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MODIFYING THE MICROCLIMATE WITH WIND BARRIERS 1/

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Abstract

Wind barriers change the ambient airflow and thus modify the microclimate and affect crop yields. Barrier characteristics that influence airflow most are permeability and height. Barriers with low permeability reduce windspeed close to the barrier but for a shorter 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, less wind erosion, 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.

Introduction

Shelter research in the Great Plains attempts to predict quantitative effects of barriers on crop yields, wind erosion, evaporation, etc., which requires an understanding of several relationships: First, the relationship between barrier and airflow must be established so that the nature of the leeward airflow may be linked to barrier characteristics and characteristics of the incident wind; second, the relationship between leeward airflow and microclimate associated with barrier-modified airflow must be elucidated; and third, the effect of the barrier-induced microclimate on plant processes (photosynthesis, respiration, transpiration, cell division and growth, etc.) that affect crop yields must be determined and related to characteristics of the barrier and the weather of the wind.

This paper discusses airflow as affected by barrier and incident wind, microclimate as influenced by barrier-modified airflow, and crop yields as influenced by barrier-induced microclimate, with an example of possible yield increases from reducing potential evapotranspiration.

Many review articles (8, 16, 19, 24, 29, 34, 37, 47, 50, 51) and (26, 28) cited by Marshall (29) have appeared in recent years on wind barriers,

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shelterbelts, and their influence on microclimate and crop yields. Several of these reviews (16, 34, 37, 47) as well as an earlier summary by Bates (4) were written for direct application to agricultural problems of the Great Plains. The author used the reviews, other relevant investigations, and personal research in the following discussion.

Airflow as Affected by Barrier and Incident Wind

Permeability

Barrier characteristics that affect leeward airflow include permeability, height, shape, width, and resilience. Of those, permeability (porosity or density) is most important. Results of many experiments are presented in terms of permeability (24, 51).

Windspeed reduction patterns are primarily determined by the porosity and distribution of pores in the barrier. Woodruff et al. (54) measured windspeed reduction patterns of many shelterbelts and found that they may be too dense as well as too porous. At lower windbreak porosities, minimum leeward windspeed occurs close to the windbreak and, after reaching minimum, tends to increase more quickly than do windspeeds leeward of more porous windbreaks (29, 42, 51, 54). At lower permeabilities the area of sheltered ground decreases and at higher permeabilities the degree of shelter provided becomes negligible.

Very dense windbreaks stimulate turbulence (3, 29, 42, 51). From wind tunnel experiments with model windbreaks, Baltaxe (3) showed a transition from leeward flow, which was independent of the Reynolds number (Re) and characterized by a turbulent wake, to flow dependent on Re and without 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.

Optimum permeability depends somewhat on the purpose of the windbreak. Windbreaks designed to distribute snow may be more porous than those to control wind erosion. Windbreaks with optimum permeability will markedly reduce windspeed without inducing strong turbulence. In a wind tunnel experiment to determine the effect of porosity on windspeed reduction, Skidmore[3/], using a 12-inch slat fence with slats spaced to give 60, 40, 20, and 0 percent porosity, found windspeed reduced most over 0 to 30H interval with 40 percent open barrier. Marshall (29) 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."

Although porosity is one of the most important characteristics of a barrier and researchers agree fairly well on optimum porosity, porosity of a living barrier is difficult to ascertain. van Eimern et al. (51) cite attempts to establish barrier porosity with pictures and attempts to use a ratio of windspeed in the open field to the windspeed at some leeward position as a porosity indicator. Neither proved satisfactory.

3/ Unpublished data, Manhattan, Kansas, 1966.

Fryrear (17) measured relative barrier density by using the ratio of the amount of light transmitted through a barrier to the amount of light available. His method met with difficulties and has not found wide use.

Another approach is to measure drag coefficients of barriers of known porosities and compare them to drag coefficients of plant barriers of unknown porosity (21, 55). However, the barriers of known porosities are generally rigid, so using slat fences and extrapolating barrier porosity-drag coefficient relationships from rigid barriers to flexible plant barriers must be done with caution.

