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The purpose of this study was to determine the effect of barrier-induced microclimate on winter wheat growth and yield. The study was conducted in Kansas in the fall of the 1969-70 season. The barrier was a 10 ft high wall of straw bales, 10 ft wide and 10 ft apart. The wheat was planted in the fall and the yield was measured in the spring. The results showed that the barrier induced a microclimate that was warmer and more humid than the open field. This resulted in a higher yield of wheat per acre.

### METHODS

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Each year between 1969 and 1971 a barrier of straw bales was erected in the fall of the 1969-70 season. The barrier was 10 ft high, 10 ft wide, and 10 ft apart. The wheat was planted in the fall and the yield was measured in the spring.

Microclimate measurements were made in the open field and in the barrier. The measurements included temperature, relative humidity, and wind speed. The results showed that the barrier induced a microclimate that was warmer and more humid than the open field.

The yield of wheat per acre was measured in the spring. The results showed that the barrier induced a higher yield of wheat per acre than the open field. This was due to the warmer and more humid microclimate induced by the barrier.

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## ABSTRACT

The purpose of this research was to investigate morphological and physiological response of winter wheat (*Triticum aestivum* L.) to microclimate induced by a slat-fence wind barrier. Six varieties of wheat were grown in 90-m-long plots running perpendicular to centrally placed, east-west barriers. Meteorological conditions and plant response were observed on selected days. Stomatal resistance and leaf water potential were measured with stomatal resistance meter and pressure bomb, respectively. Rate of photosynthesis was evaluated by determining uptake of labeled CO<sub>2</sub>. When environmental conditions were conducive to plant water stress, the plants in the sheltered area had significantly lower stomatal diffusive resistance, tended to have higher leaf-water potential, and photosynthesized at an equal or significantly greater rate than those in the open field, even though plants in shelter contained 24% less leaf chlorophyll than those in open field. On days when water stress was low, the difference in plant responses between open field and shelter was generally nonsignificant. The plants in the sheltered area generally grew taller, had larger leaves, and had improved water-stress relationships compared with those in open field. Yet, the grain yields were not consistently increased for the growing environment at Manhattan, Kansas.

**Additional index words:** Plant water stress, Stomatal resistance, Leaf-water potential, Photosynthesis, Chlorophyll.

THE literature (20, 25, 27) is replete with examples of increased crop yields accruing from the benefits of wind barriers, used extensively to ameliorate harsh climates. Though highly variable, increases of more than 200% have been observed (22, 27).

Unfortunately, it is difficult to associate increased yields or specific plant responses with specific microclimatological factors, because so few detailed data are available. Pelton (17) noted that environmental factors need to be studied in more detail. Marshall (14) considers end-of-season yield a too highly integrated function to use in interpreting shelter effect on crop production.

Radke and Burrows (18) found that soybeans (*Glycine max* L.) sheltered by corn (*Zea mays* L.) windbreaks grew taller, weighed more, and had higher grain yields, but could not relate those factors to amelioration of moisture stress, light stress, physical stress, or a combination. They suggested further investigation. More recently, Radke and Hagstrom (19) found potential transpiration and stomatal resistance appeared to be directly related when moisture stress was low, but were inversely related when moisture stress was high. Miller (16) found lower stomatal resistance of soybeans with lower windspeeds. Similarly, Brown and Rosenberg (4) observed lower stomatal resistance of sugarbeets (*Beta vulgaris* L.) in the sheltered plots than in the open. King (13) obtained evidence that wind exerts a stress on the water-balance

of sugarbeets. Sugarbeet plants growing in the sheltered area had a higher leaf water potential.

Idso (10) considers wind as secondary in the hierarchy of environmental parameters affecting photosynthesis, and light intensity, leaf temperature, leaf water, and CO<sub>2</sub> concentration as primary factors. However, Waggoner (28) has demonstrated the importance of wind in water-stress relationships. Using wind barriers to decrease windspeed and potential evapotranspiration has resulted in increased yields and more efficient (though unchanged total) water use (1, 2, 18, 21).

The purpose of the present investigation was to determine the water relations, growth, and yield of wheat (*Triticum aestivum* L.) to barrier-induced microclimate and thereby evaluate feasibility of using wind barriers for increasing wheat production.

