Technical Bulletin 131
November 1963

REDUCING WIND VELOCITY
WITH
FIELD SHELTERBELTS

AGRICULTURAL EXPERIMENT STATION
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AND APPLIED SCIENCE
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Reducing Wind Velocity with Field Shelterbelts[1]

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INTRODUCTION

The value of shelterbelts or windbreaks composed of tree and shrub plantings to protect crops, livestock, and man from wind has long been recognized. Interest in using shelterbelts in the United States and Canada (8, 9) climaxed in the 1930's as a method to combat severe dust storms. Shelterbelts also have been used extensively in the more arid steppe regions of the U.S.S.R. (2). In Canada, about 1,000 miles of 1- to 3-row caragana hedges have been planted, mainly in three locations. In the United States some 18,000 miles of shelterbelts were planted in a 6-state area in the Great Plains from Texas to North Dakota. Unlike the plantings in Canada, most of those in the United States were wide. According to Read (8) about 40 percent of the belts had 10 rows; about half, 5 to 7 rows; and the remaining 10 percent, either 3, 4, 11, or 21 rows. The wide plantings were thought to be necessary not only to provide the best barrier for wind velocity reduction but also to attain so-called forest conditions believed to be necessary for propagation and self-preservation of trees within the shelterbelts.

Wide shelterbelts have produced a type of forest condition after 30 years, as evidenced by the increased soil organic matter beneath the trees and the abundance of natural regeneration of trees and shrubs. However, it is now evident from field observation and research here and abroad that field shelterbelts need not be so wide to be effective for slowing wind velocity. Today the trend is toward narrow plantings. Narrow shelterbelts have gained widest acceptance in the Northern Great Plains, particularly in North and South Dakota where 1- to 5-row belts are now recommended (6, 7).

A single row of trees that would attain a uniform height and retain branches to the ground would have the least number of trees, occupy the least area, and perform many of the functions expected of a multirow shelterbelt. However, where suit-

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with the Kansas Agricultural Experiment Station, Department of Agronomy, Contribution No. 796.

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Grateful acknowledgment is made to Albert C. Kientz, engineering aide, for assistance in taking data; to R. A. Read, Research Forester, U.S. Forest Service, Lincoln, Nebraska; and to Walter T. Bagley, Forester, Nebraska Agricultural Experiment Station, for critical review and suggestions for improving the manuscript. 5M—11-63

able species are inadapted and where poor soil sites are a special problem it may be difficult to maintain a single-row belt having adequate height and winter and summer porosity. Under such conditions it is better, as Baltaxe (1) has pointed out, that the shelterbelt be a malleable entity, i.e., to have flexibility of height and porosity, which can be best attained with a 2- or 3-row belt of mixed coniferous and deciduous trees.

While many narrow shelterbelts have been and are now being planted, research data on their effectiveness in reducing wind velocities generally is lacking. Single caragana belts in Canada (9) and single willow belts in China (5) have been reported to be quite effective in reducing wind and soil drifting. Two wind tunnel studies (11, 12) have also shown that narrow belts are nearly as effective as wider belts; however, there are few measurements to substantiate these results under actual field conditions.

This paper presents results of a study designed to measure the effectiveness of some typical 1-, 2-, 3-, 5-, 6-, 7-, and 10-row Great Plains field shelterbelts in reducing wind velocities. Some of the belts were measured in winter; others were measured in summer. Results are presented in terms of leeward velocity reduction curves and effectiveness indexes. Also included are a wind-erosion-protected zone interpretation and a 15-year projected extent of influence evaluation which considers rate of height growth of dominant tree species on different site conditions in Kansas and Nebraska.

METHODS AND PROCEDURES

Wind velocity data were taken in the open and to the leeward of 15 different field shelterbelts in Kansas and Nebraska. Measurements were made only on belts located on level land and surrounded by either bare, tilled ground or low-growing crops. All belts were free from the influence of any other shelterbelt or obstruction. Measurements were made only during fairly brisk winds with actual open-field velocities at the 4-foot elevation ranging from 9.0 to 21.7 miles per hour. Data were obtained on both summer and winter conditions.