Height

The distance affected or sheltered by a wind barrier is increased proportionately by increasing the barrier's height; thus, height of barrier is important in considering extent of sheltered area. 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 (59), studying the effect of width (or number of rows) of a shelterbelt, got maximum protection from a 10-row belt. However, narrow belts gave nearly as much protection and used much less ground. Stoeckeler (47) observed that shelterbelt density improves with width but benefits decrease if the belts are too wide.

Dickerson and Woodruff (14), recognizing the need for plants suitable for narrow wind barriers, initiated a study to test and evaluate various trees, shrubs, and annual crops for adaptation and potential for single-row barriers.

Recognition that shelterbelts need not be so wide as formerly advocated to favorably modify airflow has led to single-row plantings in northern Great Plains (15, 18, 33, 46, 52).

Leeward airflow as influenced by the shape of the barrier is difficult to characterize. The shapes of living windbreaks vary widely and are difficult to define. Woodruff and Zingg (58) used three geometrical shapes (vertical plate, cylinder, and 45 degrees triangular) and a model tree windbreak to evaluate the shapes on flow patterns in a wind tunnel. They found that an object'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 (59) 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 (51), it appears that rooftop or inverted "V" is as consistent as any for greatest windspeed reduction leeward of the barrier.

Windspeed

Wind characteristics that affect airflow leeward of a windbreak include: speed, thermal stability, direction (angle of incident wind), and turbulence level. To compare the wind-reducing effect of barriers, relative values are generally used which automatically assumes that windspeed reduction is independent of the absolute value of the open windspeed (51). However, van Eimern et al. (51) report that the assumption is justified by theoretical investigations of Kaiser. But the effective porosity of a barrier changes with windspeed. With cottonwoods and maples, windspeed reduction patterns indicate that permeability increases with windspeed (51). On the other hand, permeability of pines decreased with increased windspeed which forced the flat, level branches together like venetian blinds. Nageli (31) concluded "that the reduction of windspeed, expressed as a percentage of wind in the open, is practically independent of the free wind velocity throughout the whole range of a shelterbelt, provided that it does not fall below about 1.5 m./sec." More information should be sought on modifying leeward airflows by barriers at windspeeds less than 1.5 m./sec.

Baltaxe (3), reviewing literature relating variations in flow patterns to changes in open windspeed, concluded that in most cases the variations could be attributed to changes in the turbulence level of the free wind.

Terrain and Surface Roughness

Other barriers and terrain features affect turbulence levels. Nageli (31) credited the lack of accumulative shelter effect from a series of windbreaks to the increased air turbulence induced by screens.

Lumley and Panofksy (27) expressed the standard deviation of longitudinal velocity component as proportional to friction velocity and stated that the proportionality constant isn't constant but seems to vary with terrain. van Eimern et al. (51) reported that wind is reduced less on a rough surface than on smooth ones and the point of greatest reduction is closer to belts with rough surfaces than it is to belts with smooth surfaces. Jensen's (24) wind tunnel data were confirming. His windspeed reduction in a rough tunnel was similar to wind reductions in the field.

Thermal Stability

van Eimern et al. (51) 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.

Wind Direction

Other characteristics of the wind that affect leeward airflow are its frequency and its direction relative to the barrier. Several publications

(10, 25, 44, 60) indicate that frequency-intensity and direction of winds vary widely in the Great Plains. Variability of wind direction or low preponderance in prevailing direction 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 (31) has shown that for a barrier with 47 percent permeability and at a distance of 25H leeward, the mean windspeed was reduced to 54, 63, 81, and 95 percent as the wind deviated 0, 25, 50, and 75 degrees, respectively, from normal. Even with wind blowing parallel to the barrier, wind is reduced up to 5H behind it (51). van Eimern et al. (51) 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 with a parallel wind results from the inevitable variation in wind direction and the friction at and above the belt."

There is evidence[4/] (51) that when wind is blowing obliquely to a barrier, the barrier is less permeable. 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 or multirowed shelterbelt, the distance through the barrier parallel to open field wind direction increases; i.e., the barrier's effective width increases.

Microclimate as Influenced by Barrier-modified Airflow

Many important microclimate factors in soil-water-plant relationships are influenced by a barrier and the reduced windspeed it causes.

Radiation

Radiation, one of the most important factors in crop environment, is only slightly affected by a barrier and only in the immediate vicinity of the barrier (29, 35, 37, 51). 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 (37) 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 (35) observed that a barrier in a sugar beet field may have slightly increased daytime net radiation but did not affect nocturnal net radiation.

