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WIND REDUCTION BY A HIGHLY PERMEABLE TREE SHELTER-BELT*

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ABSTRACT

Miller, D. R., Rosenberg, N. J. and Bagley, W. T., 1975. Wind reduction by a highly permeable tree shelterbelt. Agric. Meteorol., 14:321—333.

Vertical wind profiles above dryland wheat fields were measured simultaneously in the open and at horizontal distances of $2H$, $4H$, and $8H$ (H = shelterbelt height) in the lee of a highly permeable tree shelterbelt. Two-dimensional wind reduction patterns in the lee of the shelterbelt are presented. The effects of measurement height and atmospheric stability on the horizontal wind profiles (wind reduction curves) are presented. The wind reduction curves were most consistent during neutral atmospheric conditions. Drag coefficients for the shelterbelt were calculated utilizing the wind reduction curve data in a model by Seginer and Sagi (1972). Shelterbelt drag, characterized by the integrated wind reduction curve or a drag coefficient, is suggested as a practical basis for comparison of the effectiveness of different field shelterbelts. Utilization of the drag coefficients showed the 4-year old highly permeable windbreak was already 1/3 as effective as a fully grown shelterbelt.

INTRODUCTION

Only about 20% of the farms and ranches in the U.S. Great Plains that need shelterbelts have adequate ones (Ferber, 1969). This reluctance to plant and maintain field shelterbelts continues in spite of the usefulness of wind shelter for decreasing soil erosion, increasing crop yield (Stoeckeler, 1962; van Eimern, 1964; Bagley, 1964, and others) and decreasing water use (Miller et al., 1973; Brown and Rosenberg, 1971). A reason often given for not planting shelterbelts is the long period of time invested before the trees provide effective protection. This study was initiated to examine the effectiveness of a very young, rapidly growing tree shelterbelt.

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As Van Eimern (1968) noted, a major obstacle to systematic comparison of the effects of field shelterbelts is our inability to quantitatively estimate the permeability to wind movement of any given shelterbelt. Grundmann and Niemann (1954) as cited by Von Naegeli (1965), Hogg (1965) and Van Eimern (1968) proposed that the shape of the horizontal wind profile (also called the wind reduction curve) in the lee of shelterbelts be taken as a measure of belt permeability.

Plate (1971) pointed out that the aerodynamic action of a shelterbelt is determined by its drag force on the wind field. The drag force is compensated by a loss of momentum. The drag force is a function of shelterbelt geometry and porosity and is closely related to the horizontal wind profiles (wind reduction curves) in the lee of the shelterbelt as discussed by Seginer and Sagi (1972) who presented a model for calculating windbreak drag from wind reduction curve data. Therefore, the wind reduction curves may be a practical basis for comparison of the effectiveness of different belts. If so, the need for measurement of porosity, or density, may be avoided.

This paper describes the air flow patterns and the variability of the wind reduction curves and calculated drag coefficient in the lee of a young, highly permeable field shelterbelt.

THEORETICAL CONSIDERATIONS

The primary relationships of Seginer and Sagi's (1972) model are repeated here. The readers are referred to the original works for more detailed derivations of theory. The drag exerted by a uniform surface on air flow is proportional to the shearing stress at the surface and inversely proportional to the square of the wind speed. It can be expressed as:

$$C_d = \frac{\tau}{\rho u^2} = \left(\frac{u_*}{u}\right)^2 \qquad (1)$$

where C_d = a shear loss coefficient (drag coefficient); u_* = the reference or friction velocity; u = horizontal wind speed; ρ = air density; and τ = the surface shearing stress.

Assuming that the field boundary layer is thick enough to ensure that the effect of the windbreak on the velocity profile is confined to the constant flux region, and assuming that the wind approaching the barrier at x_1 and the wind some distance in the lee of the barrier at x_2 have the same vertical profile ($u_1 = u_2 = u$), then:

$$D = \int_{x_2}^{x_1} (\tau_o - \tau_s)\, dx \qquad (2)$$

where D = the drag force exerted by the barrier; τ_o = the open field shearing stress; and τ_s = the shearing stress on the sheltered field. τ_s can be estimated from wind profile measurements near the surface within the new boundary layer developed in the lee of the windbreak. If the new profile is logarithmic and the surface roughness parameter (z_o) in shelter is the same as z_o in the open, τ_s can be calculated.

