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Barrier-Induced Microclimate and its Influence on Growth and Yield of Winter Wheat[1]

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Abstract. Wind barriers reduce windspeed, modify the microclimate, and affect plant growth. Vegetative growth and dry matter production of winter wheat are usually higher in the area sheltered by the wind barrier than in the open field. Sometimes grain yield is also increased. However, because growth and yield next to the barrier are reduced and the land occupied by the barrier is unavailable for crop production, the net effect on grain yield is often negligible.

INTRODUCTION

Shelter research in the Great Plains attempts to predict quantitative effects of barriers on crop yields, wind erosion, evaporation, and associated factors. This requires an understanding of several relationships: 1) the relationship between barrier and airflow must be established so that the nature of the leeward airflow may be associated with barrier characteristics and characteristics of the incident wind; 2) the relationship between leeward airflow and microclimate associated with barrier-modified airflow must be elucidated; and 3) the effect of the barrier-induced microclimate on plant processes (photosynthesis, respiration, transpiration, cell division, growth, etc.) that affect crop yields must be determined and related to characteristics of the barrier and wind climatology.

In this paper, I discuss airflow as affected by barrier and incident wind, microclimate as influenced by barrier-modified airflow, and growth and yield of winter wheat as influenced by barrier-induced microclimate.

Many review articles (Caborn 1957; Forestry Committee Great Plains Agricultural Council 1966; Guyot 1963; Jensen 1954; Marshall 1967; Read 1964; Rosenberg 1967; Stoeckeler 1962; van der Linde 1962; van Eimern, Karschon, Razumova and Robertson 1964), including two (Kreutz 1952; Lupe 1952) cited by Marshall (1967), have appeared recently on wind barriers, shelterbelts, and their influence on microclimate and crop yields. Several (Forestry Committee Great Plains Agricultural Council 1966; Read 1964; Rosenberg 1967; Stoeckeler 1962), as well as an early summary by Bates (1911), were written for direct application to agricultural problems of the Great Plains.

BARRIER-MODIFIED AIRFLOW

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 have been presented in terms of permeability (Jensen 1954; van Eimern et al. 1964).

Windspeed reduction patterns are determined primarily by the porosity and distribution of pores in the barrier. Woodruff et al. (1963) measured windspeed-reduction patterns of many shelterbelts and found that they may be either too dense or too porous to be effective barriers. For windbreaks with low porosities, leeward windspeed is minimum near the windbreak and, after reaching minimum, tends to increase more quickly than do windspeeds leeward of more porous windbreaks (Marshall 1967; Skidmore and Hagen 1970a; van Eimern et al. 1964; Woodruff, Fryrear and Lyles 1963). Very dense windbreaks stimulate

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turbulence (Baltaxe 1967; Marshall 1967; Skidmore and Hagen 1970a; van Eimern et al. 1964). At low permeabilities the area of sheltered ground decreases and at high permeabilities the degree of shelter provided becomes negligible.

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. Marshall (1967) cited numerous papers before he concluded 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; thus, height of barrier is important in considering extent of sheltered area. Sheltered distances are generally expressed as multiples of the barrier height H.

Wind Characteristics

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 effects of barriers, relative values are generally used, which automatically assumes that windspeed reduction is independent of the absolute value of the open windspeed (van Eimern et al. 1964).

According to several publications (Chepil, Siddoway and Armbrust 1964; Johnson 1965; Skidmore and Woodruff 1968; Zingg 1950), 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 than when wind blows at a wider angle. However, even with wind blowing parallel to the barrier, wind is reduced up to 5H behind it; van Eimern et al. (1964) cited other work as evidence that the protective effect with a wind parallel with the belt is about one-fourth of that which is perpendicular. The protective effect with a parallel wind results from the inevitable variation in wind direction and the friction at and above the belt.

MICROCLIMATE AS INFLUENCED BY BARRIER-MODIFIED AIRFLOW

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

Radiation

Radiation, one of the most important factors in crop environment, is only slightly affected by a barrier and is affected only in the immediate vicinity of the barrier (Marshall 1967; Rosenberg 1966; Rosenberg 1967; van Eimern et al. 1964). 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. However, as Rosenberg (1967) pointed out, long shadows are cast only when the sun is low and solar radiation is low, so the effect may be unimportant.

Air Temperature

Reduced vertical diffusion and mixing of the air usually means higher daytime air temperature and lower nighttime air temperature (Marshall 1967; Rosenberg 1966a; Rosenberg 1966b; Skidmore, Jacobs and Hagen 1972; Skidmore and Hagen 1970b). However, Woodruff, Read and Chepil (1959) found both hotter and cooler daytime air leeward of a barrier. Leeward air temperature patterns were closely related to the eddy zone produced by the barrier; warm zones were located near the ground and near the barrier where eddy currents were rising; and during the day the warm zone extended 5 to 10H leeward, the daytime air temperature being lower than the open air beyond 5 to 10H leeward. Hagen and Skidmore (1971) also observed that when mean vertical flow was directed 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.