## METHODS

The response of winter wheat to microclimate induced by a slat-fence wind barrier was studied for 3 years at Manhattan, Kansas. In the fall of the first year, 'Pawnee' variety of wheat was seeded in a 90- by 180-m field; in the spring a slat-fence was installed midfield in the EW (east-west) direction, separating the field into two 90- by 90-m plots.

After the first year the field plan was modified. The south half of the 90- by 180-m field was seeded to 'Satanta' variety and the adjacent 90- by 90-m plot was subdivided into twenty-five 2.5- by 90-m plots with a 13.5-m border on each side of the 25-plot test area. 'Blueboy,' 'Caprock,' 'Parker,' 'Pronto,' and 'Shawnee' varieties of wheat were fall-seeded at the rate of 84 kg/ha (75 lb/acre) in a randomized block design with five replications. The entire site was fertilized each year according to local recommendations with liquid nitrogen and prilled 18-46-0 to give 100 kg/ha (90 lb/acre) of nitrogen and 25 kg/ha (22 lb/acre) of phosphorus.

Each year between March 20 and April 9, a 2.4-m-tall, 40%-porous, slat-fence windbreak was installed in EW direction midway in the 90 by 90-m plot of Satanta and another was installed midway in the five-variety plot so as to cut across all of the plots, leaving plots 2.5- by 45-m on each side of the barrier.

Air temperature, humidity, temperature gradients, humidity gradients, soil heat flux, and soil water depletion (gravimetric and neutron scattering) were observed periodically in the open field and 2, 6, and 12 times barrier height leeward of the south barrier. Additional micrometeorological observations includes total shortwave radiation, net shortwave radiation, net radiation above and below the canopy, and temperature and humidity vertical profiles in the open field.

Plant response—including leaf-water potential, stomatal resistance, carbon dioxide assimilation, chlorophyll content, leaf areas, and plant heights—were measured on selected days. Measurements were repeated 4 to 10 times on different leaves or plants. The measurements of the parameters with the greatest variability were repeated the greatest number of times. To measure leaf-water potential, we used a pressure bomb as described by Scholander et al. (23). This method measures the matric water potential but does not include the osmotic potential, which is usually small (3). Results (3, 5, 29) using pressure bombs agree well with those using other techniques.

Stomatal resistance was measured, using a stomatal diffusion porometer as described by Kanemasu, Thurtell, and Tanner (12), on both abaxial (bottom) and adaxial (top) surfaces of four different flag leaves. Leaf stomatal diffusive resistance,  $r_s$ , was calculated for each from

$$r_s = 2r_t r_b / (r_t + r_b)$$

where  $r_t$  and  $r_b$  are adaxial and abaxial stomatal resistances, respectively.

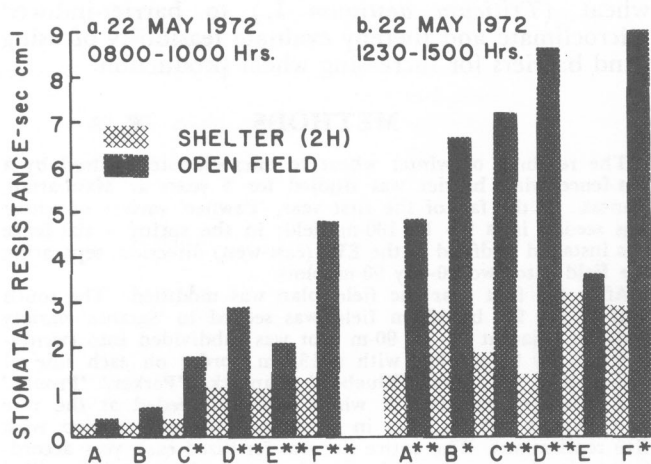
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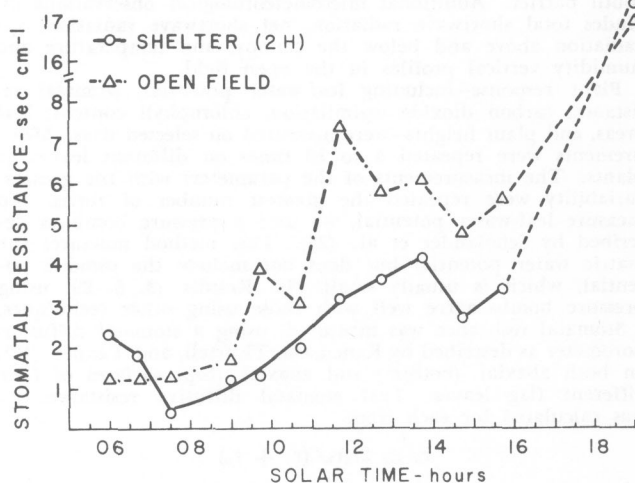
**Table 1. Stomatal diffusive resistance of flag leaf and climatic parameters at nearby weather station.**

