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EVAPOTRANSPIRATION AND THE AERIAL ENVIRONMENT AS INFLUENCED BY WINDBREAKS 1/

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Introduction

Wind barriers change the ambient airflow and thus, by modifying the aerial environment, affect crop yields. Shelter research in the Great Plains attempts to predict, quantitatively, effects of barriers on crop yields, wind erosion, evapotranspiration, etc. Such predictions require an understanding of several relationships: between barrier and airflow to link characteristics of the barrier to airflow; between leeward airflow and microclimate to elucidate barrier-modified microclimate; and between barrier-induced microclimate and such plant processes as photosynthesis, respiration, transpiration, growth, and other factors that affect crop yields and erosion susceptibility.

Leeward Airflow and Nature of Incident Wind

Shelter influence implies the presence of wind, whose properties of speed, direction, thermal stability, and turbulence level all affect leeward airflow.

Windspeed

To compare the wind-reducing effect of barriers, relative values generally are used, which assumes that windspeed reduction is independent of open-field windspeeds (48). Van Eimern et al. (48) have reported that the assumption is justified by Kaiser's theoretical investigations. They also have noted that the effective porosity of a barrier changes with windspeed. With cottonwoods and maples, windspeed reduction patterns indicate that permeability varies directly with windspeed (48). On the other hand, permeability of pines decreased with increased windspeed

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that forced the flat, level branches together like venetian blinds. Nageli (27) concluded "that the reduction of windspeed, expressed as a percentage of wind in the open, is practically independent of free wind velocity throughout the range of a shelterbelt, provided that it does not fall below about 1.5 m./sec." More information is needed on modifying leeward airflows at windspeeds less than 1.5 m./sec.

Baltaxe (2), reviewing literature relating variations in flow patterns to changes in open-field windspeed, concluded that the variations in most cases could be attributed to differences in turbulence of free wind.

Direction and Duration

Several publications (9, 23, 40, 56) indicate that frequency-intensity and direction of winds vary widely in the Great Plains. This means that a barrier will not always be oriented normal to the wind direction. With wind blowing at an angle of less than 90 degrees, a barrier protects a shorter distance. Nageli (27) reported that at 25H leeward of a 47-percent porous barrier, the mean windspeed was 54, 63, 81, or 95 percent of open-field windspeed as the wind direction deviated o, 25, 50, or 75 degrees, respectively, from normal. Even with wind direction parallel to the barrier, windspeed is reduced up to 5H behind the barrier (48). Van Eimern et al. (48) cite other work as evidence that the protective effect with a wind parallel to the belt is approximately one-fourth of that with a perpendicular wind. The protective effect continuing when wind is parallel results from the inevitable variation in wind direction and the friction at and above the belt.

When wind is blowing obliquely to a barrier, the barrier is less permeable (48). As angle of incident wind decreases below 90 degrees with a two-dimensional barrier (like a slat fence or a screen), the open area normal to wind direction decreases. As angle of incident wind decreases below 90 degrees with three-dimensional barriers (like a single row or multirowed shelterbelt), the distance through the barrier parallel to open-field wind direction increases; i.e., the barrier's effective width increases.

Thermal Stability

Van Eimern et al. (48) discuss the influence of air's thermal stratification on shelter effect. With unstable conditions, wind distribution is more like that given by a dense barrier; minimum windspeed occurs closer to the barrier and extends a shorter distance. With stable temperature gradient, more force is required for the air mass to flow over the barrier, so the amount of flow penetrating the barrier increases with increasing stability.

Terrain and Surface Roughness

Other barriers and terrain features affect turbulence levels. Nageli (27) credited the lack of accumulative shelter effect from a series of windbreaks to the increased air turbulence induced by the series.

Lumley and Panofsky (24) expressed the standard deviation of longitudinal velocity component as proportional to friction velocity and stated that the proportionality constant is not constant but seems to vary with terrain. Van Eimern et al. (48) reported that windspeed is reduced less leeward of belts on rough surfaces than leeward of belts on smooth ones. Further, the point of greatest reduction is closer to belts with rough windward surfaces than it is to belts with smooth windward surfaces. Jensen's (22) wind-tunnel data were confirming. His barrier windspeed reductions in a rough tunnel were similar to barrier windspeed reductions in the field.

