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REDUCING TURBULENT TRANSFER TO INCREASE WATER-USE EFFICIENCY

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ABSTRACT

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Because of limited precipitation in the Great Plains, it is necessary to increase crop water-use efficiency (WUE) to increase crop yields. However, to understand how windspeed affects WUE, both the energy budget and photosynthesis rate must be considered. On the leaf scale, an incremental change in windspeed changes transpiration most at windspeeds less than 100 cm sec^{-1}. Increasing windspeed may increase, decrease, or have no effect on transpiration, depending upon stomatal resistance of the leaf. High WUE often is associated with small leaves, which have significant stomatal resistance. On a canopy scale, the transfer of sensible heat to the surface (advection) is a significant source of energy used in evapotranspiration (*ET*). The amount of advection varies with season, crop, and location in the Great Plains, but in some crops a third of the energy used in *ET* comes from advection. In such cases, reducing turbulent exchange with the atmosphere should significantly increase WUE. Using shorter crops or sheltering a crop with windbreaks or a few interspersed tall plants can reduce turbulent exchange with the crop. To realize the full potential from reducing turbulent exchange, crops must be adapted specifically for a shelter environment. Such adapted plants would maintain high WUE in shelter to conserve water until needed for critical growth periods and would not grow tall enough to induce lodging. Adapted tall plants are also needed to provide shelter. These should be compatible with the sheltered crop, produce little shade under low light, have high WUE, and reach heights of at least 20 cm above the sheltered crop.

INTRODUCTION

Because precipitation is limited in the Great Plains, crop water-use efficiency (WUE) must be increased to increase crop yields. Reducing turbulent transfer offers some potential for increasing WUE because it is the "linking" mechanism between crop surface and bulk atmosphere. In this paper the effects of turbulent transfer on both leaf scale and large scale are briefly reviewed, and the use of short crops, wind barriers, or interspersed tall plants to reduce turbulent transfer is considered. Because the Great Plains encompasses a wide range of plant species and climatic conditions, both the need for windspeed modification and its success often vary.

EFFECTS OF WIND: LEAF SCALE

For a leaf exposed to full sunlight, the effect of increasing windspeed on transpiration and photosynthesis is not obvious. Thus, even on this scale, energy budget and photosynthesis calculations are necessary to arrive at WUE. Gates and Papian (1971) gave the following equation for the energy budget of a leaf:

$$Q_a = \epsilon\sigma T_\ell{}^4 + k_1 \left(\frac{U}{D}\right)^{\frac{1}{2}} (T_\ell - T_a) + \frac{{}_sd_\ell - (\text{r.h.})\, {}_sd_a}{Lr_s + k_2 \left[(W^{.20} D^{.35})/U^{.55}\right]} \quad (1)$$

where Q_a is total flux of incident radiation in cal. cm^{-2} min^{-1}; ϵ is emissivity of the leaf surface; σ is Stefan-Boltzman constant (equal $8.132 \cdot 10^{-11}$ cal. cm^{-2} min^{-1} $°K^{-4}$); T_ℓ is leaf temperature, k_1 and k_2 are coefficients (if $W > D$ or $W = D > 5$ cm or $D > 10$, then $k_1 = 10 \cdot 10^{-3}$ and $k_2 = 35 \cdot 10^{-3}$; if $W < D \leq 10$ cm or $W = D \leq 5$ cm, then $k_1 = 16.2 \cdot 10^{-3}$ and $k_2 = 26 \cdot 10^{-3}$); U is windspeed in cm sec^{-1}; D is leaf dimension parallel to the wind direction in cm; W is leaf dimension perpendicular to D in cm; T_a is air temperature in °C; L is latent heat of evaporation in cal. gm^{-1}; ${}_sd_\ell$ and ${}_sd_a$ are saturation densities of water vapor in gm cm^{-3} at leaf temperature and air temperature, respectively; r.h. is relative humidity of the air; and r_s is internal diffusion resistance in min cm^{-1}.

The effect of windspeed on transpiration of two sizes of sunlit leaves was calculated using eq.1 (Fig.1). At low r_s, transpiration is proportional to windspeed; at high r_s, transpiration is inversely proportional to windspeed; and at an intermediate r_s, windspeed changes have little effect on transpiration. Those effects, easy to illustrate on the leaf scale, also have been noted on the canopy scale (Van Bavel et al., 1967). The overshadowing importance of stomatal resistance also is illustrated in Fig.1, even though the range of resistances shown is not large. Incremental changes in windspeed cause the largest changes in transpiration at windspeeds of less than 100 cm sec^{-1}. Finally, if all else is equal, wide leaves transpire more than narrow leaves do.