Time, date	Position	Resistance		
		Adaxial	Abaxial	Stoma
sec/cm				
May 17, 1971 1615 hours	-6H	2.3	14.0*	3.9
	2	2.1	3.0	2.4
	6	2.9	6.2	3.9
	12	2.6	11.7	4.3
May 25, 1971 1515 hours	-6H	0.8	1.8**	1.1
	2	0.9	1.2	1.0
	6	0.8	1.4	1.0
	12	0.7	1.4	0.9
Water vapor pressure deficit		Windspeed at 6 m	Air temperature	Solar insolation
mb		m/sec	C	ly/day
May 17, 1971	13.2	7.0	24.8	584
May 25, 1971	6.3	4.5	17.3	733

\*, \*\* Significant at  $P = 0.05$  and  $0.01$ , respectively.



**Fig. 1. Shelter vs. open-field stomatal resistance of six wheat varieties for two periods of a day having relatively high potential evaporation. Wheat varieties were 'Satanta,' 'Blueboy,' 'Caprock,' 'Parker,' 'Shawnee,' and 'Pronto' for A, B, C, D, E, and F, respectively. (\* and \*\* significant at  $P = 0.05$  and  $0.01$ , respectively. Data presented in order obtained.)**



**Fig. 2. Stomatal diffusive resistance of wheat ('Blueboy') in open field and in sheltered area of slat-fence windbreak, June 1, 1972.**

Photosynthesis ( $\text{CO}_2$  assimilation) in the field was evaluated using labeled  $\text{CO}_2$ , as described by Shimshi (24). We applied relatively short pulses of air containing  $^{14}\text{CO}_2$  over a momentarily enclosed area on both sides of the flag leaf, and subsequently determined  $\text{CO}_2$  uptake by measuring the radioactivity in the enclosed leaf area.

Chlorophyll content was determined by standard laboratory procedure of extracting chlorophyll with ethanol-acetone solution and measuring absorbance at 645 and 633 nm with a spectrophotometer.

We measured length and width of all leaves on 10 tillers and counted number of tillers per 30 cm of row length, repeated 10 times; then, calculated leaf area (LA) from length and width measurement from

$$\text{LA (cm}^2\text{)} = -.64 + .813 (\text{length} \times \text{width})$$

(26). Leaf area index was calculated as the product of LA/tiller times tillers/unit area from leaf and ground areas per tiller. Height to flag leaf and base of head also was measured on 10 tillers per each variety when we observed phenotypes.

## RESULTS AND DISCUSSION

On high stress days, the amelioration of microclimate induced by wind barrier caused the plants in the shelter to have lower stomatal resistance than those in open field (Table 1 and Fig. 1). On May 17, 1971, with warm southerly wind and low soil water, the plants stressed. Leaves curled, partially enclosing their adaxial (upper) surface, thus reducing some of the symptoms of stress on the adaxial surface. Stomatal diffusive resistance on the abaxial surface of the leaf was higher than on the adaxial and significantly different ( $P = 0.05$ ) at the different positions from the fence. The ranking of stomatal diffusive resistance was  $2\text{H} < 6\text{H} < 12\text{H} < -6\text{H}$ , which would correspond to ranking of evaporative demand.