$$\tau_s = \rho\, u_{*_o}^{\ 2}\, \eta^2 \qquad (3)$$

where u_{*_o} = friction velocity in the open; η = the ratio of the wind speed in the shelter to the wind speed in the open;

$$\eta = \frac{u \text{ shelter}}{u \text{ open}} = \frac{u_{*_s}}{u_{*_o}} \qquad (4)$$

Substituting eq. 3 into eq. 2 and expressing horizontal distance in terms of barrier height (H), $h = x/H$, gives:

$$D = \rho\, u_{*_o}^{\ 2}\, H \int_{h_1}^{h_2} (1 - \eta^2)\, dh \qquad (5)$$

To obtain a drag coefficient (C_d), the drag force (D) is divided by the dynamic pressure which is based on a characteristic velocity of the system (u_c) and by the area of the obstacle. The area of the windbreak is represented here by its height (H), because all forces are per unit length. Thus:

$$C_d = D / \tfrac{1}{2}\, \rho u_c^{\ 2}\, H \qquad (6)$$

FIELD MEASUREMENTS

The study was conducted during the period June 4 through June 15, 1970 at the University of Nebraska Field Laboratory near Mead.

The shelterbelt utilized in this study is diagrammed in Fig.1 and pictured in Fig.2. It was planted in 1966 and made up of two rows 137 m long spaced 3 m apart with trees planted 1.8 m apart in the rows. The north row was of alternating cottonwood (*Populus deltoides* Marsh) and eastern redcedar (*Juniperus virginiana* L.). The south row was of alternating pairs of eastern redcedar and scotch pine (*Pinus sylvestris* L.) (Fig.1), The conifers were approximately 1.0—1.5 m tall after four growing seasons, while the cottonwood heights were 2.5—3.3 m (Fig.2). Mortality in the first year after planting necessitated some replanting of cottonwood during the second and third years, which caused some variation in height.

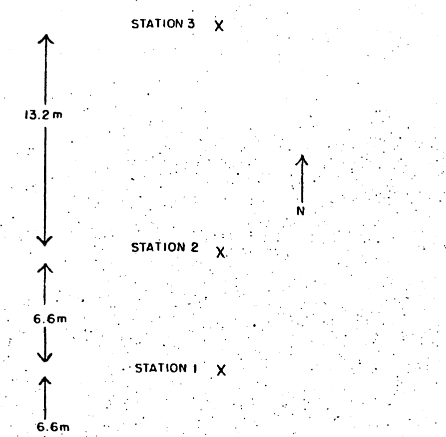

Fig. 1. Instrumentation stations in sheltered wheat field.

The combination of trees in the shelterbelt made it very dense near the ground and very permeable to wind above 1.2 m because of spaces between the faster growing cottonwoods (Fig.2).

Vertical wind profiles were measured simultaneously at four locations in two dryland wheat fields. The wheat was approximately 80 cm tall with full seed heads. Three locations were at distances of $2H$, $4H$ and $8H$ (H = shelterbelt height) north of the east—west oriented shelterbelt. The locations are designated as station 1 at $2H$, station 2 at $4H$, and station 3 at $8H$ in Fig.1. Station 4 was in the center of an unprotected 1.57-ha wheat field 400 m east of the sheltered field. The anemometers in this control plot were located 46 m north from the south edge of the field. A level grassland abutted the control wheat field on the south for several hundred meters.

Horizontal wind speed was integrated with Sheppard type 3-cup counting anemometers (C. F. Casella & Co. Ltd., London) and recorded simultaneously every 15 min at heights of 100, 125, 150 and 200 cm above the ground at each station.

Air-temperature profiles measured in the control field with thermo-

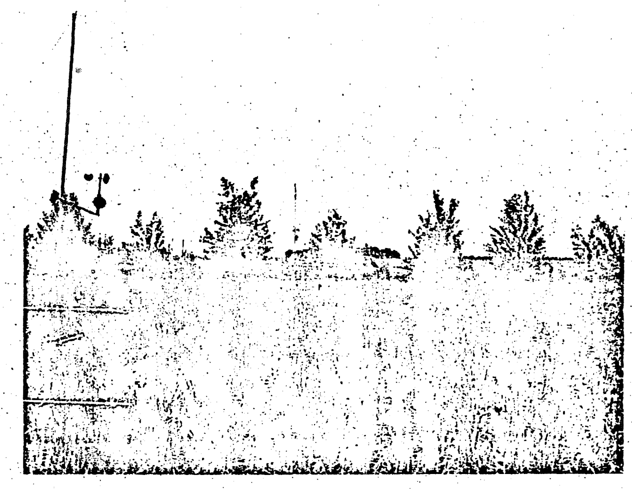

Fig. 2. Line of anemometers on masts at $2H$, $4H$ and $8H$ north of the shelterbelt.

couples, together with the control plot wind profiles were utilized to calculate Richardson number (Ri) as a measure of atmospheric stability.