Air Temperature

Reduced vertical diffusion and mixing of the air usually means higher daytime air temperature and lower nighttime air temperature (29, 35, 36,

4/ E. L. Skidmore, unpublished data, Manhattan, Kansas, 1966.

51). However, Woodruff et al. (56) 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 when mean vertical flow was up, the temperature was higher, and when mean vertical flow was down, the daytime air temperature leeward of the barrier was lower than corresponding open field temperatures.

Skidmore and Hagen (42) evaluated the influence on evaporation of slat-fence windbreaks with various porosities. Their micrometeorological observations showed ambient air temperatures 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. The temperature tended to match open field temperatures at greater distances from the barrier.

Rosenberg (37) 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 straight forward 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 the conditions" (51). Many studies show only slight variation of relative humidity in sheltered areas compared with unsheltered (29, 51). Rosenberg (35) found absolute humidity content of the air above sugar beets not influenced by snow fence and two rows of corn. But he found (36) absolute humidity remained consistently higher (2 to 3 mb.) in sheltered areas of an irrigated bean field.

Skidmore and Hagen (42) 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 porosity barriers.

Soil Moisture

Two processes associated with shelter benefit soil moisture: Decreased evaporation and both beneficial snow accumulation and distribution. Reduced evaporation is frequently the main purpose of windbreaks (4, 12, 45, 51).

Evaporation is reduced proportionately less than windspeed by windbreaks (1, 42, 51). Two conditions must exist for evaporation to occur: A source of energy for latent heat of vaporization and a mechanism for vapor transfer. Most of the energy is derived from solar radiation, and radiant flux is unaffected by wind. Therefore, wind is not expected to alter evaporation rate caused by radiant flux. However, wind, along with temperature and water vapor pressure gradients, causes sensible heat and vapor to transfer, which results in evaporation. Reduced windspeed tends to reduce turbulent transfer.

However, while reducing windspeed, a barrier often induces turbulence that tends to compensate for reduced windspeed in affecting transfer. Blenk (5) reported rate of evaporation lower in the open wind than in the lee of a solid barrier. He ascribed the phenomenon to greater turbulence behind the barrier. Russian workers (1) report that weakly pervious barriers only slightly influence turbulent exchange and have little effect on evaporability.

Skidmore and Hagen (42) evaluated the influence of slat-fence windbreaks with various porosities on evaporation from a wet surface and found evaporation reduced by the windbreaks somewhat parallel to windspeed reduction but less. Evaporation measured with atmometers and evaporation calculated from a revised combination model for instantaneous potential evaporation rate agreed fairly well.

Rosenberg (36) observed that evaporation from atmometers was less in the area sheltered by snow fence than in unsheltered areas but transpiration of beans and depletion of soil moisture were greater. Because of lower evaporative demand in the shelter, the duration and degree of nonphotolytically controlled stomatal closure in leaves of plants growing in shelter were reduced, which restricted transpiration less than did unsheltered areas.

Another complicating factor in studying the effect on evaporation of reduced windspeed is critical value for canopy resistance below which evaporation increases with increasing windspeed and above which it decreases with increasing windspeed. That was shown by van Bavel et al. (49) using the procedure of Monteith (30).

In addition to reducing evaporation, barriers conserve soil moisture by controlling distribution of snow. In the absence of a barrier 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 (34).

In addition to trees, shrubs, fences, and stubble, various grasses are being used to conserve water and improve soil moisture by trapping snow on rangeland.

Soil Temperature

Soil temperature, like soil moisture, can be affected by barriers in two ways. First, increased soil moisture from snowmelt leeward from a barrier lowers soil temperature. The higher water content of the soil raises the heat capacity of the soil--more energy is required to warm it. If more water causes more evaporation, energy is used in evaporating water that otherwise would contribute to soil heat storage. Second, as the barrier modifies leeward airflow, heat transfer to and from the soil is altered. Rosenberg (36) observed that soil temperature in sheltered areas was usually elevated during the day and slightly depressed at night. According to reviews by Marshall (29) and van Eimern et al. (51), most researchers who observed soil temperature found it slightly higher in shelter. Increases were greatest when the soil was bare and dry, less when the soil surface was moist or the sky was cloudy.