Velocities were measured with both contacting-type 3-conical cup and direct-reading vane anemometers. The contacting anemometers were mounted on portable pipe stands 4 feet above the mean ground surface level (Figures 1-A and 1-B). The vane anemometers were mounted on an aluminum staff at 1-, 2-, and 4-foot elevations (Figure 1-B).

The contacting anemometers were used at various distances leeward and windward from the belt. Leeward velocity impulses were counted by means of individual totalizing, electrically actuated counters mounted on each anemometer stand (Figure 1-A). Open field velocity impulses, taken windward of the belt, were recorded on a strip chart recorder (Figure 1-B). In running a test, the belt height was first determined

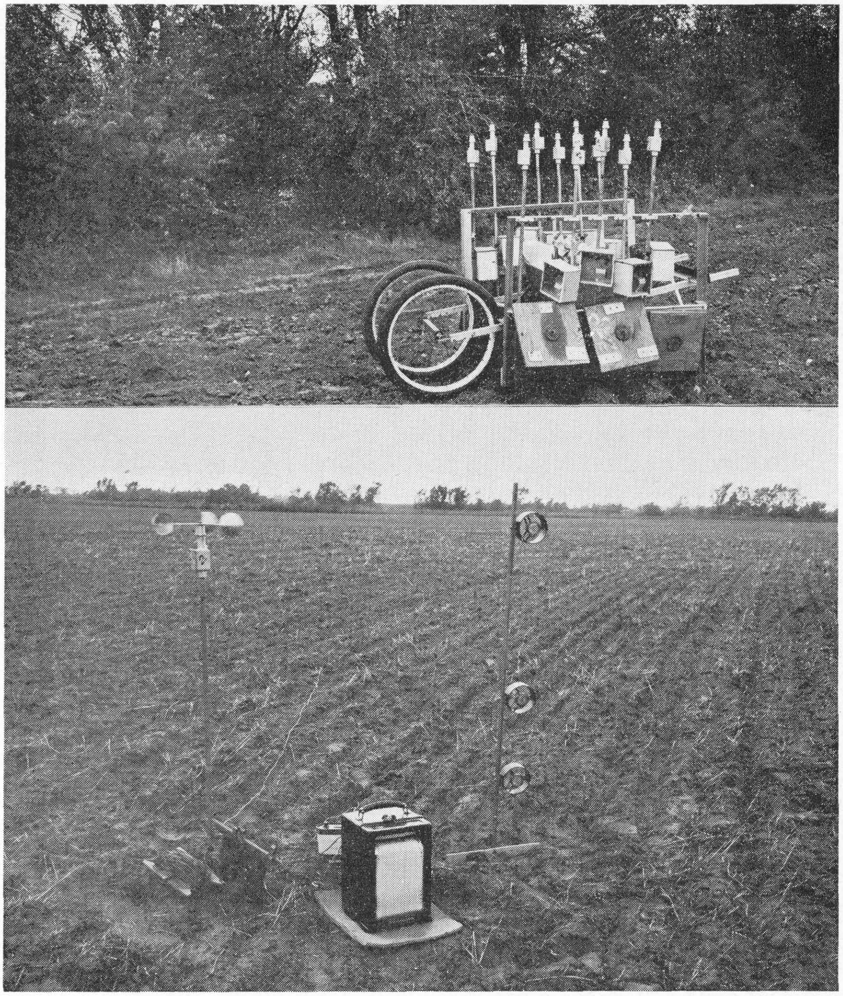

Fig. 1.—Instruments and equipment; A (top) Contacting-type anemometers on pipe stands equipped with individual counters (note box on pipe stand) loaded on push cart ready for distribution to various leeward locations. B (bottom) Left to right: one of the open-wind contacting anemometers, the strip chart recorder, and the staff of vane anemometers.

with a hand level and the anemometers were then placed at the 1, 2, 4, 6, 8, 12, 16, 20, 24, and 30 H[3] leeward locations, each at the 4-foot height. A small cart was used to transport them across fields to the desired locations (Figure 1-A). The open field anemometers were placed 100 feet apart in a line parallel to the belt and about 10 H windward of it.