Leeward Airflow and Windbreak Characteristics

Permeability

Airflow leeward of a windbreak is influenced by barrier characteristics which include: permeability, height, shape, width, and resilience. Of those, permeability (porosity or density) and height are most important. Results of many experiments are presented in terms of windbreak permeability (22, 38, 48).

Windspeed reduction patterns are primarily determined by the porosity and distribution of pores in the barrier. Woodruff et al. (52) measured windspeed reduction patterns of many shelterbelts and found that they may be too dense as well as too porous. At densities too high, the area of leeward sheltered ground decreases, while at porosities too high, the percentage of windspeed reduction becomes negligible. At low windbreak porosities, minimum leeward windspeed occurs close to the windbreak, and after reaching minimum, tends to increase more quickly than do windspeeds leeward of porous windbreaks (25, 38, 48, 52).

Very dense windbreaks stimulate turbulence (2, 25, 38, 48). From wind tunnel experiments with model windbreaks, Baltaxe (2) showed a transition from leeward flow characterized by a turbulent wake to flow with reduced eddying at a level of permeability between 25 and 38 percent. With 50 percent permeability, leeward windspeed was reduced considerably without appreciable disturbance of flow. Hagen and Skidmore (20) also found turbulent fluctuations and barrier porosity varied inversely leeward of slat-fence barriers in the field.

Optimum permeability depends somewhat on the purpose of the windbreak. Windbreaks designed to distribute snow may be more porous than those designed to control wind erosion. Windbreaks with optimum permeability will markedly reduce windspeed without inducing strong turbulence. In a wind-tunnel experiment using 12-inch-high slat fences 60, 40, 20, and 0 percent porous to determine the effect of porosity on windspeed reduction, windspeed was reduced most over the 0 to 30H interval with the 40 percent open barrier. Marshall (25) cites numerous papers for his statement that "optimum protection for vegetation is provided by a barrier with a geometric permeability of 40 to 50 percent."

Height

The distance affected or sheltered by a wind barrier is increased proportionately by increasing the barrier's height. Sheltered distances are generally expressed as multiples of the barrier height.

Shape and Width

Both width and shape of windbreaks modify leeward airflow. Woodruff and Zingg (55) got maximum protection from a 10-row-wide belt. However, narrow belts gave nearly as much protection and used much less ground. Stoeckeler (44) observed that shelterbelt density improves with width, but benefits decrease if the belts are too wide.

To favorably modify airflow, shelterbelts need not be so wide as formerly advocated. This recognition has led to single-row plantings in Northern Great Plains (14, 17, 29, 43, 49). Dickerson and Woodruff (13) tested and evaluated various trees, shrubs, and annual crops for adaptation and potential for single-row barriers.

Leeward airflow as influenced by the shape of the barrier is difficult to characterize. Shapes of living windbreaks vary widely and are difficult to define. Woodruff and Zingg (54) used three geometrical shapes (vertical plate, cylinder, and 45-degree triangular) and a model tree windbreak to evaluate the effect of shapes on flow patterns in a wind tunnel. They found that a barrier's value in protecting the leeward area depended on the criteria for effectiveness. To reduce airflow $\geq$ 50 percent, the order of effectiveness was: plate, triangular shape, model trees, and cylinder. But for $\geq$ 25 percent reduction, the order was: model trees, plate, triangular shape, and cylinder.

They (55) also modeled 5-, 7- and 10-row shelterbelts in a wind tunnel with various arrangements of trees to give the belts different shapes. From their results and others' (48), it appears that rooftop or inverted "V" is as consistent a shape as any for greatest windspeed reduction leeward of the barrier.

Modification of Aerial Environment

Air Temperature

Reduced vertical diffusion and mixing of air usually causes higher daytime air temperature and lower nighttime air temperature (25, 31, 32, 48). However, Woodruff et al. (53) found both hotter and cooler air leeward of a barrier. Leeward air temperature patterns were closely related to the eddy zone produced by the barrier. Warm zones were located close to the ground and near the barrier where eddy currents were rising. During the day the warm zone extended 5 to 10H leeward; beyond 5 to 10H leeward, the daytime air temperature was lower than the open air.