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 from the plants, organic matter, and soil occurs continuously, whereas assimilation occurs only during daylight; then assimilation consumes CO_2 much faster than respiration produces it (51). Therefore at low windspeeds and conditions for 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 (40) 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. Any reduction in CO_2 content induced by a barrier has not been reflected in yield and, as Rosenberg (36) observed, CO_2 quantity unaccompanied by a simultaneous measurement of CO_2 flux is subject to misinterpretation.

Wind Erosion

Barriers are effectively used to control wind erosion in the Great Plains (11, 41, 44, 57). Rate of soil movement is proportional to windspeed cubed after the windspeed attains some minimum or threshold speed required to initiate soil movement (2, 9, 61). Therefore, wind erosion is greatly reduced when barriers reduce windspeed.

A summary of the effect of barriers on several micrometeorological factors is shown in figure 1.

Crop Yields as Influenced by Barrier-induced Microclimate

The literature (34, 47, 50) is replete with examples of increased yields accruing from the benefits of shelter. These yield increases have been highly variable; in some cases over 200 percent increases have been observed, whereas no increases were observed in other cases (39, 50).

Unfortunately, detailed microclimatological data associated with increased crop yields are scarce and it is difficult to associate increased yields

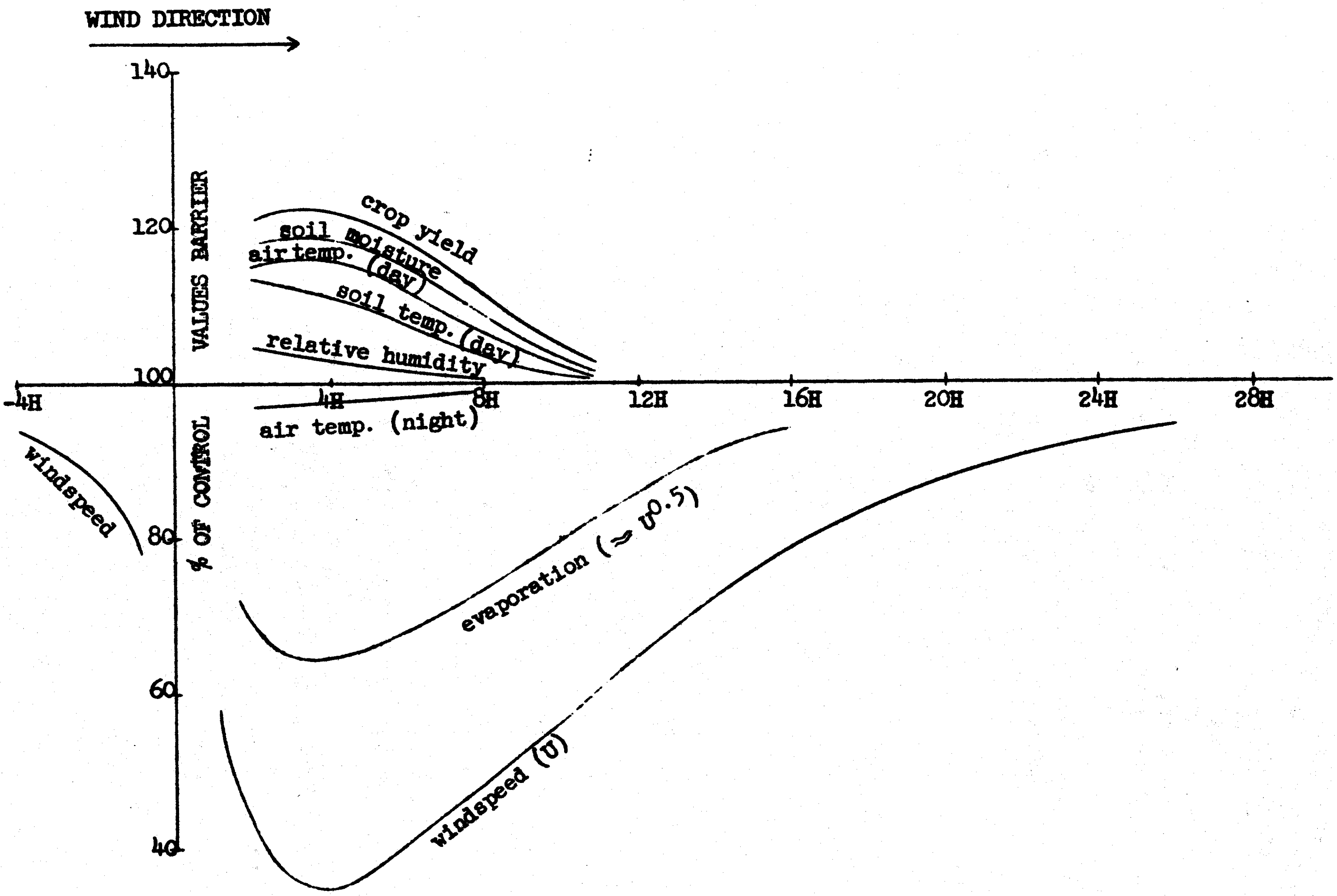

Figure 1.--Summary diagram of the effect of barriers on micrometeorological and other indicated factors (after Marshall (29)).

with specific microclimatological factors. Pelton (32) noted that more detailed environmental factors need to be studied. Marshall (29) considers end-of-season yield a too highly integrated function to allow casual interpretation of shelter effect on crop production.

In the hierarchy of environmental parameters that affect net photosynthesis, Idso (23) lists light intensity, leaf temperature, leaf water, and CO_2 concentration as primary factors and considers wind secondary.