The logarithmic wind profile:

$$u = \frac{u_*}{k} \ \ln \frac{(z-d)}{z_o} \tag{7}$$

where k = von Karman's constant (assumed to be 0.4); z_o = the surface roughness parameter; and d = the zero plane displacement; measured during neutral conditions ($0.0 > Ri > -0.03$), was used to determine the values of z_o and d for the wheat fields. The profiles utilized were from station 3 for periods when the wind was northerly and the shelterbelt had no detectable influence on the wind movement.

d and z_o varied from 43 and 1.8 cm, respectively, at high wind speeds to 50.9 and 9.5 cm at low wind speeds. The decrease in surface roughness with increased wind speed can be attributed to the bending of the wheat in strong wind, making it shorter and smoother.

Friction velocity, u_*, was calculated from the logarithmic wind profiles for the high, average and low values of z_o and d. The ratio u_*/u, measured 100 cm above ground in the open, ranged from 0.11 to 0.31 for the low and high values of z_o and d, respectively.

WIND SPEED REDUCTION BY THE SHELTERBELT

Ratios of wind speeds (shelter/open) were calculated and then averaged for 4-h periods when the wind was from the south. Two-dimensional plots of contours of equal wind reduction (lines of equal ratio) were drawn for the area in the lee of the shelterbelt in order to graphically depict the wind reduction in the area of measurement. Fig.3 shows data from June 7, a day

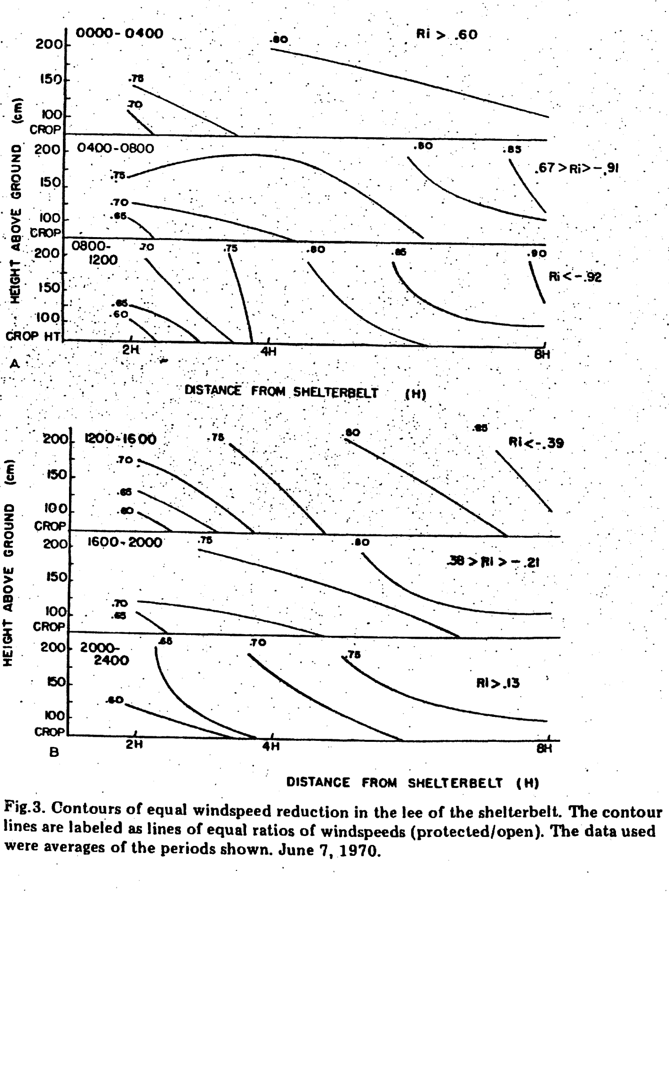

Fig.3. Contours of equal windspeed reduction in the lee of the shelterbelt. The contour lines are labeled as lines of equal ratios of windspeeds (protected/open). The data used were averages of the periods shown. June 7, 1970.

of moderate wind speed. At 100 cm in the open, wind speed ranged from about 1.0 m sec^{-1} just before dawn to 3.5 m sec^{-1} in mid-afternoon. Fig.3 shows that wind reduction was greatest at 2*H* and decreased with height and distance from the shelterbelt. The windspeed ranged from 60 to 70% of the open wind speed at 2*H* to 80 to 85% at 8*H*. Similar reductions occurred on other days of the study when the wind was southerly. The difference in patterns during the different time periods show the interaction of atmospheric stability with the shelterbelt effect.