Hagen and Skidmore (20) also observed that where mean vertical component of flow was up, the temperature was higher, and where mean vertical component of flow was down, the daytime air temperature leeward of the barrier was lower than corresponding open-field temperatures.

Skidmore and Hagen (38) evaluated the influence on evaporation of slat-fence windbreaks with various porosities. Their micrometeorological observations showed ambient air temperature over evaporating sudangrass at 2H leeward was higher than at 6H windward by 0.9, 1.2, and 1.5 degrees C. for 60, 40, and 0 percent porous barriers, respectively.

Rosenberg (33) cites Guyot (19) as believing that the effects of shelter on air temperature may be predicted on the basis of whether evapotranspiration is increased or decreased. When evapotranspiration uses more available energy, less is available to heat the air. Certainly if the evaporation rate of a body were decreased with a large but unchanged radiation load, that body's temperature would rise.

Air Humidity

The humidity regime leeward of a wind barrier is not always straightforward and uniform. "Several factors like soil moisture, evaporation and transpiration, diffusion and air mixing, as well as temperature and radiation influence the air humidity and complicate conditions" (48). Many studies show only slight variation of relative humidity in sheltered areas compared with unsheltered (25, 48). Rosenberg (31) found absolute humidity content of the air above sugar beets not influenced by snow fence and two rows of corn, but consistently higher (32) (2 to 3 mb.) in sheltered areas of an irrigated bean field.

Skidmore and Hagen (38) found that absolute humidity was slightly higher 2H leeward of a barrier than in the open. The differences were 1.5, 3.1, and 2.6 mb., respectively, for 60, 40, and 0 porosity barriers. At 12H leeward the vapor pressure was less than windward by 0.7, 2.0, and 2.5 mb., respectively, for 60-, 40-, and 0-percent porous barriers.

Radiation

Radiation, one of the most important factors in crop environment, is only slightly affected by a barrier and then only in the immediate vicinity of the barrier (25, 31, 33, 48). The barrier may intercept, reflect, and reradiate some solar or terrestrial radiation. Depending on the barrier's orientation, it may reflect solar radiation from one side and shade an area on the other side. However, as Rosenberg (33) pointed out, long shadows are cast only when the sun is low and solar radiation is low, so the effect may be unimportant.

Wind on plants will influence the orientation of canopy leaves, may change the plant's albedo, and thus affect net radiation. Rosenberg (31) observed that a barrier in a sugarbeet field may have slightly increased daytime net radiation but did not affect nocturnal net radiation.

Carbon Dioxide

The plant canopy provides both a source (respiration) and a sink (assimilation) for CO_2. Respiration, assimilation, and diffusion all affect CO_2 concentrations. Respiration occurs from the plants, organic matter, and soil continuously. Assimilation occurs only during daylight but during that time consumes CO_2 much faster than respiration produces it (48). Therefore, with low windspeeds creating low diffusion rates, CO_2 concentration in the crop canopy tends to increase above atmospheric concentration during the night and decrease below it during the day. Rusch (36) found the unsheltered atmosphere at 1 m. above the ground about 4 percent richer in CO_2 between 10 a.m. and 3 p.m. than at other times. Brown (7) found the CO_2 content above sheltered sugarbeet crops 1 p.p.m. lower and 3.5 p.p.m. greater than the corresponding CO_2 content in the open during day and night, respectively. Thus the percentage difference is very small. Any reduction in CO_2 content induced by a barrier has not been reflected in yield, and as Rosenberg (32) observed, CO_2 quantity unaccompanied by a simultaneous measurement of CO_2 flux is subject to misinterpretation.

Influence of Barrier-Induced Microclimate on Evaporation: Potential and Actual

Wind greatly contributes to potential evaporation in the semiarid climate typical of much of the Great Plains. Hence, barrier-reduced windspeed should reduce evaporation, and this frequently is the main purpose of windbreaks (3, 11, 42, 48). Using the van Bavel (45) version of the combination model for estimating potential evaporation, Skidmore et al. (39) found that on a relatively calm day the wind-dominant term contributed one-third as much as the radiation-dominant term to the total calculated potential evaporation, whereas on the following day with high windspeeds, the wind-dominant term contributed 13 percent more than the radiation-dominant term.