We have already discussed the influence of barrier-reduced windspeed on radiation, air temperature, and CO_2 concentration and noted that wind does affect these primary factors to some extent but generally not greatly. Idso (23) observed "that wind can influence net photosynthesis through its role in sensible and latent heat exchange from the plant, whereby leaf temperature is altered and respiration either increased or decreased."

The primary environmental factor affected most by wind appears to be leaf water availability. Waggoner (53) suggested in his "Environmental manipulation for higher yields" that wind is important in water-stress relationships. By decreasing potential evapotranspiration with barriers, yields have been increased and water used more efficiently (6, 7).

Since climatic conditions in the Great Plains favor high evaporation rates (22, 38, 43), perhaps our greatest benefit from barriers will be reduced potential evapotranspiration and, thus, improved water relations for photosynthesizing leaves.

We have used a hypothetical example to show how yield may be benefited from reducing potential evapotranspiration with wind barriers.

Potential evapotranspiration was computed by the combination model (48) using climatological data for July 1968, Dodge City, Kansas. Net radiation was estimated from solar radiation by multiplying by 0.6. Soil heat flux was neglected. Values for leeward windspeed were obtained by multiplying daily average windspeed by $\left[1 - 4(e^{-0.2H} - e^{-0.3H})\right]$, which gives a typical (29, 54) windspeed reduction pattern (figure 2).

Potential evapotranspiration was computed at 2, 4, 6, 8, 10, 15, 20, 25, and 30H leeward for each day in July 1968. Continuing with the hypothetical example, we assumed three levels of soil water potential at which the crop loses turgor when potential evapotranspiration reaches 1.0, 0.9, and 0.8 cm. per day, respectively. Then we counted the number of days in July that the plants would have lost turgor for the various positions behind the barrier. That, of course, was the number of days that potential evapotranspiration was greater than 1.0, 0.9, and 0.8 cm. per day. Results are shown in figure 3.

Now assuming that a 1.0 percent increase in yield over the control would result for each fewer turgor loss day, we can construct a relative yield curve (figure 4). Denmead and Shaw (13) found that for each day below estimated turgor loss point, dry weight was reduced approximately equal to the mean growth rate of control plants.