The usual argument for reducing windspeed is that calmer air will impede both CO_2 and water exchange. Because resistances are greater in the CO_2 exchange path than in the transpiration path, however, the percentage reduction in transpiration should be greater than the percentage reduction in CO_2 exchange. The net result would be increased WUE with decreased windspeed. Waggoner (1969) tested this hypothesis in a simulation model of a plant canopy having moderate stomatal resistance. He found that decreasing windspeed from 1,225 cm sec^{-1} to 22 cm sec^{-1} decreased photosynthesis by 2% but decreased transpiration by 15%. In field experiments, however, stomates often open wider in the sheltered area than in open field. Consequently, water use in shelter and open field is often similar, but WUE still remains greater in the shelter (Rosenberg and Powers, 1970).

High windspeeds also may affect other leaf processes. Todd et al. (1972) found that windspeeds exceeding 3.6 m sec^{-1} increased respiration in many crop plants, and that respiration increases of 20 to 40% were typical at windspeeds of 7.1 m sec^{-1}. High windspeeds also commonly decrease leaf areas; however, the root/shoot ratio may be increased (Whitehead and Luti, 1962). Not all shelter effects are beneficial. Chlorophyll content of flag leaves of several winter wheat varieties averaged 24% less in sheltered plants than in plants grown in the open field (Skidmore et al., 1974). Sheltered plants also may have a higher incidence of disease, pests, and lodging (Marshall, 1967).

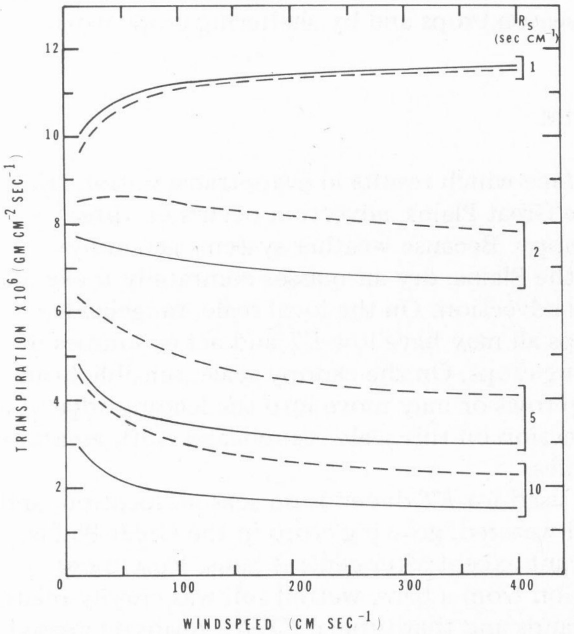

Fig.1. Effect of windspeed on transpiration for 1 x 10 cm (solid lines) and 10 x 10 cm (dashed lines) leaves, where first value is leaf dimension parallel to the airflow. Other conditions are: T_a = 30°C; r.h. = 60%; Q_a = 1.15 cal. cm^{-2} min^{-1}.

Both theory and experiments show that decreasing the windspeed often increases WUE; however, many data show that in the Great Plains environment dry-matter production is often proportional to transpiration (for a review, see Olson et al., 1970), which implies that plant leaves are maintaining a constant WUE over the range of environmental conditions encountered. This may be caused by breeding plants for wide adaptability in the Great Plains, but it also occurs elsewhere. For example, Taylor and Sexton (1972) found that Musaceae leaves in the tropics maintained a constant WUE during both wet and dry seasons, even though stomatal resistances ranged from 1 to 30 sec cm^{-1}

between seasons. They also showed, theoretically, that higher WUE could have been obtained in the dry season by decreasing the leaf size. Highest WUE was associated with small leaves and high stomatal resistances.

On the leaf scale, WUE apparently can be increased at least two ways. The first is to increase the ability of leaves to adjust to their environment by such mechanisms as leaf curl, leaf tilting, and selective stomatal closure. Selective stomatal closure in a canopy can conserve water with little reduction in photosynthesis (Waggoner, 1969). Further, the mechanisms can combine to produce lowest r_s (and probably maximum photosynthesis) at different levels in canopies under similar environments, as demonstrated by soybean and sorghum data of Teare and Kanemasu (1972). A second method for increasing WUE is to restrict the range of environments to which a leaf must adapt; this can be done by planting short-season crops and by sheltering crops from wind.

EFFECTS OF WIND: LARGE SCALE

Sensible heat flux to the surface which results in evapotranspiration (*ET*) is often called advection. In the Great Plains, advection occurs on three scales — regional, local, and canopy. Because weather systems generally move from west to east across the Plains, dry air masses commonly move into humid regions, causing regional advection. On the local scale, rangelands, fallow fields, and maturing crops all may have low *ET* and act as sources of sensible heat for actively growing crops. On the canopy scale, sensible heat may be generated between crop rows or may move into the leading edge of a canopy from nearby areas; advection on this scale complicates both measuring and modeling *ET* in crop canopies.