Awareness of high potential evaporation rates associated with hot, dry winds of the Plains prompted us to study the influence of windbreaks with various porosities on evaporation from wet surfaces. We (38) found that windbreaks reduced evaporation from atmometers in proportion to windspeed reduction and that measured evaporation agreed fairly well with evaporation calculated, using the van Bavel version of the combination model for instantaneous potential evaporation rates.

Even though barriers reduce evaporation in proportion to windspeed, they reduce evaporation less than they reduce windspeed, which is explained by the model used (45) for predicting potential evaporation. It can be expressed (38) as the sum of energy input and turbulent transfer or wind terms. The energy input term is mainly net radiation and is not affected by wind. Under advection, the turbulent transfer term may be large. If the two terms were equal and a barrier reduced windspeed 50 percent, evaporation would not be affected by the contribution of energy input term and the contribution of the second term would be reduced 50 percent; therefore, overall evaporation would be reduced 25 percent.

Actual evapotranspiration may be reduced less than potential evapotranspiration for at least two reasons. First, because of the higher potential evapotranspiration in the open field, plants may be stressed and their stomata may partially close. The increased canopy resistance to diffusion due to stomatal closure may decrease evaporation in the open, whereas in a sheltered area, the plants may remain more passive to transpiration. Rosenberg (32) found that a decrease in atmometer evaporation in the shelter of a two-tier snowfence was accompanied by increased soil-moisture depletion.

Second, if evaporating surfaces are not wet and the diffusive resistances are high, evaporation may not decrease at all when windspeed decreases. van Bavel et al. (46) have shown that a critical value for canopy resistance exists. Below that value, evaporation increases with increasing windspeed; above it, evaporation decreases with increasing windspeed.

Although actual evapotranspiration is reduced less than potential evapotranspiration by decreasing windspeeds, several (4, 5, 6) have observed that decreasing potential evapotranspiration with windbreaks has increased yields and water-use efficiency. Leaf-water availability and lowering of leaf resistance to CO_2 flux now appear to be the primary environmental factors affected by wind (6, 7, 8, 10, 50)--factors that likely caused the increase in yields reported in the literature (1, 28, 30, 32, 35, 47).

Since climatic conditions in the Great Plains favor high evaporation (21, 34, 39), windbreaks should improve water relations for photosynthesizing leaves by reducing potential evapotranspiration. To show how yield may benefit from reducing potential evapotranspiration with windbreaks, Skidmore (37) used a hypothetical example. The relative yield curve generated from the example, based on lowering the evaporative demand relative to soil water supply, was similar to yields observed by others leeward of barriers (25, 44). Denmead and Shaw (12) found that for each day below estimated turgor loss point, dry weight was reduced approximately equal to the mean growth rate of control plants.

To show how potential evapotranspiration may be reduced by windbreaks, we have computed potential evapotranspiration and its reduction from climatological data at a location in the Great Plains. Weather Bureau data from Dodge City, Kansas, were used in the combination model (45) to predict potential evaporation. The computations were made at the temperature and dewpoint measurement height--4 feet above the surface. Because windspeed was measured at 20 feet above the surface, it was adjusted to the 4-foot level using the log-profile law. Daily averages of the meteorological variables were used.

Windspeed reduction patterns measured leeward of a 40-percent porous barrier were fitted to an equation to give:

$$\frac{U}{U_o} = .85 - 4e^{-.2H'} + 4e^{-3H'} + .0002H'^2 \qquad (1)$$

where U and U_o are windspeeds leeward of barrier and in the open field at corresponding heights. H' accounted for incident wind directions not normal to the barrier and was defined as:

$$H' = H/\sin\theta \qquad (2)$$

where H and θ are leeward distance in barrier heights and acute angle of incident wind, respectively.

The resultant windspeed patterns for various angles of incident wind direction are shown in figure 1. A minimum value of .18 was set on sin θ. That value corresponds to about 10 degrees and accounts for windspeed reductions near windbreaks due to barrier roughness and wind direction fluctuations when the mean wind direction is parallel to the barrier.