Stomatal resistance of six wheat varieties on May 22, 1972, was generally higher in the open field (Fig. 1). Potential evaporation as determined by combination method was relatively high, caused by moderately strong southerly wind, warm temperature, and bright sunshine. In the beginning of the first period (between 0800 and 1000 hours), stomatal resistance was low with essentially no difference between sheltered and unsheltered areas. Late in the period stomatal resistance had increased somewhat, especially on the plants in the open field. Stomatal resistance was greater in the open field at the 1% level. By early to mid-afternoon, as shown in the second period, the difference between shelter and open field was even greater, except for the Shawnee variety.

On June 1, 1972, (Fig. 2), with environmental conditions similar to May 22, stomatal resistance was measured on Blueboy variety, starting at 0600 and continuing throughout most of the day in both shelter and open field. Stomatal resistance in the shelter was significantly lower than in the open field at  $P = 0.01$  or  $0.05$  for all observations after 0700 and before 1900 hours (except at 0900). Stomatal resistance was low in the early morning in both the shelter and the open but increased more quickly in the open field than in sheltered area as the day progressed. In the open field, stomatal resistance reached  $3.9 \text{ sec cm}^{-1}$  by 0940. Rate of photosynthesis (Fig. 3) also increased almost linearly after 0600 hours until about 0940 and 1240 for open field and shelter, respectively, then declined sharply. Those times correspond to

stomatal resistances of  $3.8 \text{ sec cm}^{-1}$  for both cases. The minimum midday rate of photosynthesis at 1150 and 1340 for open field and shelter, respectively, corresponded to relative maximum for stomatal resistances. This apparent correspondence between stomatal resistance and photosynthesis did not follow for all days. On May 22, 1972, the mean stomatal resistance in the open field was more than a three-fold increase over the mean stomatal resistance in the shelter. Photosynthesis was greater in shelter than open field (Table 2). But measurements varied greatly and rate of photosynthesis in the shelter was not significantly higher statistically except for that of Blueboy made just prior to 1200 hours. Likewise, rate of photosynthesis was greater in the shelter for the measurements made after 1300 hours, but mean differences were not significant.

Gaastra (7), who compared the maximum capacity of the diffusion process and the maximum rate of photochemical process at a given light intensity, concluded that under conditions of light limitation, a considerable closure of the stomata may occur without affecting photosynthesis rate. Under light saturation, rate of diffusion determines rate of photosynthesis, but the stomatal control of photosynthesis depends on the relation between stomatal resistance ( $r_s$ ) and the sum of the resistances in the external air, in the stomata, and in the mesophyll cells ( $r_a + r_s + r_{me}$ ). If the mesophyll resistance was relatively high, the much higher stomatal resistance we found in open field on May 22, 1972, would not have caused a corresponding percentage decrease in photosynthesis.

Photosynthesis rate on May 24 and May 31, 1972, was much higher than on May 22, when light intensities were about as high but evaporative demand was lower. Also, on May 31 the difference between shelter and open field was significant at 5% level for four of the five varieties (Table 2). Because of the lower windspeed, lower temperature, and generally non-southerly wind, the apparent shelter influence was much less on May 31 than on May 22 and June 1.

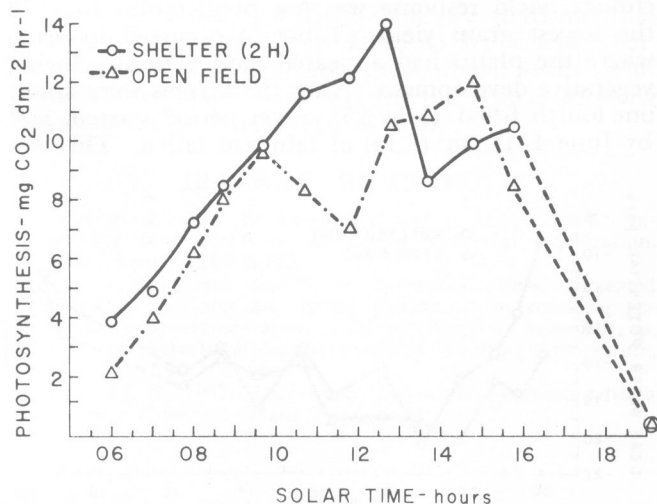


Fig. 3. Photosynthesis of wheat in open field and in area sheltered by slat-fence windbreak, June 1, 1972, Manhattan, Kansas.