The amount of sensible heat used for *ET* depends on season, location, and kind of crop. However, for well-watered, growing crops in the Great Plains, advection appears to be significant except after general rains. Rosenberg (1969a) reported that evaporation from a bare, wetted soil was closely related to the wetness of surrounding lands and that typical ET/R_n ratios decreased to 0.8—0.9 only when surrounding lands were wet (R_n is net radiation). Rosenberg (1969b) also reported that in eastern Nebraska, dry winds from north through southwest during late spring and early summer frequently caused *ET* in alfalfa to exceed R_n by 30 to 80%. However, in midsummer *ET* was nearly equal to R_n because of the humid, prevailing southerly winds.

The amount of advected energy also varies sharply from year to year. Advected energy of significant duration has occurred in eastern Kansas during only one spring in the last 3 years. In 1970, 3 weeks of warm southerly winds caused sheltered winter wheat to be 11 cm taller and to have 44 and 10% greater leaf-area indices of flag and all leaves, respectively, than wheat in open field (Skidmore et al., 1974).

Hanks et al. (1968) used lysimeters to measure *ET* from fallow, sudangrass, native grass, sorghum, winter wheat, oats, and millet at Akron, Colorado.

They concluded that when soil moisture was limited, ET from all those crops was less than R_n but that when soil moisture was not limited, ET was highly dependent on the crop. They observed few periods when part of R_n in native grass was not going to sensible heating of the air. In contrast, they observed a 20-day period when a third of the energy for ET in oats came from advective energy.

The potential for modifying turbulent transport for higher WUE varies over the Great Plains. Skidmore and Hagen (1973) used a form of van Bavel's combination equation (Van Bavel, 1966) to compute potential evapotranspiration (ET_p) at two central Great Plains locations (Dodge City, Kansas, and Bismarck, North Dakota) for the 1960's. In addition, they calculated the percentage reduction in ET_p that a 40% porous barrier would produce (Table I). Average ET_p was 410 ly day^{-1} at Bismarck and 600 ly day^{-1} at Dodge City from May through September. ET_p was usually slightly higher in the shelter at Dodge City than in the open field at Bismarck. Potential for a barrier to reduce ET_p was higher at Dodge City, partly because the higher preponderance of southerly winds — 73% of the time at Dodge City, compared with 52% at Bismarck. Apparently, advected energy in the central Great Plains has no strong seasonal influence on ET_p as it does in the eastern Great Plains. As our understanding of advection increases, we should be able to produce charts of the Great Plains delineating (by season and area) where reduced ET_p (increased WUE) is most likely from turbulent-transfer modification.

TABLE I

Average monthly reduction in calculated potential evaporation in area 0-to-10 barrier heights north of east—west oriented barriers near Dodge City, Kansas, and Bismarck, North Dakota, 1960—1969; the north side was the leeward side 73 and 52% of the time for Dodge City and Bismarck, respectively

(Data from Skidmore and Hagen, 1973)

Month	Dodge City		Bismarck	
	all days (%)	leeward days only (%)	all days (%)	leeward days only (%)
May	29	39	16	27
June	29	36	13	22
July	32	36	13	23
August	32	37	17	27
September	31	39	21	31
Average	30.6	37.4	16.0	26.0

MODIFYING CROP HEIGHT

Turbulent transfer possibly can be decreased by decreasing crop height. The interaction of windspeed and crop height is described by the atmospheric diffusion resistance (r_a)as:

$$r_a = \{\ln [(Z - d)/Z_0]\}^2/(Uk^2) \tag{2}$$

where Z is height above the surface, d is displacement length, Z_0 is roughness length, U is windspeed at Z, and k is Von Karman's constant ($\simeq 0.4$). At low windspeeds the drag coefficient decreases as windspeed increases; hence, crops often become aerodynamically smoother as windspeed increases. Szeicz et al. (1969) found that Z_0 decreased by 1/2 as windspeeds increased from 1 to 3m sec^{-1} (at 170 cm height) above pliable agricultural crops. Consequently, for a given crop, r_a is relatively conservative at low windspeeds.