The barrier orientation was east-west and thus, normal to the prevailing southerly winds at Dodge City. A roughness length (Z_o) of 1 cm. was used in all calculations of potential evaporation.

Computations of average potential evaporation on a daily basis show for July 1967 that north was the lee side of the barrier during 25 days of the month (figure 2). During that period, potential evaporation was reduced substantially on the north side of the barrier. The potential evaporation was similarly lowered on the south side of the barrier during the 6 days with northerly winds. Further, on days with northerly winds, the open field potential evaporation was low compared with the monthly average potential evaporation. Daily potential evaporation on the north side of the windbreak, averaged over the entire month, was substantially reduced out to about 12H, but little affected on the south side (figure 3). Bagley and Gowen (1) concluded from their shelter research with tomatoes and snap beans that the spacing of snow fence windbreaks for maximum yields should be about 10 times barrier height.

Similar results were noted during 4 years of June and July computations (table 1). Average reductions in potential evaporation were 41, 27, and 19 percent for the lee areas (north side) 0 to 10H, 0 to 20H, and 0 to 30H, respectively, for the two months. However, large differences in open field potential evaporation were noted in between-year data. The average potential evaporation was 788 langleys per day during July 1966 compared with only 506 langleys per day during July 1967.

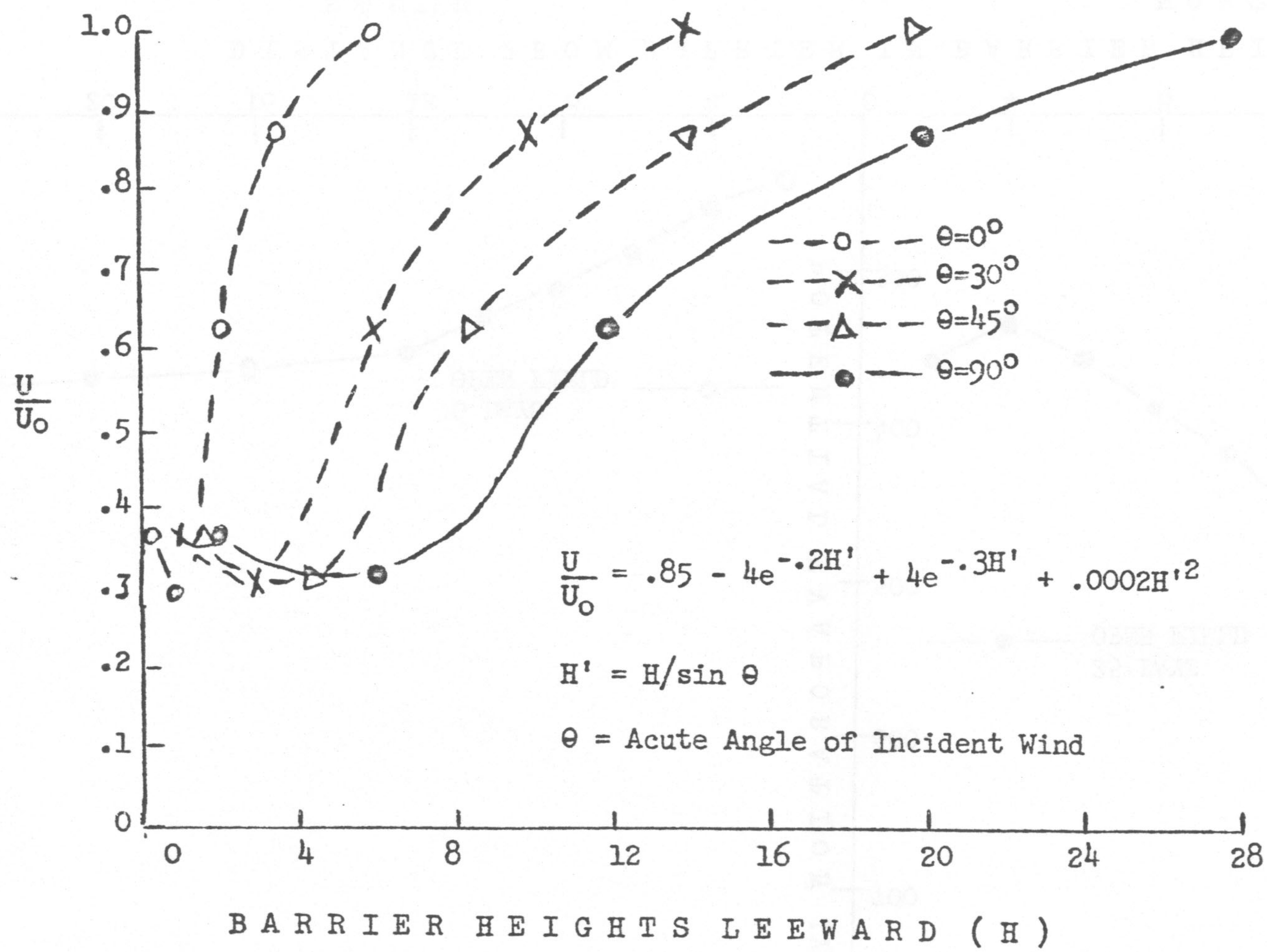

Figure 1.--Windspeed reduction as influenced by distance from barrier and acute angle of incident wind.