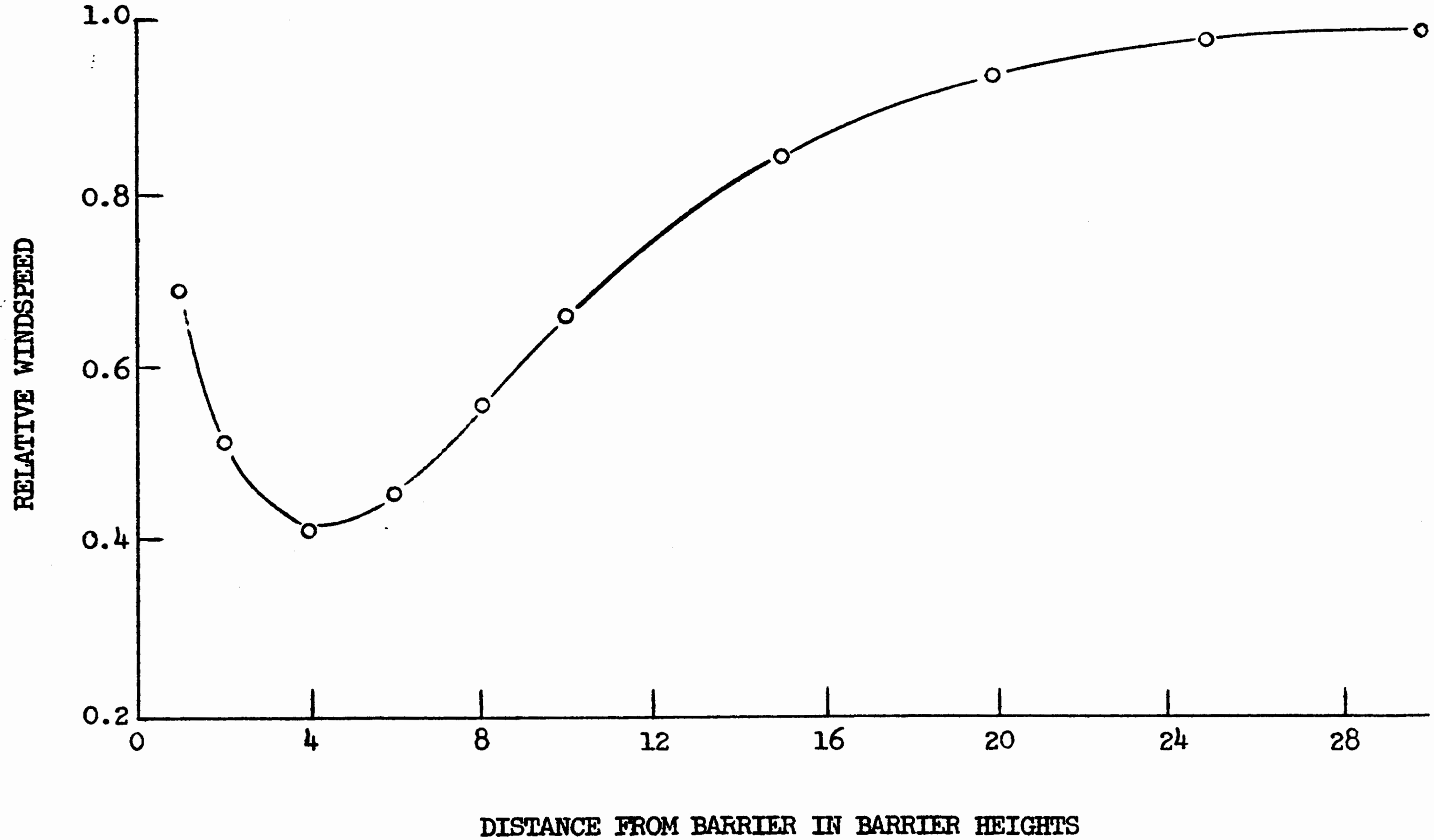

Figure 2.--Hypothetical windspeed reduction expressed by multiplying open field windspeed by $\left[1 - 4(e^{-0.2H} - e^{-0.3H})\right]$.