HORIZONTAL WIND PROFILES

Wind reduction curves were drawn for each of the four measurement heights. Curves were drawn using data from periods of neutral, stable, and unstable atmospheric conditions and for varying wind speeds. Wind ratios (wind speed in the shelter/wind speed in the open) were plotted as a function of distance from the shelterbelt. A smooth curve was then drawn connecting the three points.

Fig.4 shows horizontal profiles during three different periods of neutral atmospheric stability. Curves are presented for each measurement height. The curves all have similar shapes with the point of greatest reduction at 2*H* from the shelterbelt. The wind reduction decreased rather smoothly with distance from the shelterbelt. Extrapolations of the curves indicated that reductions may have occurred to approximately 14*H* on some occasions. Most reports have shown highly permeable belts cause greatest reduction further from the belt than 2*H* and that the reduction extends over a longer distance than 14*H* (Smalko, 1963, reviewed by Van Eimern, 1968; Van Eimern, 1964; Von Naegeli, 1965). This inconsistency with previous reports is attributed to the fact that most previous investigators used much more uniform windbreaks. The effective height of the shelterbelt was much lower than its actual height due to the highly permeable nature of the upper part of the belt. Apparently uniformity with height adds to the effectiveness of a shelterbelt.

The wind reduction curves in Fig.4, measured at the various heights, showed similar differences in both magnitude and area of reduction among the three curves. Only slight deviations between the curves for June 7, 8 and 15 can be seen at the four measurement heights and these are of the same order of magnitude as the instrument error.

Fig.5 demonstrates the effect of atmospheric stability on wind reduction at the 100-cm level. The scatter of the calculated Richardson number (*Ri*) during both stable and unstable periods was large. This made the selection of short term (15-min average) representative measurements difficult. Therefore averages were used from 4-h periods of relatively uniform stability conditions to draw the curves representing stable and unstable conditions in Fig.5.

Atmospheric instability caused the greatest distortions in the wind reduction curves (bottom graph, Fig.5). The maximum wind reduction was at 2*H* during both stable and unstable conditions, but the wind speed recov-

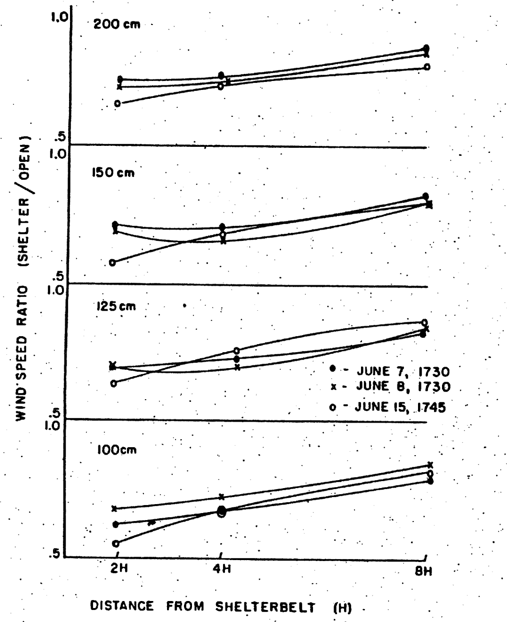

Fig.4. Wind reduction curves under neutral stability conditions ($-0.03 < Ri < 0.0$). Curves from three different days are shown at each measurement height.

ery with distance was more rapid under unstable conditions than under neutral or stable conditions, causing the overall effectiveness of the shelterbelt to decrease.

Stable conditions caused the wind speed to recover more slowly with distance, thus the area of influence was increased considerably. The curve shapes were very similar for all the stable periods observed but differences in magnitude of wind reduction at different times were observed (top graph, Fig.5). Generally, the reduction was greater with the low speeds. The slopes of neutral period curves at 100 cm (average slope: 0.029 η/H) tended to fall between those of the stable (average: 0.015 η/H) and unstable (average: 0.030 η/H) curves. The effects of atmospheric stability on shelterbelt effectiveness we find to agree with previous reports (Van Eimern, 1968) as to the greater distance of shelterbelt influence during stable periods than during unstable periods.