Both d and Z_0 apparently depend on crop height (h). For many crops $Z_0/h \simeq 0.1$, but for wide-leafed crops such as sugarcane and maize $Z_0/h^{1.1} \simeq 0.025$ (Szeicz et al., 1969): $d/h \simeq 0.64$ (Stanhill, 1969). These results indicate that an effective way to increase r_a of flexible crops is to decrease crop height. For typical small grain crops, r_a can be increased more than 20% by reducing h by 20 cm. Field experiments also have confirmed that decreasing crop height can decrease ET, particularly under advective conditions (Stanhill, 1965; El Nadi and Hudson, 1965).

The strong dependence of Z_0 on crop height is not easy to explain. Because the upper layer of most crops absorbs the drag on the canopy, little momentum is transmitted to lower layers. In fact, calculations of canopy flow from a reasonable model (Seginer and Rosenzweig, 1972) suggest that height changes of upper layers of a rigid, uniform canopy should not change Z_0 and d (Fig.2).

Perhaps the flexibility of many crops permits them to absorb more drag with height, in a manner similar to waves. We can calculate the effect of

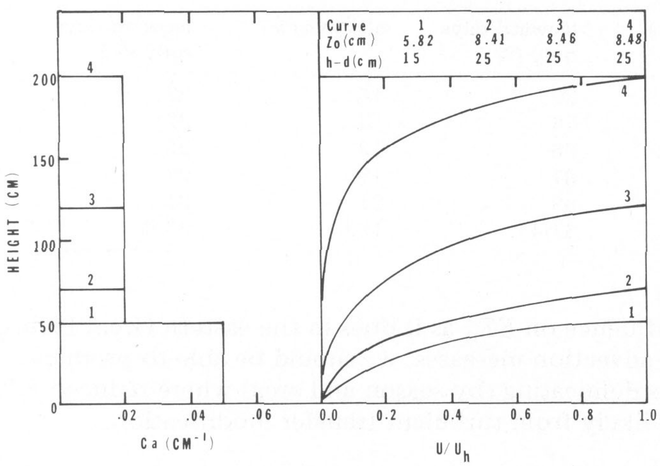

Fig.2. Vertical distribution of product of drag coefficient and leaf area per unit volume (Ca); vertical distribution of relative windspeed (U/U_h) along with calculated profile parameters Z_0 and ($h - d$) where h is canopy height (after Seginer and Rosenzweig, 1972).

changing plant height on plant deflection to see if it is significant. The velocity profile in simple canopies often follows the form (Shinn and Cionco, 1973):

$$U = U_h \exp[\alpha(Z/h - 1)] \tag{3}$$

where U is windspeed at height Z, U_h is windspeed at canopy top, and α is a coefficient characteristic of the crop. Momentum diffusivity is often assumed to decrease with depth in the canopy, similar to the velocity decrease (Waggoner, 1969). Consequently, the drag (D) at any point in the canopy can be described by:

$$D = D_m \exp[2\alpha(Z/h - 1)] \tag{4}$$

where D_m is the maximum drag on the top increment of the canopy.

Deflection (S) of a cantilever cylinder can be calculated from the equation (Miller and Doeringsfeld, 1962):

$$EI\, d^2S/dZ^2 = M(Z) \tag{5}$$

where E is the modulus of elasticity, I is moment of inertia, and $M(Z)$ is the bending moment in the stalk caused by the drag distribution.

Assuming that the stalks have uniform diameter, the solution for the preceding equation can be written as:

$$ES/D_mB = h^4/I \tag{6}$$

where B is a constant, $I = (\pi/4)(r_2)^4$ for solid stalks, and $I = (\pi/4)(r_2{}^4 - r_1{}^4)$

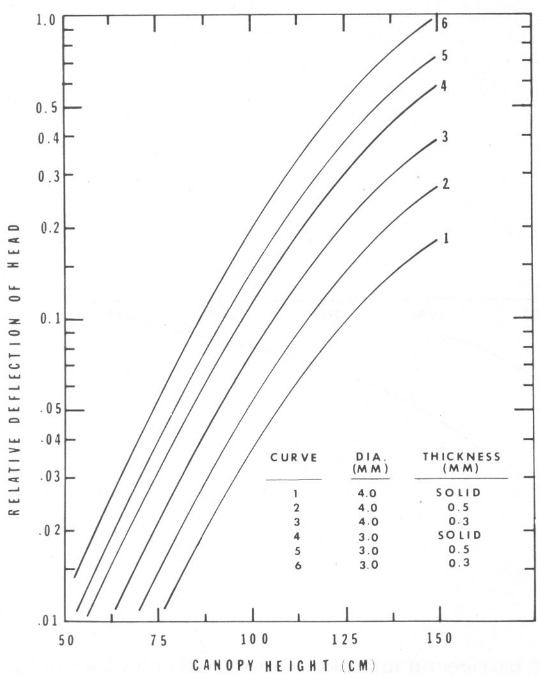

Fig.3. Relative deflections of wheat stalks of various diameters, thicknesses, and heights.

for hollow stalks (r_2 is outer and r_1 is inner stalk radius). Wheat stalks have nearly uniform diameter with height, and relative deflections among typical heights and diameters are shown in Fig.3. Relative deflections are shown because water content strongly influences absolute flexibility (Hancock and Smith, 1963). The absolute deflection of small grains decreases with time because water content drops sharply between soft dough and maturity.