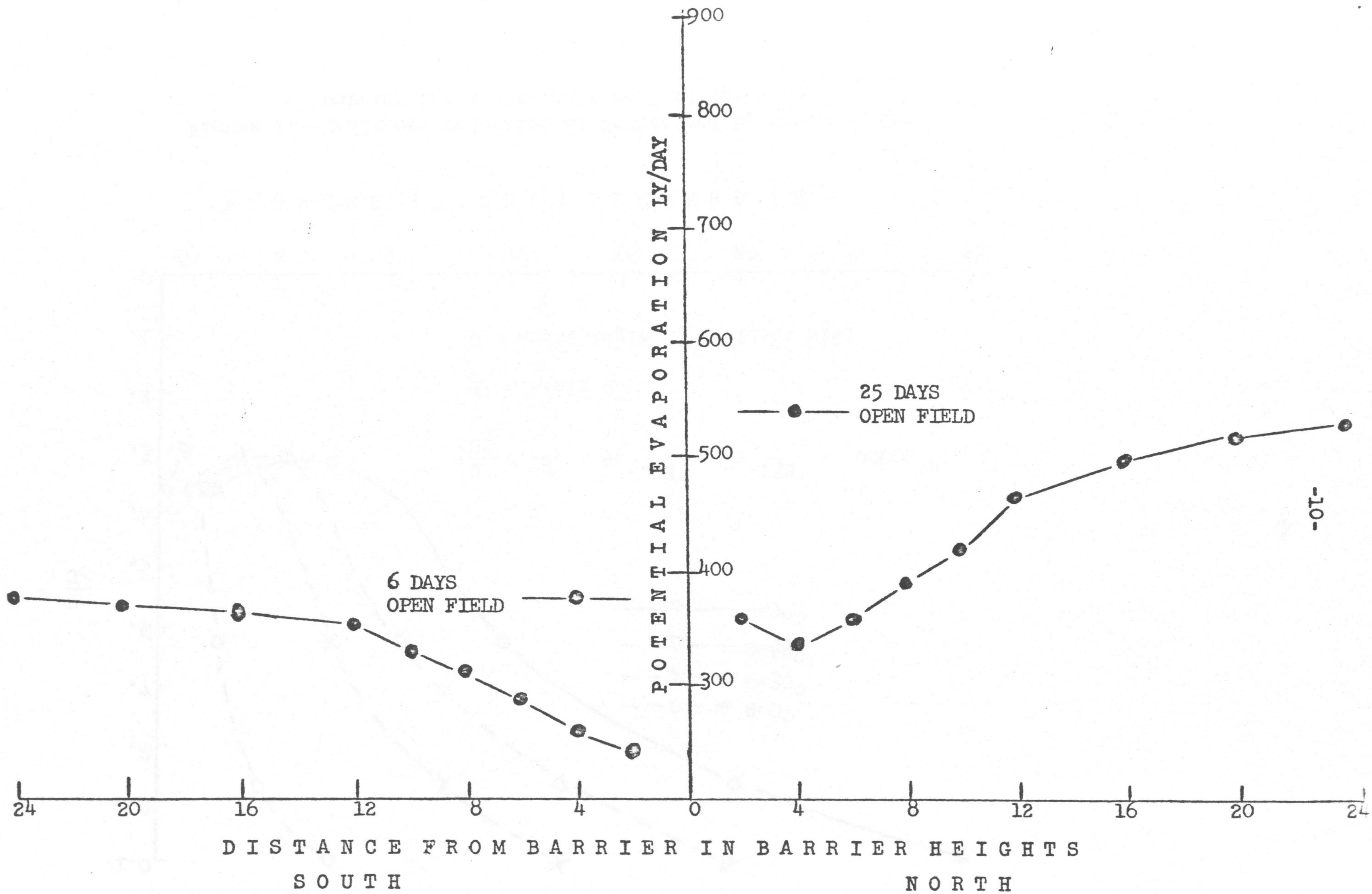

Figure 2.--Average computed potential evapotranspiration (leeward data only) at Dodge City, Kansas, July 1967.