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[3] H = average height of trees in a single-row windbreak and average height of tallest trees in a multiple-row windbreak.

Testing procedure consisted of first starting the open field wind recorder and recording the time. Leeward contacting anemometer switches were then turned on and the time recorded. These anemometers were allowed to run for 1 to 2 hours. During this period 3-minute measurements of windward and leeward velocity at the 1-, 2-, and 4-foot levels were made by moving the staff of vane anemometers from location to location.

The 1- to 2-hour test data obtained with contacting anemometers for the 4-foot height were used to prepare velocity-reduction curves for each of the belts. The velocity reduction was expressed as a percentage:

$$\text{percent velocity reduction} = 100\ (1 - U_L/U_o)$$

where U_L is the average leeward velocity and U_o is the average open field velocity for the same time period and elevation. The curves were prepared by plotting these values versus leeward H distances measured along the direction of the wind.

An effectiveness index, based on data obtained with contacting anemometers at 4-foot height, was computed by summing the ten products (velocity-reduction ratio times its leeward H distance), thus:

Effectiveness index =

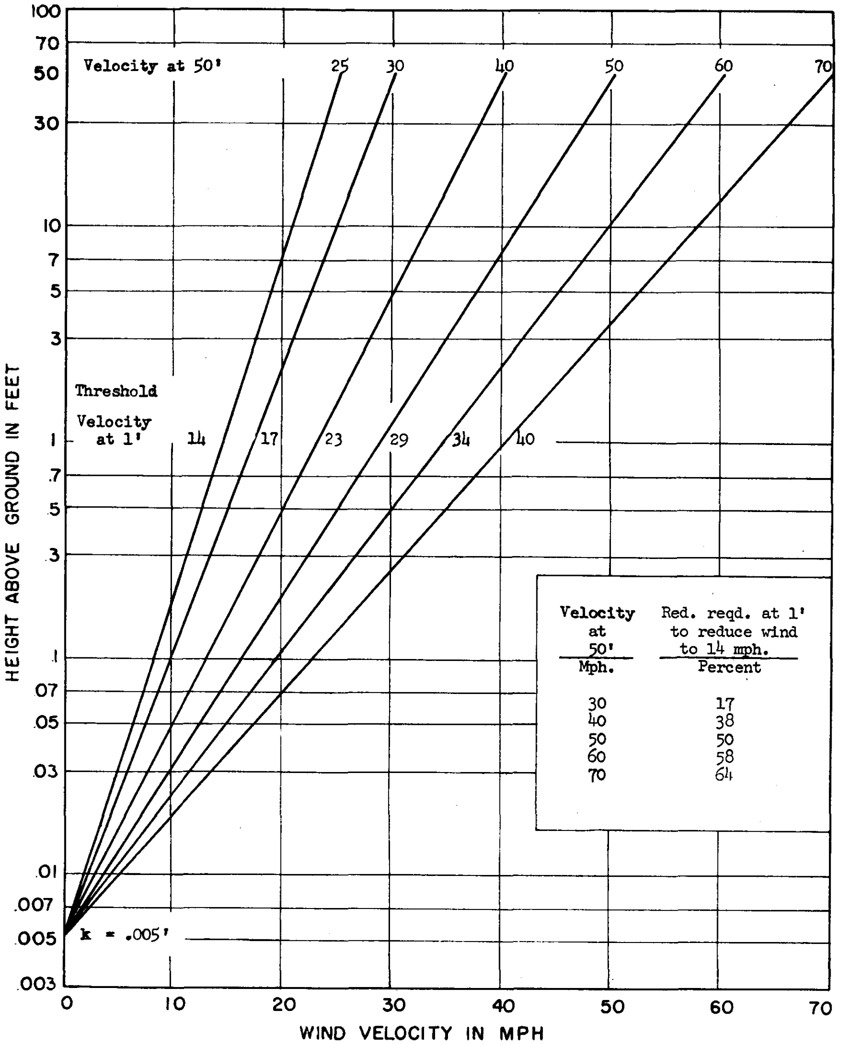
$$(1 - U_{L1}/U_o)1 + (1 - U_{L2}/U_o)2 + (1 - U_{L4}/U_o)4 +$$
$$(1 - U_{L6}/U_o)6 + (1 - U_{L8}/U_o)8 + (1 - U_{L12}/U_o)12 +$$
$$(1 - U_{L16}/U_o)16 + (1 - U_{L20}/U_o)20 + (1 - U_{L24}/U_o)24 +$$
$$(1 - U_{L30}/U_o)30$$