Because deflection is proportional to the fourth power of height, the results (Fig.3) show that decreasing plant height by 20 cm can sharply reduce a plant top's deflection. In addition to decreasing deflection, decreasing crop height also decreases a plant's bending moment; Consequently, less material is needed in the stalk to prevent lodging. Though deflection is less in solid-stem than in hollow-stem wheat varieties, solid stems use plant material inefficiently for this purpose. For example, the material in the solid stalk in curve *4* is about twice that of the larger, but stiffer, hollow stalk in curve *3*. Some experimental work also has shown a negative correlation between wheat yield and stem solidness (McNeal et al., 1965).

MODIFICATION BY WIND BARRIERS

The subject of wind barriers, a popular method for reducing turbulent transfer, has been reviewed recently (Marshall, 1967; Brown, 1969; Skidmore and Hagen, 1970a). Frequently observed barrier effects are summarized in Fig.4.

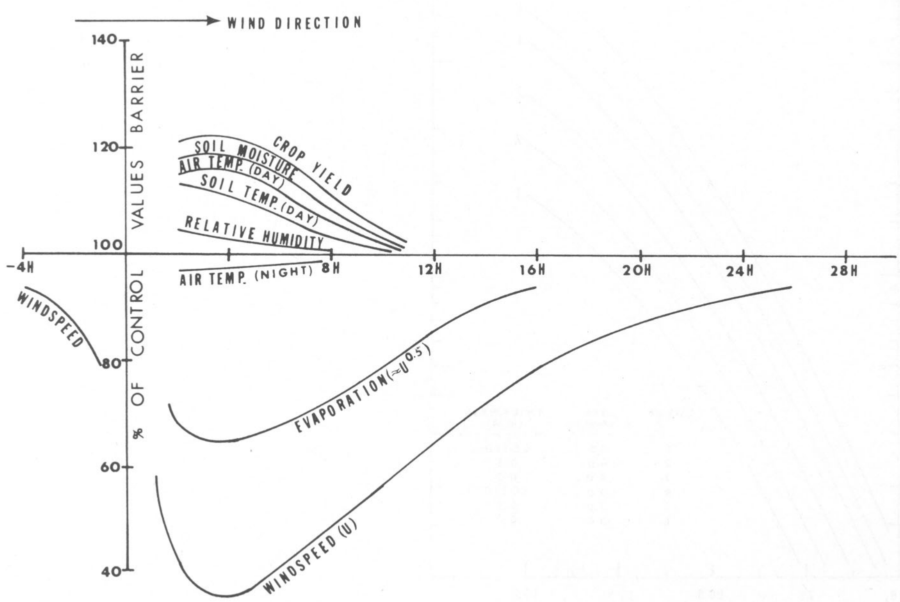

Fig.4. Summary diagram of the effect of barriers on micrometeorological and other indicated factors (after Marshall, 1967).

Much effort has gone into measuring the windspeed reduction by barriers of various porosity (Jensen, 1954; Van Eimern et al., 1964). Recently, research also has included measuring turbulence generated by wind barriers (Hagen and Skidmore, 1971: Plate, 1971). These measurements show that: the zone of maximum turbulence begins near the barrier top in the zone of maximum wind shear; the turbulence zone then diffuses upward and downward in the leeward direction. Close to the surface, however, turbulence is largely controlled by the nature of the surface, so that the intensity within a sheltered plant canopy is similar to that in the open field canopy (Table II).

TABLE II

Measurements of turbulence intensity (i.e., R.M.S. windspeed/mean windspeed) near a 40%-porous wind barrier in fields of winter wheat (112 cm tall) and soybeans (70 cm tall windward and 90 cm tall leeward)
(Unpublished data of Hagen)

Crop	Height above surface (m)	Position			
		windward	leeward		
			02h	06h	12h
Soybeans	64	0.46	0.45	0.50	0.50
	40	0.43	0.41	0.41	0.50
	25	0.38	0.47	0.39	0.46
Wheat	117	0.48	0.46	0.53	0.42
	64	0.39	0.42	0.43	0.49
	40	0.39	0.42	0.43	0.43

In contrast to turbulence intensity, the mean flow close to the surface is influenced by the presence of a barrier. We have begun to simulate barrier effects on two-dimensional airflow in the computer; Fig.5 shows some simulated and measured mean vertical velocities leeward of a 40%-porous barrier. In this case, the simulator used a smaller surface roughness than was present in the field; consequently, the point of zero vertical flow is closer to the barrier in the simulated case. Both results show, however, that mean flow accounts for much of the vertical transfer leeward of a barrier close to a short grass surface. Further, the large downward flow beyond $8H$ (H is barrier height) helps explain why air temperatures under lapse conditions are often lower (Woodruff et al., 1959) and relative humidity is lower (Skidmore and Hagen, 1970b) beyond $8H$ than in open field.