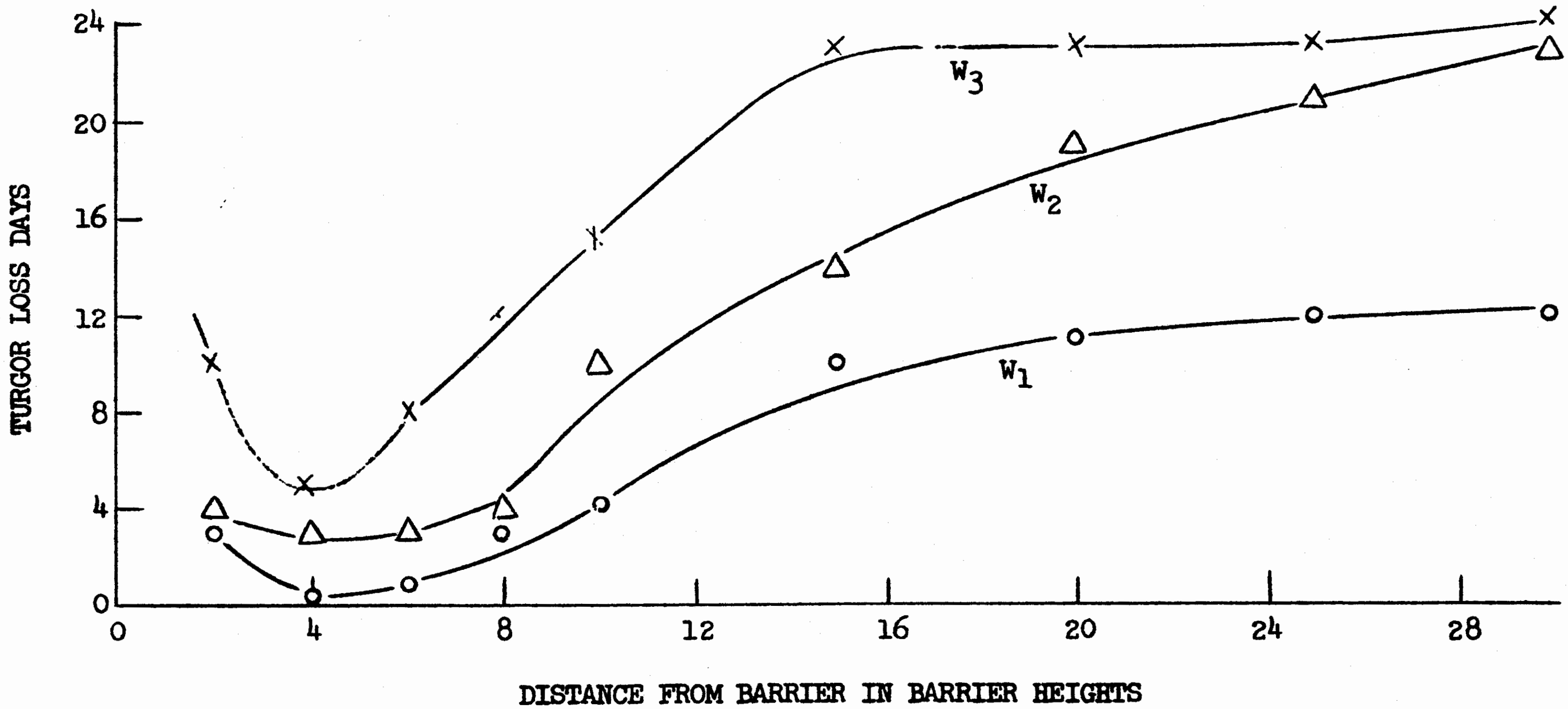

Figure 3.--Predicted turgor loss days at indicated distances leeward from windbreak for three levels of soil water. Calculations were made for Dodge City, Kansas, weather of July 1968. Windspeed leeward of barriers was assumed equal to open field windspeed multiplied by $\left[1 - 4(e^{-0.2H} - e^{-0.3H})\right]$. W_1, W_2, and W_3 are the levels of soil water potential at which a crop loses turgor when potential evapotranspiration reaches 1.0, 0.9, and 0.8 cm. per day, respectively.