where U_{L1}, U_{L2} .... U_{L30} = velocity at 1, 2 .... 30 H leeward of the belt.

The 3-minute data from the vane anemometers were converted to contacting-type, 1- to 2-hour data by comparing the two types of anemometers at the 4-foot level. On this basis, the 1-foot elevation ratios U_L/U_o were computed and used to determine the leeward distance fully protected from wind erosion. The leeward fully protected distances were determined, based on the average ultimate threshold velocity for initiation of soil movement of 14 miles per hour at the 1-foot height (4) assuming that wind velocity varies as the logarithm of height (Figure 2) and average surface condition for a smooth, bare fallow field, with level terrain having a ridge roughness equivalent of about 2.0 inches (15). These distances are given for wind velocities of 17, 23, 29, 34, and 40 miles per hour at 1-foot elevation. Corresponding velocities at the 50-foot elevation, the reporting height used by many U.S. Weather Stations, also are given to facilitate use of this information.

An estimate of extent of barrier influence, in terms of distance fully protected from wind erosion, that could be expected 15 years after planting also was made for each belt.

This evaluation used tree height data of three different soil sites obtained in a 1954 survey of field windbreaks in Kansas and Nebraska by Read (8) (shown in Table 6), the information on fully protected distances found by the procedures outlined in the preceding paragraph, and assumed that a belt would be produced having a conformation equal to those measured in this study.



Velocity at 50' Mph.	Red. reqd. at 1' to reduce wind to 14 mph. Percent
30	17
40	38
50	50
60	58
70	64

Fig. 2.—Logarithmic velocity-height relationships for winds of varying velocity blowing over a bare, smooth fallow surface.

RESULTS

Velocity Reduction

Figures 3 through 7 show the 4-foot elevation velocity reduction curves for the 15 shelterbelts measured. Included in each figure are photographs of the frontal and end height-density profiles of each shelterbelt. Also included is a table of species composition, average tree and shrub height, and effectiveness index for each belt. The scientific names of tree species are given in Table 1. Table 2 presents a summary of effectiveness index per belt and per row of trees for each of the belts measured.

Table 1.—Common and scientific names of tree species under this study.

Common	Scientific
Arborvitae	*Thuja orientalis* L.
Ash, Green	*Fraximus pennsylvanica* Marsh.
Catalpa, Northern	*Catalpa speciosa* Warder.
Coffeetree, Kentucky	*Gymnocladus dioicus* (L.) K. Koch.
Cottonwood	*Populus Sargentii* Dode.
Elm, American	*Ulmus americana* L.
Elm, Siberian	*Ulmus pumila* L.
Honeylocust	*Gleditsia triacanthos* L.
Honeysuckle, Tatarian	*Lonicera tatarica* L.
Mulberry, Russian	*Morus alba var. tatarica* Seringe.
Osage-orange	*Maclura pomifera* (Raf.) Schneid.
Pine, Jack	*Pinus Banksiana* Lamb.
Pine, Ponderosa	*Pinus ponderosa scopulorum* Engelm.
Plum, American	*Prumus americana* Marsh.
Redcedar, Eastern	*Juniperus virginiana* L.
Russian-olive	*Elaeagnus angustifolia* L.
Tamarisk	*Tamarix pentandra* Dall.
Walnut, Black	*Juglans nigra* L.