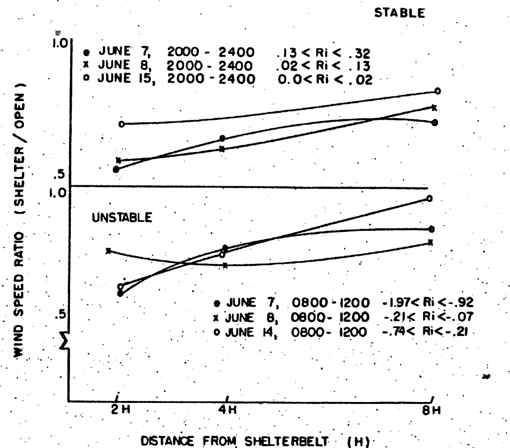

Fig.5. Wind reduction curves measured 100 cm above the ground during stable and unstable atmospheric conditions. The plotted points represent 4-h averages from the dates and times shown.

SHELTERBELT DRAG

The horizontal wind profiles and surface roughness lengths reported here were used in Seginer and Sagi's model (1972) to calculate dimensionless drag coefficients for the shelterbelt under different atmospheric conditions.

The integral in eq.5 was determined graphically by plotting the squares of the wind reduction ratios (η^2) as a function of distance from the shelterbelt. Smooth curves were then drawn to connect the points and extrapolated to the line of zero wind reduction. Extrapolations were also made in the windward direction to intersect with the 1.0 line (line of zero wind reduction) at $4H$ windward of the shelterbelt. The windward extrapolations were convex parabolic curves from the maximum wind reduction at $2H$ to 0.0 at $-4H$. The shape and extent of these extrapolations follow the patterns generally observed by previous researchers (Van Eimern, 1964) of decreasing wind reduction to 4 or $5H$ windward of wind barriers. The area (A) was then determined between this curve and the $\eta^2 = 1.0$ line:

$$A = \int_{h_1}^{h_2} (1 - \eta^2)\, dh \qquad (8)$$

Seginer and Sagi suggested two choices for the characteristic velocity, u_C, in eq.6. They considered the approach friction velocity, u_*, and the approach velocity at height H. Use of the approach velocity reduces eq.6 to:

$$C_{d_*} = 2A \qquad (9)$$

where C_{d_*} = drag coefficient using u_*. The approach velocity at height H can be estimated by the log wind profile (eq.7). Then eq.6 becomes:

$$C_{d_H} = 2\,k^2\,A / \left(\ln \frac{H-d}{z_o}\right)^2 \qquad (10)$$

where C_{d_H} = the drag coefficient using the approach velocity at height H. Both equations were used to calculate drag coefficients from the data used for the wind reduction curves in the previous section.

Seginer (1972) pointed out that the model may have serious drawbacks for practical use. He noted that the assumptions of the model for upper- and downwind boundaries are questionable and that data far downwind must be representative of strict two-dimensional flow for the model to be valid. In the case examined here the windbreak was 137 m long and all measurements were made within 13.2 m of the shelterbelt on a line normal to the shelterbelt center. Thus, the wind in the data region (+2H to +8H) is assumed free from turbulence effects at the ends of the belt and is therefore representative of two-dimensional flow. Data further downwind and upwind are extrapolations from this region and any deviation from true windspeeds is assumed to be similar for all the wind-reduction curves compared.

Table I lists values of C_{d_*} and C_{d_H} for periods of varying atmospheric stability conditions.

The drag coefficients calculated for the stable periods show the same dependence upon wind speed as do the wind reduction curves. Greater wind speeds resulted in a lower drag coefficient.

The drag coefficients during unstable periods demonstrated surprisingly little variation with wind speed. The integral values (A) for high and moderate winds were numerically close in spite of the distortions in the shape of the wind reduction curve, noted previously in Fig.5.

The neutral-period drag coefficients were the least variable, overall, and their values were intermediate between those calculated during stable and unstable periods. A slight dependence on wind speed is indicated in Table I with the shelterbelt drag decreasing at the greater wind speeds. The neutral data from June 7 and 8 show a 5.6% increase in C_{d*} and C_{d_H} with a 42% decrease in wind speed. This was an expected result since the flexible cottonwood branches bend during high winds and decrease the density of the shelterbelt.