Micrometeorological observations of Skidmore and Hagen (1970a) 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 (1967) cited Guyot (1963) stating that the effects of shelter on air temperature may be predicted based on whether evapotranspiration is increased or decreased. When evapotranspiration uses more available energy, less is available to heat the air. Certainly, if the evaporation rate is decreased with a large but unchanged radiation load, temperature of evaporating surface would rise.

Air Humidity

The humidity regime leeward of a wind barrier is not always straight forward. 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 (van Eimern et al. 1964). Many studies showed only slight variation of relative humidity in sheltered areas as compared with that of unsheltered (Marshall 1967; van Eimern et al. 1964). Rosenberg (1966a) found absolute humidity content of the air above sugarbeets not influenced by snow fence and two rows of corn. But he (1966b) found that absolute humidity remained consistently higher (2 to 3 mb) in sheltered areas of an irrigated bean field.

Skidmore and Hagen (1970a) 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-percent 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 porosity barriers.

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 (1966b) observed that soil temperature in sheltered areas was usually elevated during the day and slightly depressed at night. According to reviews by Marshall (1967) and van Eimern et al. (1964), most researchers who observed soil temperature found it was slightly higher inside the shelter. Increases were greatest when the soil was bare and dry, least 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. Plants, organic matter, and soil respire continuously, whereas they assimilate only during daylight; then assimilation consumes CO_2 much faster than respiration produces it (van Eimern et al. 1964). Therefore, at low windspeeds and under 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 (1955) found the unsheltered atmosphere 1 m above the ground was about 4-percent richer in CO_2 between 10 a.m. and 3 p.m. than at other times. Any decrease in CO_2 content, induced by a barrier, has not been reflected in yield and, as Rosenberg (1966b) observed, CO_2 quantity unaccompanied by a simultaneous measurement of CO_2 flux can be misinterpreted.

Evaporation

Evaporation rate integrates many of the climatic variables modified by a wind barrier. The high temperature and humidity in the sheltered region tend to offset each other in changing evaporative demand (Skidmore and Hagen 1970a; Skidmore and Hagen 1973). Because neglecting barrier-induced changes in temperature and humidity is of small consequence in regulating evaporation, the influence of a wind barrier on potential evaporation can be approximated with an appropriate model by accounting for effects of reduced windspeed on potential evaporation.

A characterization of the contribution of wind to potential evapotranspiration for a climate typical of the Great Plains demonstrated that for high temperature/low humidity environments a decrease in windspeed also profoundly decreases evaporation from freely evaporating surfaces (Skidmore and Hagen 1970a; Skidmore and Hagen 1973; Skidmore, Jacobs and Powers 1969). On representative and consecutive "nonwindy" and "windy" days at Manhattan, Kansas (average daily windspeeds at 45 cm were 0.88 and 2.26 m/sec), a wind-dominant term contributed 33 and 113 percent, respectively -- as much as a radiation-dominant term -- to total calculated potential evapotranspiration (Skidmore et al. 1969).

Calculations (Skidmore and Hagen 1970b; Skidmore and Hagen 1973) using climatological data (May through September, 1960-1969) from two sample locations in the Great Plains showed a 31- and 26-percent average-potential-evaporation reduction from 0 to 10H north of east-west oriented barriers near Dodge City, Kansas, and Bismark, North Dakota, respectively. When the area was extended to 30 barrier heights, the average evaporation decrease was 14 and 7 percent for Dodge City and Bismark, respectively.

GROWTH AND YIELD OF WINTER WHEAT AS INFLUENCED BY BARRIER-INDUCED MICROCLIMATE

Expected Benefit

The lowering of evaporation demand with reduced windspeed in the area sheltered by the wind barrier provides an environment for improved water relations. Although wind may not rank with light intensity, leaf temperature, leaf water, and CO_2 concentration in the hierachy of environmental parameters that affect net photosynthesis (Idso 1968), it is important in water-stress relationships (Hagen and Skidmore 1974; Waggoner 1969). By decreasing potential evaporation with barriers, yields have been increased and water used more efficiently (Bouchet 1963; Bouchet, De Parcevaus and Arnox 1963).

The possible yield benefit from decreasing potential evapotranspiration with wind barriers was demonstrated by Skidmore (1969), using a hypothetical example. Using climatological data at Dodge City, Kansas, he calculated windspeed-reduction patterns; assuming that turgor loss and associated yield decrease, when potential evaporation was above a specified level. He generated a relative yield curve similar to that leeward of barriers reported by Marshall (1967) and Stoeckeler (1962).

For a net yield increase, yield increase in sheltered area must more than offset the absence of yield in the area occupied by the barrier and the small area of reduced yield that usually occurs near the barrier. In a detailed experiment with spring wheat, McMartin et al. (1974) found a slight decrease in total wheat production for an entire field. In a 5-year study Staple and Lehane (1955), also taking into account the area occupied by the barrier, found a modest net increase in yield of 47 kg/ha (0.7 bu/ac) in one group of sheltered fields.