Table 2. Comparison of shelter vs. open field rate of photosynthesis ( $\text{mg CO}_2 \text{ dm}^{-2} \text{ hr}^{-1}$ ).

Wheat variety	Position	May 22, 1972			
		0900-1200	1300-1430	1245-1420	1300-1520
Satanta	Open field	2.96	3.75	10.08	6.94*
	Shelter	5.13	4.32	9.58	11.57*
Blueboy	Open field	3.67*	----	8.65**	10.77*
	Shelter	7.09*	----	12.32**	12.23*
Caprock	Open field	2.71	3.32	8.20	9.49
	Shelter	2.56	4.44	8.87	10.35
Shawnee	Open field	4.36	----	7.81	8.70*
	Shelter	5.92	----	9.51	12.50*
Parker	Open field	4.54	4.40	10.02	8.33*
	Shelter	5.48	5.21	9.12	12.49*

\* \*\* Significant at  $P = 0.05$  and  $0.01$ , respectively.

We observed that plant leaves in the sheltered area were a lighter green and had more spots of discoloration than those in the open field. The leaf spots were similar to those described by Johnston (11): "... varied from small, indistinct stippling (resembling flecking stage of leaf rust) to large, yellowish spots that coalesce and form tan or brown areas." We could find no organism associated with the discoloration. Johnston's attempts to isolate organisms as causal agents also invariably failed.

Flag leaves from Caprock, Blueboy, and Pronto wheat varieties were obtained from the open field and sheltered areas on May 25, 1972, (three-fourths to full berry), then analyzed for chlorophyll content. The means (five replications) of plants in the sheltered area were 4.38, 4.41, and 4.33, and in the open field, 5.48, 5.55, and 6.21 mg chlorophyll (a + b) per  $\text{dm}^2$  for Caprock, Blueboy, and Pronto, respectively. The mean chlorophyll content was significantly greater in the open field at 0.02, 0.01, and 0.01 levels for Caprock, Blueboy, and Pronto, respectively.

Results of experimental work (8, 9) show a less-than-proportional increase in absorption of  $\text{CO}_2$  with increasing chlorophyll content. At low chlorophyll concentrations, a small difference in chlorophyll content will have a large effect but at high concentrations it will make very little difference. Even at low light intensity, increasing the chlorophyll concentration above about  $5 \text{ mg dm}^{-2}$  had little further effect. Apparently any fully green leaf has an excess of chlorophyll even for light intensities approaching the compensation point.

Although the leaves in open field were noticeably greener and contained 32% more chlorophyll ( $5.74 \text{ mg dm}^{-2}$  of a + b) than leaves in shelter ( $4.35 \text{ mg dm}^{-2}$  of a + b), we do not know to what extent the difference in chlorophyll content influenced  $\text{CO}_2$  assimilation.

Effects of shelter on leaf water potential (LWP) for each variety were investigated late in May 1972. Data shown (Fig. 4) are average LWPs from samples of four flag leaves. Satanta, Parker, and Blueboy varieties generally had higher LWP in shelter than in open field. That usually was reflected in higher photosynthetic rates in shelter compared with open field in those varieties (Table 2). In contrast, Caprock LWP was not affected by shelter; neither was its photosynthetic rate.

Over all days, there was no significant difference in LWP among varieties in the open field, but there was a difference among varieties in the shelter area (i.e., some varieties responded to shelter, others did not). Satanta responded to shelter consistently and