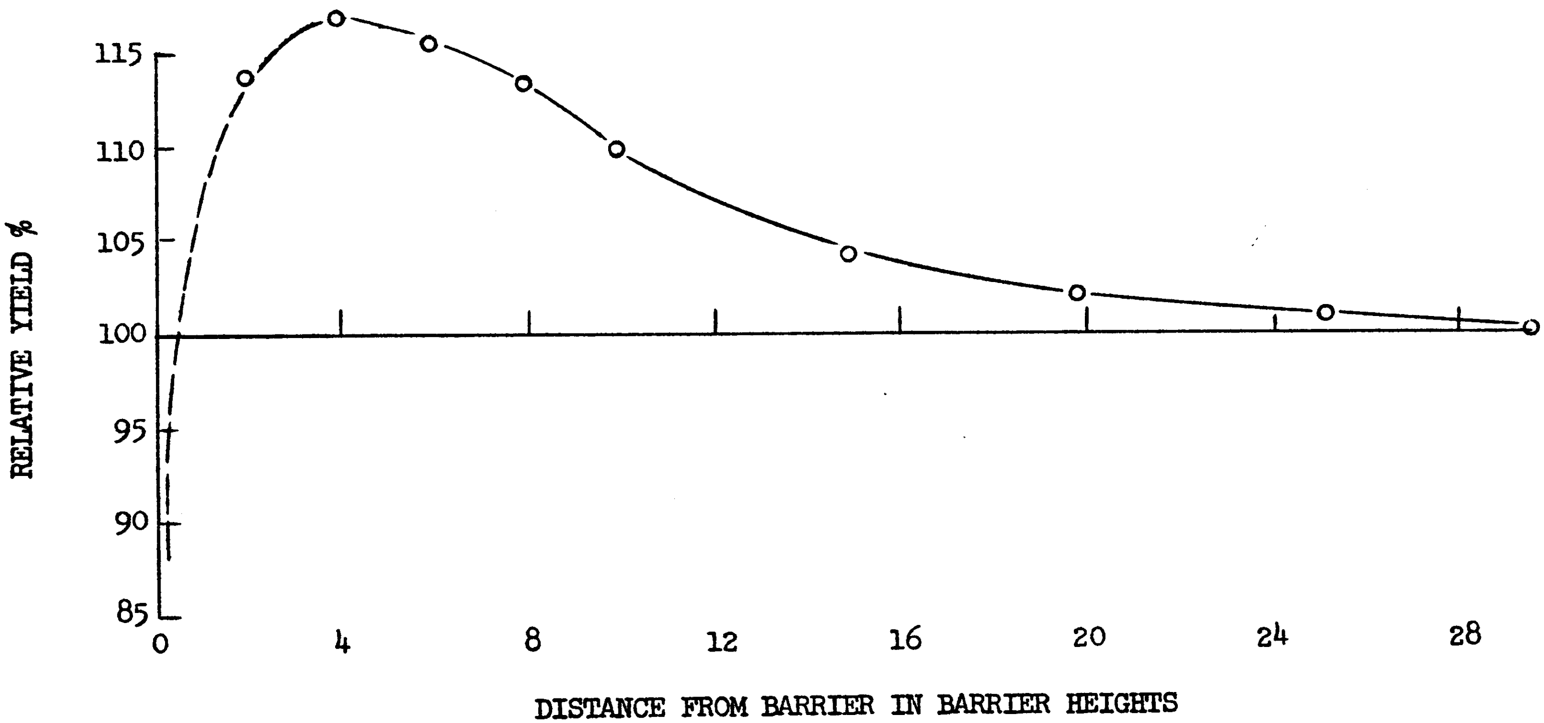

Figure 4.--Relative yield calculated from average number of turgor loss days for the three moisture levels of figure 3 by assuming that a 1.0 percent increase in yield results for each fewer turgor loss day in sheltered area than in the open.

The relative yield curve (figure 4) generated from the example based on lowering potential evapotranspiration leeward of barrier is similar to observed yields leeward of barriers (29, 47).

Summary and Conclusions

Barrier effects on microclimate have been researched with special attention to reduced windspeed and increased yields. Barrier characteristics of permeability, height, shape, and width, and wind properties of speed, turbulence, thermal stability, and direction, all influence windspeed reduction and leeward airflow. In turn, modified airflow affects the microclimate. Air temperature usually is higher in daytime and lower at night in a sheltered area. Soil moisture is benefited by snow accumulation and reduced evaporation. CO_2 concentration in the sheltered crop canopy tends to increase above atmospheric concentration during the night and decrease below it during the day. Variations in absolute humidity are slight--humidity usually increases near the barrier. Barriers only slightly influence radiation exchange and only in their immediate vicinity.

Yield increases often observed from use of barriers generally have not been associated with specific factors of the microclimate. However, it is apparent that one of the primary benefits from barriers is lowering potential evapotranspiration.

More research is required before we understand 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 consequences of various strategies of barrier use in the Great Plains climate.

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