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Windbreak Drag as Influenced by Porosity

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WINDBREAK width, porosity, and flexibility all influence windspeed reduction lee of windbreaks. Atmospheric stability and surface roughness of the surounding area also affect windspeed reduction (5)*. But windbreak porosity is the major factor (11).

Classifying plant windbreaks on the basis of porosity would facilitate comparisons of effectiveness among plant windbreaks. Also, experimental results from nonliving windbreaks usually are presented in terms of windbreak porosity; hence, the results would be easier to apply to plant windbreaks if they too were classified by porosity (5, 11, 13).

Investigators have attempted to determine the porosity of plant windbreaks. Nokkentved (7) and Jensen (5) tried to use pictures, while Grundmann and Niemann (4) attempted to use a ratio of windspeed in the open field to windspeed at a leeward position to indicate porosity. Neither method proved satisfactory (11). George et al (3) used enlarged photographs and an overlayed dotted grid, and reported the method reliable when checked against windbreaks of known porosity. Fryrear (2) used shielded photocells to measure reflected sunlight that penetrated annual-crop windbreaks and then compared photocell output with and without the windbreaks to calculate relative porosities. Because the photocells must be shielded from direct sunlight, his method would be difficult to apply to large windbreaks.

Another approach to the porosity problem is to measure drag coefficients of windbreaks with known porosities and compare them with drag coefficients of plant windbreaks with unknown porosities. Drag coefficients can be computed using momentum transfer principles, which are well established for airfoil drag measurements (10). They recently have been used successfully to determine windbreak drag in the surface boundary layer (12).

This investigation determined relationships between windbreak drag coefficients and windbreak porosities for slat-fence windbreaks. It also considered conditions under which the results could be used to determine porosities of plant windbreaks.

Methods and Equipment

Windspeed and temperature profiles were measured windward and leeward of 0, 20, 40, and 60 percent porous slat-fence windbreaks. The windbreaks were 2.44 m high and 60 m long. Two portable towers were instrumented with 15 sensitive cup-type anemometers (6 windward and 9 leeward) and radiation-shielded thermocouples. The windward and leeward profile measurements were made simultaneously to a height of 4H (H is windbreak height) when the wind direction was normal ± 25 deg to the windbreak.

Windspeed profile measurements also were made windward and leeward of single-row windbreaks of tamarisk, Siberian elm, American plum, and pampasgrass, all about 2 m high.

Considering a windbreak in the boundary layer as a two-dimensional flow problem and using the procedure Woodruff et al described (12), we computed the drag force by integrating the momentum transfer through parallel vertical planes windward and leeward of each windbreak. The planes were considered normal to the windflow, and their height (wake depth) as the point in the velocity profiles where windward and leeward velocities became equal. The drag force on the windbreak was computed from the difference in momentum transfer, T, through the two vertical planes using the following equation:

$$D_b + D_g = \int_0^s (T_1 - T_2)\,dz \text{ ---- } [1]$$

where $T_1 = P_1 + 1/2\rho_1 U_1^2$

$T_2 = P_2 + 1/2\rho_2 U_2^2$

The subscript "one" refers to the windward profile; "two," to the leeward profile; P is pressure; ρ, air density; U, windspeed; and z, vertical distance. D_b and D_g are the drag forces on the windbreak and ground, respectively.

From the drag force per unit length of windbreak, the drag coefficient for a given windbreak was computed from the relationship

$$C_d = D_b/(1/2\rho\bar{u}^2H) \text{ .... } [2]$$

where H is the windbreak height and $\bar{u}$ is the mean windward windspeed over the wake depth.

To avoid describing windward and leeward velocity profiles in mathematical equations, integrations for momentum transfer were performed graphically. Drag coefficients were computed from the windward and the 6H and 12H leeward velocity profiles for 32 runs of 10-min duration each. The 6H and 12H lee positions were chosen to avoid pressure effects close to the windbreaks and possible windbreak end effects at larger leeward distances. Both pressure effects and ground drag were assumed to be negligible in computing drag from equation [1].

Results and Discussion

Drag coefficients and their means for each slat-fence windbreak are shown

TABLE 1. DRAG COEFFICIENTS (C_d) AND MEAN WINDWARD WINDSPEEDS ($\bar{u}$) FOR SLAT-FENCE WINDBREAKS OF INDICATED POROSITIES.

0 percent open		20 percent open		40 percent open		60 percent open	
C_d	$\bar{u}$,	C_d	$\bar{u}$,	C_d	$\bar{u}$,	C_d	$\bar{u}$,
	m per sec		m per sec		m per sec		m per sec
1.59	6.1	1.24	4.8	1.19	5.5	0.77	4.8
1.36	6.7	1.29	4.8	1.13	5.6	0.72	4.9
1.32	6.8	1.31	4.9	1.11	5.8	0.92	5.1
1.52	6.8	1.37	5.4	1.16	6.6	0.97	6.4
1.55	7.5			1.23	6.6	0.87	10.8
1.48	8.1			1.17	8.0	0.72	11.4
1.54	8.2			1.26	9.2	0.75	11.9
1.44	8.4			1.07	9.6	0.89	11.9
				1.04	9.7		
				1.23	9.9		
				1.21	10.7		
				1.24	10.8		
Mean C_d 1.47		1.30		1.17		0.83	

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* Numbers in parentheses refer to the appended references.