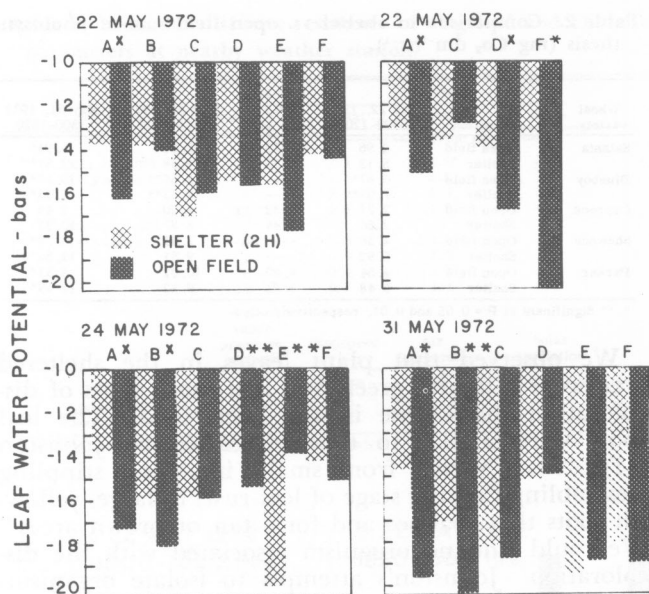


Fig. 4. Shelter vs. open-field leaf-water potential of six wheat varieties: 'Satanta,' 'Blueboy,' 'Caprock,' 'Parker,' 'Shawnee,' and 'Pronto' for A, B, C, D, E, and F, respectively. (x, \*, and \*\* indicate statistically significant differences at  $P = 0.10$ ,  $0.05$ , and  $0.01$  levels, respectively.)

its LWP ranged from  $-13.0$  bars in shelter to  $-19.6$  bars in open field. Frank and Willis (6) found that under stress environment, LWP of 'Waldron' variety of spring wheat was usually 2 to 4 bars higher when sheltered by slat-fence than in open field. Average standard deviation of LWP in open field was 1.54 bars; in shelter, 1.48 bars. Highest standard deviations in LWP occurred in open field with high wind-speeds and occasionally exceeded 2.0 bars.

Our results suggest wheat varieties vary in their response to similar microclimates, and that LWP measurements can be used to distinguish between varieties sensitive to and those insensitive to small changes in microclimate. Further, in sensitive varieties such as Blueboy, a small increase in LWP can result in a significant increase in photosynthesis rate (Table 2), even under low stress conditions.

Hourly LWP measurements were made on Blueboy wheat on June 1, 1972, (Fig. 5). Lowest values of LWP occurred when transpiration exceeded absorption of water early in the morning. The minimum LWP in the sheltered area was an hour later than the minimum in open field. Before noon, LWP in the sheltered area generally remained above that in the open field, and the photosynthesis rate was also higher in shelter than in open field (Fig. 3). After noon, however, LWP in the open field briefly exceeded that in the shelter, and a corresponding change in photosynthesis rate was observed. From 1500 hours on, shelter and open field had similar LWPs, which increased rapidly with stomatal closure in the evening.

The hourly measurements of LWP illustrate the dynamic state of water in the plant throughout the day and its interaction with the microclimate. The measurements also illustrate that interpreting effects of barriers, based on single sampling periods, must be done cautiously. Finally, the data show a close cor-

Table 3. Height and leaf area in open field and shelter, compared, May 25, 1970, Pawnee. Data for other varieties were obtained May 25, 1972. Height and leaf area data were not obtained in 1971.

Wheat variety	Position	Height		Flag leaf		
		Flag leaf	Head	Area	Area index	
		cm				
		cm <sup>2</sup>				
Pawnee	Open field	73.5*	96.8**	---	1.15**	
	Shelter	79.5*	107.6**	---	1.65**	
Pronto	Open field	71.9*	93.9**	10.1 NS	0.90 NS	
	Shelter	80.0*	106.4*	11.8 NS	1.05 NS	
Caprock	Open field	65.7 NS	82.4 NS	11.1 NS	0.88 NS	
	Shelter	65.7 NS	84.5 NS	11.4 NS	0.90 NS	
Blueboy	Open field	70.0**	92.1**	18.9*	1.44*	
	Shelter	77.7**	101.5**	24.0*	1.83*	
Parker	Open field	70.3 NS	94.6**	10.0*	0.85 NS	
	Shelter	74.2 NS	101.9**	12.5*	1.06 NS	
Satanta	Open field	67.7 NS	87.7 NS	10.1 NS	0.74 NS	
	Shelter	69.5 NS	91.8 NS	10.3 NS	0.76 NS	
Shawnee	Open field	76.6**	107.7**	15.2 NS	1.51 NS	
	Shelter	84.1**	120.7**	17.1 NS	1.70 NS	

\*, \*\* Difference between open field and shelter significant at  $P = 0.05$  and  $0.01$ , respectively.

respondence between LWP and photosynthesis rate throughout the day.