C_{d_H} values demonstrated large differences over the range of z_o shown. A 27% difference in C_{d_H} is noted using the maximum (9.5 cm) and minimum (1.8 cm) roughness lengths. This difference in C_{d_H} with changes in z_o may

TABLE I

Drag coefficients calculated by the method of Seginer and Sagi (1972) for various conditions of atmospheric stability, wind speed and surface roughness parameters z_o and d

Atmospheric stability	Measurement height (cm)	Average open wind speed at 100 cm (m sec^{-1})	A	C_{d_*}	$C_{d_{\eta 1}}$ *1	$C_{d_{\eta 2}}$ *2	$C_{d_{\eta 3}}$ *3	Time	Date
Neutral*4	100	5.73	5.12	10.24	.06	.10	.14	17h14—17h30	6/8
		3.12	5.40	10.80	.07	.11	.15	17h15—17h30	6/7
		3.50	5.45	11.90	.07	.11	.15	17h30—17h45	6/15
Stable*5	100	3.87	6.17	12.34	.07	.12	.17	20h00—00h00	6/8
		2.30	8.17	16.34	.10	.16	.23	20h00—00h00	6/7
		2.83	4.85	9.70	.06	.09	.13	20h00—00h00	6/15
Unstable*5	100	4.51	5.20	10.40	.06	.10	.14	08h00—12h00	6/8
		2.09	4.90	9.80	.06	.10	.14	08h00—12h00	6/7
		1.84	4.02	8.04	.05	.08	.11	08h00—12h00	6/14

*1 Using z_o = 1.8 cm, d = 43.0 cm.
*2 Using z_o = 5.0 cm, d = 47.0 cm.
*3 Using z_o = 9.5 cm, d = 50.9 cm.
*4 Wind speeds are 15-min averages.
*5 Wind speeds are 4-h averages.

make the use of eq.10 difficult when the crop protected is pliable, since changes in surface roughness occur with changing wind speed, and the assumption in eq.3 that z_o in shelter = z_o in the open is, apparently, not valid.

DISCUSSION

Seginer and Sagi utilized data reported by Woodruff et al. (1963) for a fully developed field shelterbelt in Kansas and computed values of $A = 17.0$, $C_{d*} = 34.0$, and $C_{d_H} = 0.09$, values which were approximately three times those computed for our shelterbelt. This suggests that the shelterbelt used here was about 1/3 as effective in only four years as a fully developed belt.

The consistency of the wind reduction curves and the computed C_d values during neutral stability indicate that these parameters hold some promise for comparative purposes as a measure of shelterbelt influence. The assumption of a logarithmic wind profile in eqs.3 and 10 makes the accuracy of the model questionable in stable and unstable conditions. This is borne out by the variations of the calculated C_{d_H} with stability changes. The fluctuation of the wind reduction curves with stability limits the usefulness of A and C_{d*} as a basis for comparisons when measurements are made under conditions other than neutral, even though they may accurately portray the drag exerted by the shelterbelt at such a time.

A simple integration parameter such as A or C_{d*} is probably more practical for comparisons of shelterbelt effectiveness than is C_{d_H}. The parameter C_{d*} does not change with z_o. The fact that it does not require the measurement of z_o makes its calculation simpler and less instrumentation is necessary for its use. Seginer and Sagi (1972) also pointed out that the values of C_{d*} and A will vary with H/z_o. For comparison of the effectiveness of different shelterbelts this may be an advantage since any realistic comparisons should take into account the interactions of the shelterbelt with the crop it is protecting. The use of C_{d*} or A, therefore, will be a measure of the effectiveness of the shelterbelt in the specific environment of its use.

It should be pointed out that all the drag coefficients presented in this report are, at best, estimates. The accuracy of the absolute values of the calculated drag coefficients is dependent upon the extrapolations made of the wind reduction curves.

CONCLUSIONS

The measurements presented here demonstrate that a field shelterbelt can be effective in a very short period of time after planting. Even though the crowns of the cottonwood were not closed, they were about one-third as effective as a belt with a continuous crown.

Parameters determined by integrating the wind reduction curves give relatively consistent results. They may have more value as a standard on which the comparisons of different shelterbelts can be based than the traditional estimates of shelterbelt density or permeability. The primary restriction on their use is that such parameters must be determined during periods of neutral atmospheric stability.

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