Soon, we hope to add the energy equations to our simulation model to simulate the energy budget in the sheltered area. Unfortunately, some of the limitations that plague simulators in the open field are further complicated when a barrier is added. As Lemon et al. (1971) note, "probably the most difficult problem to resolve is that of predicting how stomates open and close under drought stress . . ."

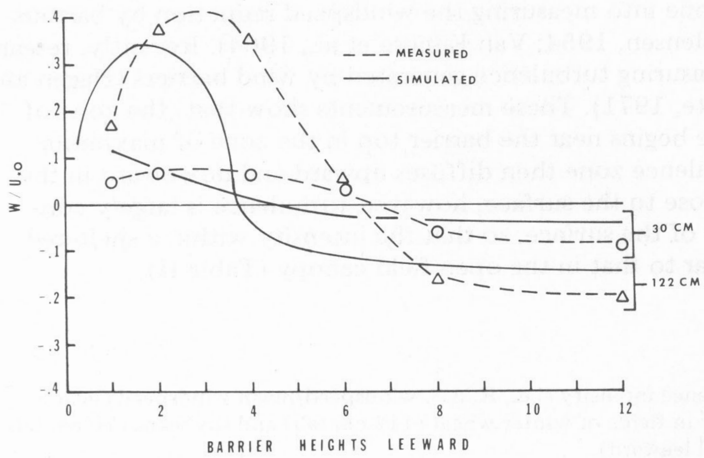

Fig.5. Measured and simulated vertical velocity (W) at 30 and 122 cm above the surface (scaled by open-field friction velocity (U_{*0})) leeward of a 40%-porous barrier. (Unpublished data of Hagen.)

While progress has been made in understanding barrier effects, very little has been done to select varieties adapted to the shelter environment. Often, we simply assume that crops adapted to the open field should yield better in the shelter. However, measurements show that even on a day with low windspeed, various varieties of wheat respond to shelter differently (Fig.6). The high photosynthesis rates in shelter for Satanta, Blueboy, and Parker were accompanied by favorable water potentials in the shelter. For Parker, water potential in the open was also high but this was maintained by high stomatal resistance. In contrast, Caprock did not respond to shelter influence on the day shown or on other days with similar environmental conditions (Skidmore et al., 1974).

The choice of crop variety for a shelter probably depends on water available. When soil moisture is expected to be adequate throughout the growing season, a variety that maintains a high photosynthesis rate per unit land area will most likely produce highest yields. However, for most dryland grain crops, lack of water limits production, and highest WUE is obtained from additional water when crops are heading (Fig.7). Thus, the highest yielding dryland varieties may be those that minimize vegetative growth and conserve water until the critical period. In addition, such varieties should remain short to avoid lodging and should have high disease resistance.

MODIFICATION WITH TALL PLANTS

An untried way to shelter a crop is to use a few tall barrier plants interspersed among the lower crop to be sheltered. How tall roughness elements shelter the intervening area is illustrated by measurements of Lyles et al. (1972)

in the wind tunnel (Fig.8). They placed small, uniformly spaced cylinders on the tunnel floor and filled the intervening spaces with sand. As the cylinders were exposed by wind erosion of the sand, total drag on the surface increased but drag on the intervening sand decreased. (Total drag is the sum of drag on the roughness elements and drag on the intervening area.)

Seginer and Rosenzweig (1972) used a numerical model to investigate sheltering with roughness elements. They assumed values for the drag coefficient (C), surface area per unit volume (a), and mixing length in each layer of the canopy. (In the case of cylinders, a is equal to the projected area per unit volume normal to the flow, and C is nearly independent of cylinder spacing when $1/b\sqrt{n} > 10$; b is diameter and n is number per unit area.) They then computed normalized velocity profiles in the canopy to use in calculating friction velocity (U_*) and Z_0. Some of their results, along with those of Lyles