Row Comparisons.—It is difficult to directly compare the influence of number of rows of trees in a belt because of the interacting effects of tree species and porosity of barriers. However, the relative influence per row of trees can be compared by considering the effectiveness index per belt and per row.

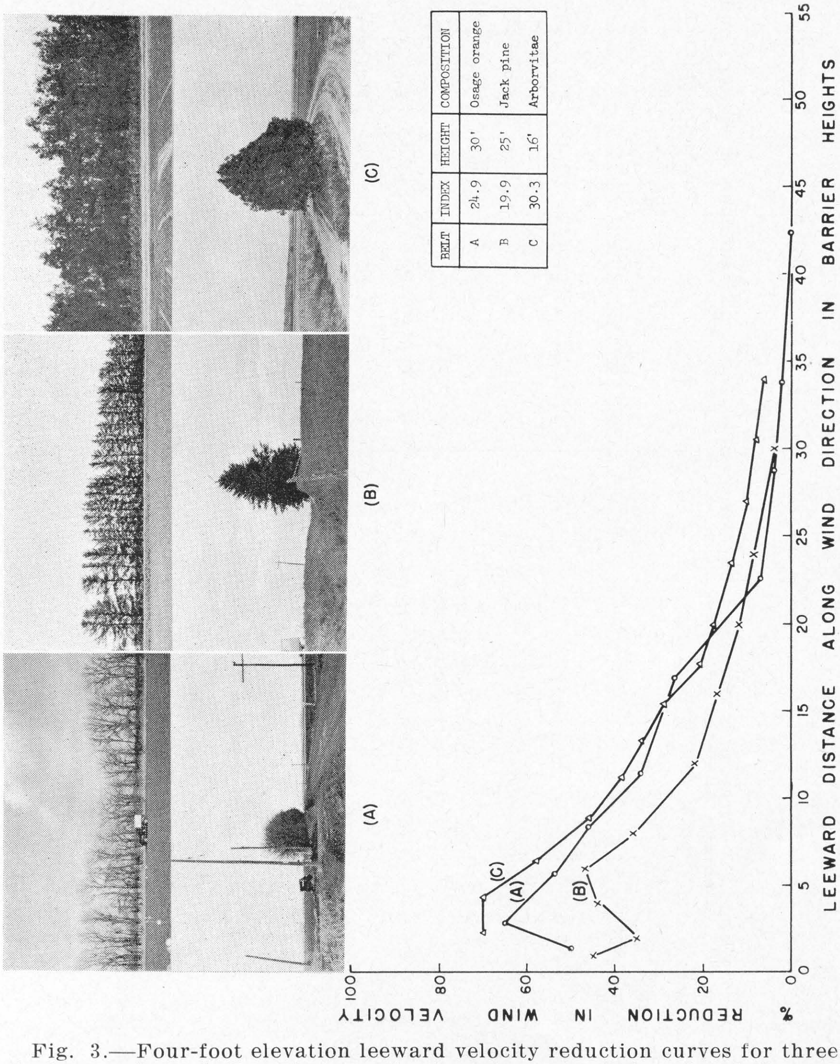
The effectiveness index per belt data showed that it was possible to obtain a very effective barrier with two or three rows of trees, e.g., belts G and I. Both of these belts in summer had a higher effectiveness index than did the 5- and 6-row cedar-deciduous combination belts J and M (Table 2). A comparison of the effect of the 10-row belt, O, and the 5-row belts,

Table 2.—Array of shelterbelts by effectiveness index and summer or winter condition.

