0	1.0	1.0	1.0

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

Symbol	*Explanation*	*Units*
B_v	Transfer coefficient	$g\,cm^{-2}t^{-1}mb^{-1}$
E_p	Potential evaporation	$cal\,cm^{-2}t^{-1}$
G	Heat flux density into ground	$cal\,cm^{-2}$
H	Barrier height	length
H'	$x/\sin\theta$	length
P	Ambient air pressure	mb
R_n	Net radiation flux density	$cal\,cm^{-2}t^{-1}$
R_s	Solar radiation flux density	$cal\,cm^{-2}t^{-1}$
T	Air temperature	C
T_d	Dewpoint temperature	C
c_p	Specific heat at constant pressure	$cal\,g^{-1}C^{-1}$
e	Vapor pressure	mb
e*	Saturation vapor pressure	mb

e_z	Vapor pressure at height z	mb
k	von Karman's constant, k=0.4	1
ly	Langley	cal cm^{-2}
t	Time-units consistent with application	sec, min, day
u	Horizontal windspeed	cm sec^{-1}
u_o	Open-field windspeed	cm sec^{-1}
u_x	Horizontal windspeed at x for corresponding height at u_o	cm sec^{-1}
x	Horizontal distance from barrier	barrier height
z	Height	cm
z_o	Roughness length	cm
Δ	Slope of saturation vapor pressure curve, $\Delta = de/dT$	mb C^{-1}
γ	Psychrometer constant, $\gamma = c_p P/\varepsilon \lambda$	mb C^{-1}
ε	Ratio molecular weight water vapor to air 0.622	1
θ	Acute angle between wind directions & barrier	degrees
λ	Latent heat of vaporization	cal g^{-1}
ϱ	Density of air	g cm^{-3}

References

BUSINGER, J. A.: Some remarks on Penman's equation for the evapotranspiration. Neth. J. Agr. Sci. **4**, 77–80 (1956).

BOUCHET, R. J.: Actual evapotranspiration, potential evapotranspiration, and agricultural production. (In French, with English, German, and Russian summaries). Annls. Agron. **4**, 743–824 (1963).

BOUCHET, R. J., DE PARCEVAUX, S., ARNOUX, J.: Improving crop yields by decreasing potential evaporation. (In French, with English, German, and Russian summaries). Annls. Agron. **14**, 825–833 (1963).

BOUCHET, R. J., GUYOT, G., DE PARCEVAUX, S.: Increased efficiency of water and better production by reducing potential evapotranspiration with windbreaks. Summary p. 172. In: Agroclimatological Methods. Proc. of the Reading Symposium. Paris: UNESCO 1968, Summary p. 172.

DENMEAD, O. T., SHAW, R. H.: Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. Jour. **45**, 385–390 (1962).

JENSEN, M. E., WRIGHT, J. L. PRATT, B. J.: Estimating soil moisture depletion from climate, crop, and soil data. Presented at Winter Meeting of the Am. Soc. of Agric. Engineers, Chicago, Ill., Dec. 1969.

MARHALL, J. K.: The effect of shelter on the productivity of grasslands and field crops. Field Crop Abstracts **20**, 1–14 (1967).

PENHAM, H. L.: Evaporation: An introductory survey. Neth. J. Agr. Sci. **4**, 9–29 (1956).

ROSENBERG, N. J.: Microclimate, air mixing, and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. Agr. Meteorol. **3**, 197–224 (1966).

SELLERS, W. D.: Potential evapotranspiration in arid regions. J. Applied Meteorol. **3**, 98–104 (1964).

SKIDMORE, E. L.: Modifying the microclimate with wind barriers. Proc. of seminar "Modifying the Soil and Water Environment for Approaching the Agricultural Potential of The Great Plains." Great Plains Agr. Council Pub. No. **34**, Vol. 1, pp. 107–120 (1969).

SKIDMORE, E. L., HAGEN, L. J.: Evaporation in sheltered areas as influenced by windbreak porosity. Agr. Meteorol. **7**, 363–374 (1970).

SKIDMORE, E. L., HAGEN, L. J.: Evapotranspiration and the aerial environment as influenced by windbreaks. Proc. of Great Plains Evapotranspiration Seminar, Bushland, Texas, 1970.

SKIDMORE, E. L., JACOBS, H. S., POWERS, W. L.: Potential evapotranspiration as influenced by wind. Agron. J. **61**, 543–546 (1969).

STOECKELER, J. H.: Shelterbelt influence on Great Plains field environment and crops. USDA Forest Service, Prod. Res. Rpt. No. **62**, 1962.

TANNER, C. B., PELTON, W. L.: Potential evapotranspiration estimates by the approximate energy balance method of Penman. J. Geophys. Res. **65**, 3391–3413 (1960).

VAN BAVEL, C. H. M.: Potential evapotranspiration: The combination concept and its experimental verification. Water Resources Res. **2**, 455–467 (1966).

VAN EIMERN, J., KARSCHON, R., RAZUMOVA, L. A., ROBERTSON, G. W.: Windbreaks and shelter belts. World Meteorol. Organ. Tech. Notes **59**, 188 pp (1964).