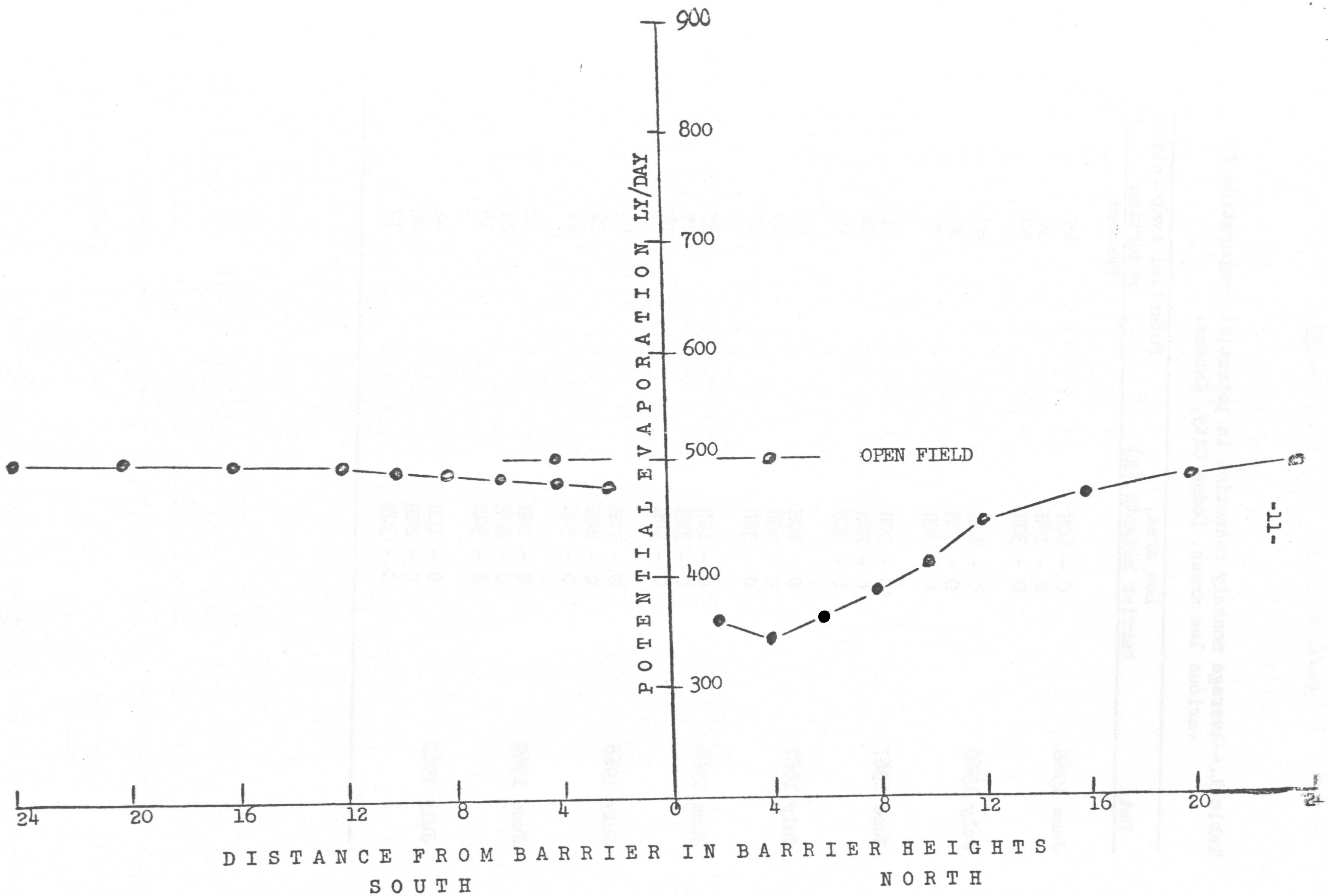

Figure 3.--Average computed potential evapotranspiration (windward and leeward data) at Dodge City, Kansas, July 1967.

Table 1.--Average monthly reduction in potential evaporation for various lee areas, Dodge City, Kansas.

Date	Lee area, barrier heights (H)	Potential evaporation reduction
		Percent
June 1966	0 - 10H	45
	0 - 20H	30
	0 - 30H	20
July 1966	0 - 10H	47
	0 - 20H	30
	0 - 30H	20
June 1967	0 - 10H	41
	0 - 20H	28
	0 - 30H	19
July 1967	0 - 10H	43
	0 - 20H	29
	0 - 30H	20
June 1968	0 - 10H	37
	0 - 20H	25
	0 - 30H	18
July 1968	0 - 10H	42
	0 - 20H	29
	0 - 30H	22
June 1969	0 - 10H	32
	0 - 20H	21
	0 - 30H	14
July 1969	0 - 10H	41
	0 - 20H	26
	0 - 30H	17

At other locations in the Great Plains, where there is no predominant leeward and windward side for windbreaks, we would anticipate reductions in potential evaporation smaller than those computed for Dodge City, but significant reductions on both sides of the windbreak.

In addition to reducing evaporation, windbreaks often conserve water by accumulating and distributing snow3/ (16, 26, 41). In the absence of windbreaks or stubble, wind often sweeps snow off fields in the Northern Great Plains. Barriers with proper porosity will allow uniform distribution and accumulation of snow leeward. If barriers are too dense, snow will accumulate near the barrier rather than being distributed across the field. Drifting patterns are similar to windspeed reduction patterns (30).

Trees, shrubs, slat-fences, stubble, annual crops, and various grasses all have been used in an effort to conserve water and improve soil moisture by trapping snow on crop and rangeland3/ (15, 17, 18, 26, 51).

Summary