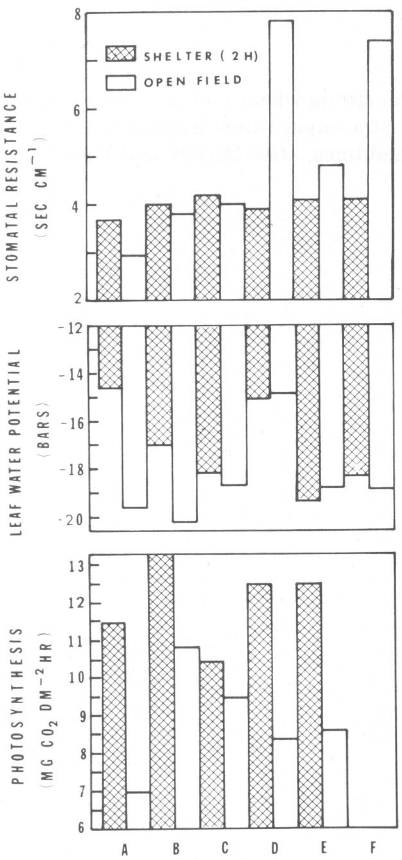

Fig.6. Shelter vs. open-field plant response of winter wheat varieties: Satanta, Blueboy, Caprock, Parker, Shawnee, and Pronto (*A*, *B*, *C*, *D*, *E*, and *F*, respectively) on afternoon of May 31, 1972 (Skidmore et al., 1974).

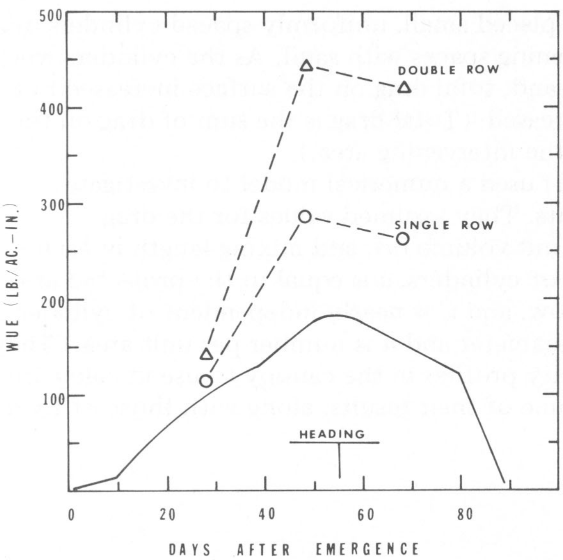

Fig.7. Effect of added inch of rainfall during season on spring wheat yields in the northern Great Plains (solid line, after Bauer, 1972) and effect of a single 4-inch irrigation during season on single- and double-row grain sorghum (dashed lines, after Musick and Dusek, 1969).

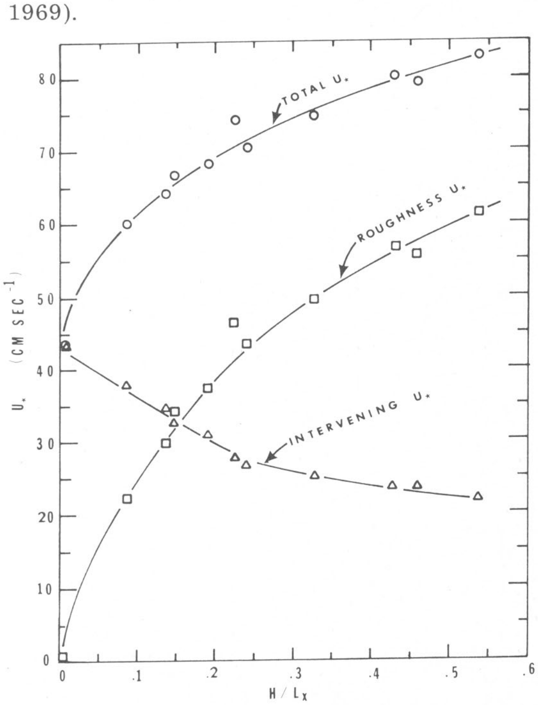

Fig.8. How friction velocity (U_*) changes as a surface stabilizes by exposing nonerodible cylinders 1.6 cm in diameter. Distance between cylinders (L_x) is 3.49 cm (after Lyles et al., 1972).