The difference in vegetative growth between shelter and open field was especially pronounced in 1970 with Pawnee variety. The difference developed during about a 3-week period in May when warm southerly winds prevailed. On May 25 the height to heads was 11 cm more in the sheltered area. The leaf-area index of the flag leaves in the shelter was 43% greater than those in the open field (Table 3).

Height and flag leaf area for open field and shelter on May 25, 1972, for the six varieties under study are compared in Table 3. Height to base of flag leaf and head was significantly greater at 1% level for Blueboy and Shawnee in the sheltered area than in open field. Parker and Pronto were also significantly taller, but Caprock and Satanta were non-significantly taller.

The mean area of flag leaves was greater for plants in the shelter than in open field for all varieties, but the difference was significant for only Pronto, Blueboy, and Parker.

The tall plants in the sheltered area were prone to lodge.

Though wheat plants in their vegetative growth stage responded favorably to barrier-induced microclimate, yield response was less predictable. In 1970 the lowest grain yield (Table 3) occurred in areas where the plants had appeared most vigorous during vegetative development. After the kernels were about one-fourth filled (May 25), a wet period started, and by June 4, 18 cm (7 in) of rain had fallen. This wet

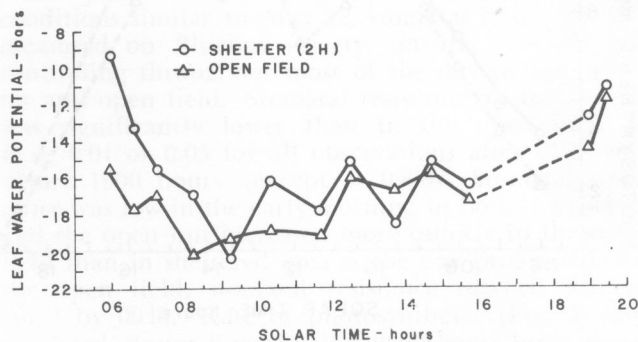


Fig. 5. Water potential of flag leaves in 'Blueboy' wheat on June 1, 1972.

Table 4. 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.

Position*	Year			Avg 1971-1972
	1970	1971	1972	
	q/ha			
-12.5	----	41.5	33.3	37.4
-8.0	14.4	41.8	33.2	37.5
-4.5	----	43.0	34.0	38.9
-2.0	9.3	38.3	32.8	35.9
2.0	6.3	40.7	31.5	36.1
4.5	13.0	43.3	33.9	38.6
8.0	----	44.0	34.1	39.1
12.5	14.5	39.4	35.6	37.5

\* 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.

period impaired the filling of grain heads and was conducive to incidence of disease and physiological flecking. Wheat leaf rust badly infested the entire field. But damage and lodging were severer in the sheltered area, where by June 8 all leaves below the flag leaf had turned brown and shriveled (to about half their area on May 25). The flag leaf also was infested badly with rust and had lost much of its green color.

As a result of many favorable factors for wheat production, the 1971 Kansas wheat yield was the highest on record. The yield in our experimental plots averaged 14 and 42 q/ha for 1970 and 1971, respectively, on the same field site. With favorable weather and absence of hot winds, the barrier influence on yield was minimal, as expected (Table 4). Comparing treatment means shows relative position to barrier only slightly influenced the differences in yield. Yield data of 1971 illustrate a possible trend: lowest yielding positions were close to and far from the fence; yield at intermediate positions apparently was favorably influenced by the barrier. McMartin et al. (15) harvested spring wheat for 3 years from sample areas at regular intervals from 14 single-row shelterbelts in North Dakota. They found maximum yield at 5H. If the area occupied by the tree row was not included, the yield for the area 1H to 13H was the same as the check area.

An analysis of variance of the 1972 yield data showed no difference in yield with position from the barrier.

From the 3 years of yield data, we conclude that although the microclimate induced by a wind barrier promotes vegetative growth of wheat, grain yields are not consistently increased for the typical growing environment at Manhattan, Kansas.

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