Windbreaks change the ambient airflow and thus modify the microclimate and affect crop yields. Characteristics of the wind that affect the influence of windbreaks include speed, direction, thermal stability, and turbulence level. Windspeed reduction is generally independent of open-field windspeed if windspeed is greater than 1.5 m./sec. When wind blows at angles other than normal to the windbreak, a windbreak protects over a shorter leeward distance and is effectively less permeable than with wind direction normal to the windbreak. With increased turbulence in the open-field wind, leeward windspeed distribution is more like that produced by a dense barrier. Other windbreaks, rough terrain, and thermal instability increase wind turbulence.

Barrier characteristics that influence airflow most are permeability and height. Barriers with low permeability reduce windspeed close to the barrier but for less distance than more permeable ones. The distance sheltered by a barrier is proportional to its height. The reduced windspeed leeward of barriers generally reduces mixing and turbulent exchange of mass, momentum, and energy. That tends to cause higher daytime air temperatures, lower nighttime air temperatures, higher humidity, more variation in CO_2 concentration, lower evaporation rates, and beneficial snow distribution. The net effect of the barrier-induced microclimate in the harsh Great Plains is a more favorable crop environment that increases yields in sheltered areas.

3/ F. H. Siddoway, personal communication.

As our understanding develops from further research, we shall comprehend well enough the relationships of barrier characteristics to leeward airflow, leeward airflow to microclimate, and microclimate to plant response to build a workable model and use simulation to explore in more detail the consequences of various strategies of barrier use in the Great Plains climate.

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