Vegetative Growth

Aase and Siddoway (1974) investigated the development of winter wheat as influenced by double rows of tall wheatgrass barriers spaced 15.2 m (10H) apart. The first two rows of wheat next to the barriers were poor; production peaked at about 1 to 3H from the barriers. All the barrier wheat, except the first two rows next to each barrier, grew more vigorously than did the check wheat. Dry-matter yields were 6,293 and 5,723 kg/ha for barrier and check, respectively, in 1971. The dry-matter yields in 1972 were 8,545 and 8,243 kg/ha for barrier and check, respectively. The higher yields in the sheltered areas were significant at the 5 percent level in 1971 and nonsignificant in 1972. The shelter also enhanced leaf-area development, height, and number of heads per meter row length (Table 1).

Table 1. Winter wheat grown between tall wheatgrass barriers and on check near Culbertson, Montana compared (after Aase and Siddoway, 1974).

Growth factor	1971 Barrier	1971 Check	1972 Barrier	1972 Check
Height (cm)	102*	94	109*	106
Heads/m	99.4*	87.2	129*	109
Leaf area index, 28 April	0.5 1/	0.1	——	——
Leaf area index, 31 May	2.5 1/	1.5	——	——
Dry Matter (kg/ha)	6,293*	5,723	8,545	8,243
Grain (kg/ha)	2,770*	2,519	3,545	3,482

* Comparisons within years different at 5-percent level of significance.

1/ Statistics not given.

In a 3-year (1970-1972) study of winter-wheat response to barrier-induced microclimate at subhumid Manhattan, Kansas, Skidmore et al. (1974) found that plants in the sheltered area generally grew taller, had larger leaves, and improved water-stress relationships as compared to those in open field. The difference in vegetative growth between plants in shelter and open field was especially pronounced in 1970, with Pawnee variety wheat, during a 3-wk period in May, when warm southerly winds prevailed. On May 25 the height to heads was 11 cm more in sheltered than in unsheltered areas. The leaf area index of the flag leaves of plants in shelter was 43 percent greater than those in the open field. In subsequent years of the study, most wheat varieties responded vegetatively to barrier-induced microclimate, but because the general climate was more favorable for wheat production, response was less, and hence also benefit of the barrier.

In another study (Skidmore, Hagen and Gwin 1975) in semiarid western Kansas, winter wheat produced more vegetative growth in the sheltered area than in the unsheltered areas (Table 2). The barriers in the Kansas studies were slat-fence 1.4 m (8 ft) tall and were installed after winter snows had melted. Therefore, the Kansas locations did not benefit from snow catch and distribution across the field as did the Montana location (Aase and Siddoway 1974).

Table 2. Growth and yield of winter wheat in area sheltered by slat-fence barrier compared with that in open field, Tribune, Kansas, 8 June 1973 (after Skidmore et al. 1975).

Comparison	Shelter (2HS)	Open (12HN)
Height to top of head, cm	95.2	78.6
Height to base of flag leaf, cm	69.4	61.3
Area of flag leaf, cm^2	19.7	11.4
Functional area of flag leaf (green), cm^2	15.4	5.6
Dry matter, g/30-cm row length	100.9	80.2
Mean grain yield (kg/ha)	2,381	1,924

Grain Yield

Though winter wheat plants in their vegetative growth stage responded favorably to barrier-induced microclimate, grain-yield response was less predictable. At Manhattan, Kansas, in 1970 the grain yield was lowest (Table 3) in areas where the plants had appeared most vigorous during vegetative development. After kernels were about one-fourth filled, a wet period started, which impaired head filling and was conducive to incidence of disease.

With favorable precipitation and not so much hot wind in 1971, the barrier influence was minimal, as might be expected (Skidmore, Hagen and Teare 1975). Comparing treatment means of grain yield shows that relative position of wheat to barrier only slightly influenced the difference in yield between plants in shelter and those in open field (Table 3). Yield data of 1971 illustrate a possible trend: lowest-yield positions were near and far from the fence; yield at intermediate positions apparently was favorably influenced by the barrier. These results agreed with those of Aase and Siddoway (1974). The data, presented in Table 2 for Tribune, also show yield response was favorable in the sheltered area. But if we consider data from other positions in the field, favorable yield response might be questioned (Skidmore et al. 1975).

Table 3. Average wheat yield at indicated position from slat-fence wind barrier, Manhattan, Kansas. The 1971 and 1972 data are averages of five varieties and five replications each (after Skidmore, Hagen, Naylor, and Teare, 1974).

Position[1/]	Year 1970	1971	1972	Average (1971-1972)
	kg/ha			
-12.5	----	4150	3330	3740
-8.0	1440	4180	3320	3750
-4.5	----	4300	3400	3890
-2.0	930	3830	3280	3590
2.0	630	4070	3150	3610
4.5	1300	4330	3390	3860
8.0	----	4400	3410	3910
12.5	1450	3940	3560	3750

1/ Distance from barrier in barrier heights. Positive and negative indicate north and south sides of an east-west barrier, respectively. Prevailing wind direction was southerly.

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