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in Table 1. Also, mean windward windspeed over the wake depth is given for each run. An unequal sample size analysis of variance and Duncan's multiple range test revealed that all drag coefficient means were different at the 5 percent significance level. Drag coefficients were independent of windspeed and the two lee measurement positions.

Mean drag coefficients and standard deviations for each slat-fence porosity are shown in Fig. 1. Drag coefficients decreased linearly with increasing porosity until the windbreak was 40 percent open. The sharp drop in the drag coefficient for the 60 percent porous windbreak suggested it was not as effective in reducing leeward windspeed as the 40 percent porous windbreak, which agrees with the effect of porosity on windspeed reported by others (1, 5, 11). The scatter of the drag coefficients at each porosity can be attributed partly to difficulty in determining the exact wake depth when calculating momentum transfer. A second cause of scatter is variation in atmospheric stability under which the runs were made. The dashed line is an extrapolation toward zero windbreak drag.

Data of Fig. 1 can be used to determine the porosity of plant windbreaks when drag coefficients for the plant windbreaks are known. However, because width, porosity distribution, and flexibility of plant windbreaks are different from the rigid windbreaks used, the data should be applied to plant windbreaks with caution. The windspeed reduction patterns of narrow, flexible plant windbreaks may change with windspeed (2). The drag coefficients of individual trees may vary from 1.0 to 0.3, but do not change much for windspeeds less than 6 to 8 m per sec (6). In contrast, drag coefficients for the slat-fence windbreaks were independent of windspeeds, which ranged from 4 to 12 m per sec.

To compare windbreak windspeed reductions, Jensen (5) has shown that atmospheric stabilities and windward roughness lengths (Z_o) must be similar. For the slat-fence windbreaks, the windward Z_o was 0.94 cm and the stabilities ranged from neutral to moderately unstable.

Finally, slat-fence drag coefficients are not likely to apply to wide shelterbelts. Bluff barriers characteristically produce lower drag coefficients and shallower wakes than do sharp, vertical barriers in the laboratory (8, 10). Woodruff et al (12) reported a drag coefficient of 0.55 to 0.6 for a 10-row field shelterbelt with a wake depth of 1.8H at 12H leeward. For the slat fences the wake depths ranged from 3.5H for the solid windbreak to 2.5H for the 60 percent porous windbreak. Such results suggest that windbreak width also will significantly affect windbreak drag, but further research is needed to delineate width effects.

Based on the preceding limitations, narrow plant windbreaks with relatively uniform porosities should have drag coefficients comparable to those of slat fences. Drag coefficients (Table 2) for four single-row tree windbreaks were computed using momentum-transfer methods. The wake depths ranged from 2.4H to 2.6H, and the windward roughness length (Z_o) varied from 0.8 to 1.5 cm. Although not measured, atmospheric stability was near neutral during the tests. From Fig. 1, indicated porosities ranged from 57 to 78 percent for the 2-m-high windbreaks. Drag coefficients for individual trees and porosities of narrow annual crop windbreaks reported by other investigators are also included in Table 2.

Data presented suggest that single-row plant windbreaks range from about 50 to 80 percent porous. Dense single-row hedges, not represented in the data, probably are less porous, however. Indicated porosities of individual trees and measured porosities of two rows of annual plants suggest that multi-row windbreaks of the species shown would be necessary to create porosities much below 35 percent.

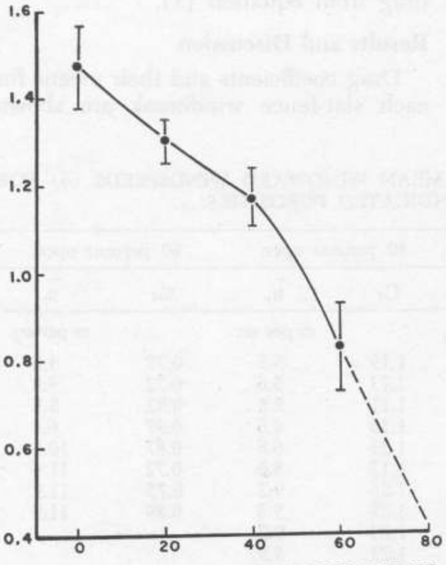

Fig. 1 Mean drag coefficients and their standard deviations for indicated windbreak porosities

TABLE 2. DRAG COEFFICIENTS AND POROSITIES.

Item	Windbreak species			
	Tamarisk	Siberian elm	American plum	Pampasgrass
Drag coefficients of single-row windbreaks (windspeed 4 to 6 m per sec)	0.89	0.46	0.52	0.56
Windbreak porosity (from Fig. 1)	57	78	75	73
	Colorado spruce	Juniper	Spruce	Pine
Drag coefficients of individual trees (windspeed 6 m per sec)	1.2*	0.95*	0.8†	0.6*
Porosity (from Fig. 1)	35	55	61	71
	Sudangrass	Grain sorghum	Forage sorghum	Broomcorn
Average porosities of annual plant windbreaks in percent‡ (windspeed 3 to 7 m per sec)	(1 row) 49 (2 row) 34	60 55	58 58	68 59
Drag coefficients (from Fig. 1)	(2 row) 1.21	.94	.87	.85

* After Meroney (6)
† After Rayner (9)
‡ After Fryrear (2)

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