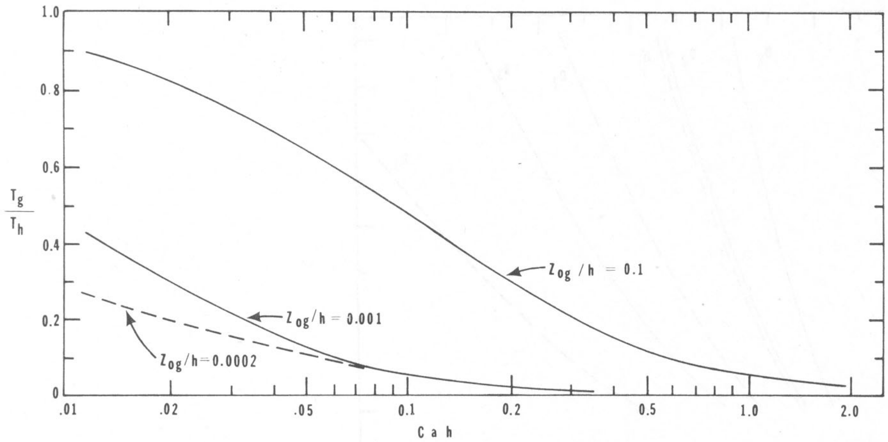

Fig.9. Ratio of ground (T_g) to total shear stress (T_h) at canopy height (h) for various amounts of cover and three ground roughness lengths (Z_{0g}/h). (Solid lines from calculations of Seginer and Rosenzweig, 1972; Dashed line from Lyles et al., 1972.)

et al. (1972), are shown in Fig.9. Obviously, as roughness of the lower boundary (Z_{0g}) increases, it absorbs a larger proportion of the total drag.

If the lower boundary is a dense crop canopy instead of the ground surface, the results in Fig.9 can be used to calculate spacing of a tall crop necessary to provide various amounts of shelter. In that case, $Z_{0g}/h = 0.1$ would appear realistic. For an example, let $T_g/T_h = 0.5$ and 0.65, which corresponds to *Cah* of 0.1 and 0.5, respectively. At moderate and high windspeeds, the drag coefficient of cylinders is about 1.2, though for a narrow leaf normal to the wind it may reach 2.2. If we use the conservative drag coefficient for cylinders, the heights and spacings necessary to reduce shear 50 and 35% on the sheltered crop are shown in Fig.10.

The results are conservative for plants with leaves and heads. For headed wheat with a flag leaf, the increased drag due to head and leaf will reduce shear 35% with only a spacing of 17 cm and a height of 25 cm above the lower crop. This result is between D_1 and D_2. The 17 cm spacing corresponds to about 4% of the usual plant population in wheat. Thus, it is possible to provide substantial shelter to a low crop with only a small percentage of tall plants, provided the tall plants are at least 20—30 cm above the sheltered crop.

A system of shelter using interspersed plants has the obvious advantage that it is not affected by wind direction. It should work best to shelter crops that are nearly light saturated, so that slight shading from the barrier crop would not substantially decrease photosynthesis in the sheltered crop. In addition, the crops should be compatible and closely adapted to their respective environments. For example, sheltering alfalfa with a tall grass might increase alfalfa's WUE without affecting WUE in the grass, which normally maintains high stomatal resistance. Some research results show that nontranspiring elements reduce *ET*. For example, Fritschen and Van Bavel (1964) found that non-

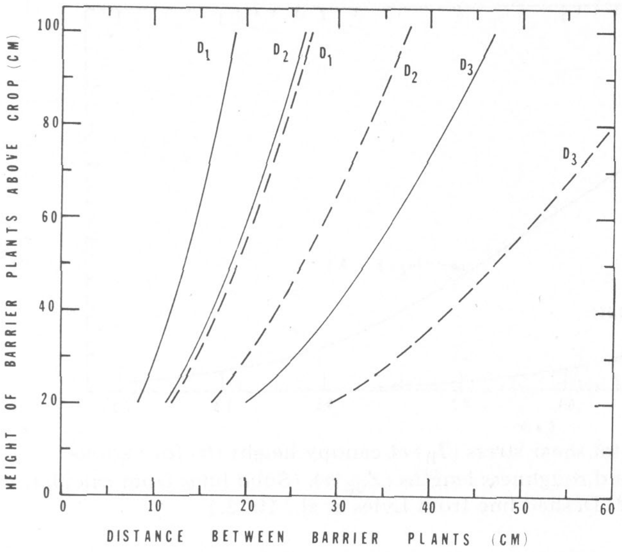

Fig.10. Spacing and height of barrier plants (≃ cylinders) necessary to reduce shear stress on the sheltered crop 50% (solid lines) and 35% (dashed lines) where diameters D_1 = 0.3, D_2 = 0.6, and D_3 = 2.0 cm.

transpiring inflorescences in sudangrass could convert radiant energy to sensible heat, little of which was transferred to lower transpiring leaves.

It also may be possible to use tall and semidwarf varieties of the same crop to produce increase WUE. In this case, the tall variety should have small, upright leaves and a rigid stalk. Some of these possibilities deserve further investigation.

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