Summer condition						Winter condition					
		Eff. index						Eff. index			
Belt	Rows	Per belt	Per row	Composition	Maximum height	Belt	Rows	Per belt	Per row	Composition	Maximum height
					Feet						Feet
G	2	55.9	28.0	Mulberry	13	O	10	46.6	4.6	Mulberry, elm, locust, coffee, ash, Osage-orange, cedar, olive	12
I	3	44.5	14.8	Amer. elm, Sib. elm, ash	25						
J	5	42.6	8.5	Plum, cedar, mulberry, elm, olive	34	K	5	24.9	5.0	Plum, Amer. elm, Sib. elm, cedar, honeysuckle	22
M	6	39.9	6.7	Cedar, pine, elm, locust, catalpa, walnut	22	A	1	24.9	24.9	Osage-orange	30
D	1	32.4	32.4	Osage-orange	16	L	5	24.1	4.8	Mulberry, elm, locust, cedar, Osage-orange	26
H	3	30.8	10.3	Cedar (2), shrub	16	N	7	7.2	1.0	Ash (2), elm, cottonwood (2), Osage-orange, coffee	37
C	1	30.3	30.3	Arborvitae	16						
E	1	27.1	27.1	Sib. elm	27						
F	1	25.3	25.3	Cottonwood	63						
B	1	19.9	19.9	Jack pine	25						

K and L, all cedar-deciduous combinations, showed that in winter the 10-row belt was considerably more effective than the 5-row. However, Table 2 also shows that in winter there was no difference between a single-row Osage-orange, belt A, and the 5-row belts, K and L, and further, that the 7-row belt N with an index of only 7.2 was the least effective belt tested.

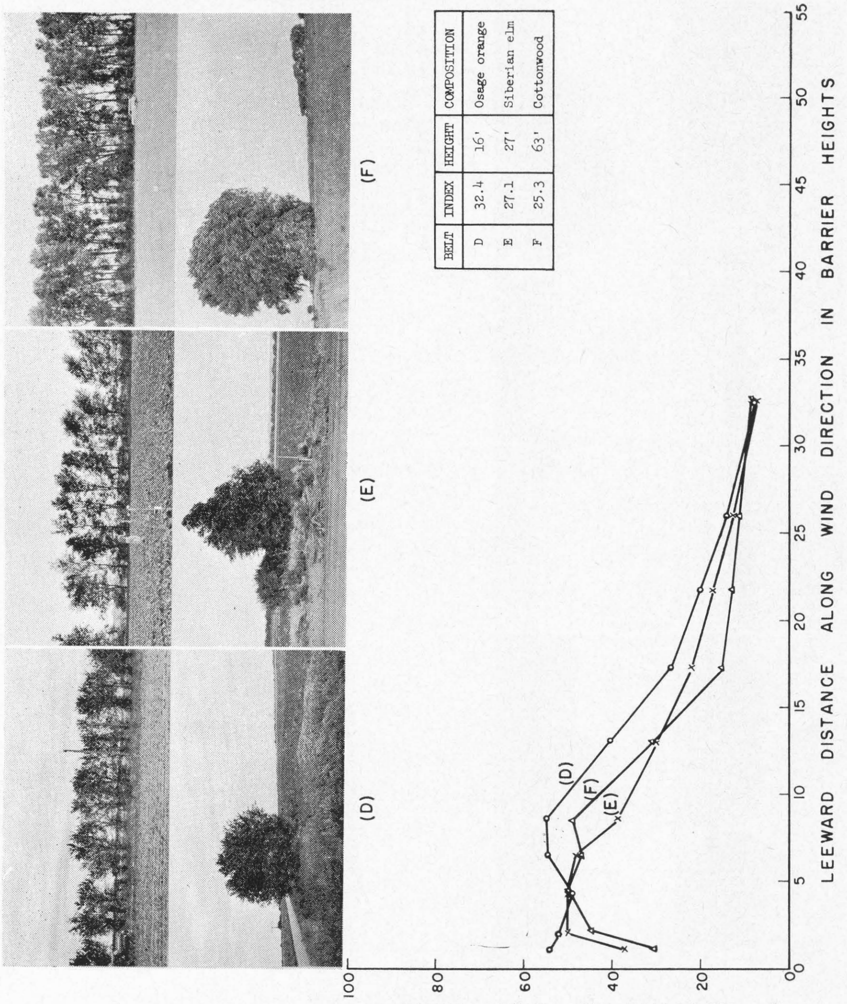
The effectiveness index per row data showed that trees



BELT	INDEX	HEIGHT	COMPOSITION
A	24.9	30'	Osage orange
B	19.9	25'	Jack pine
C	30.3	16'	Arborvitae

Fig. 3.—Four-foot elevation leeward velocity reduction curves for three single-row shelterbelts. Photographs show front (upper) and end (lower) views of each belt. Table indicates effectiveness index, height of dominant species, and tree-species composition.

planted in a single row provided more protection per row than if planted in multiple rows. Single-row Osage-orange belts, D and A, are particularly effective in both winter and summer, and belts C, E, and F, single rows of arborvitae, Siberian elm, and cottonwood, respectively, were shown to have an effectiveness per row about equal to two rows of mulberry, belt G. On the other hand, wide belts, e.g., 10-row belt O, 5- and 6-row

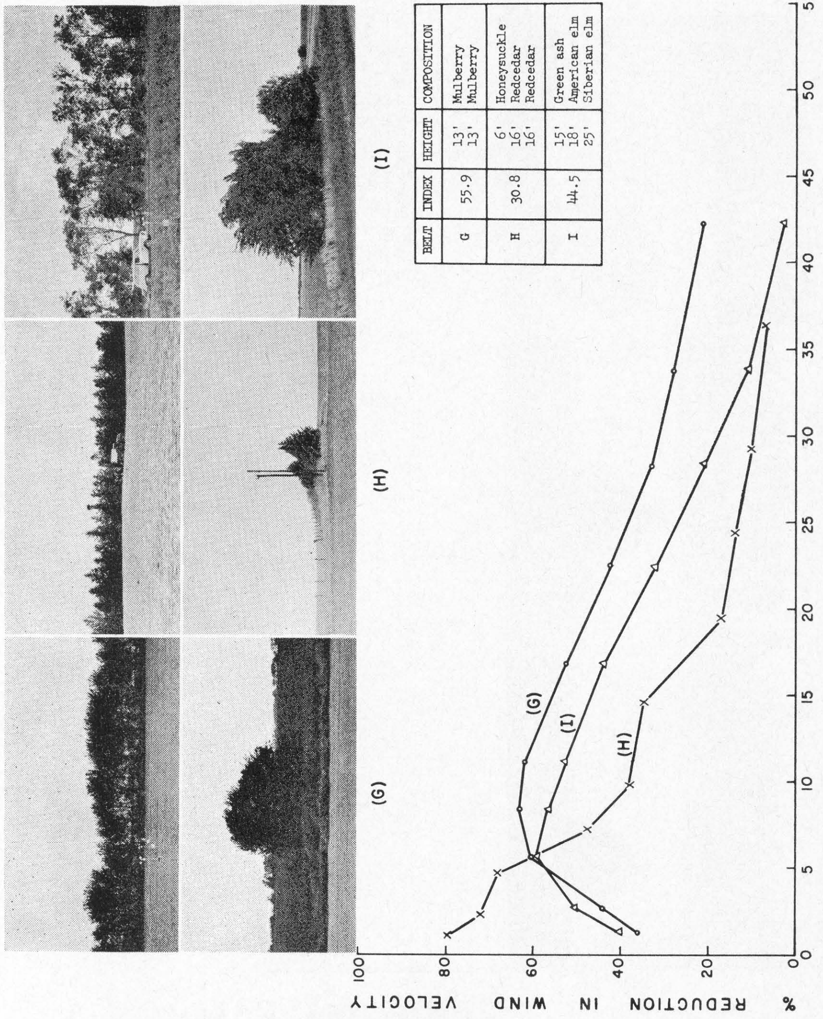


BELT	INDEX	HEIGHT	COMPOSITION
D	32.4	16'	Osage orange
E	27.1	27'	Siberian elm
F	25.3	63'	Cottonwood

Fig. 4.—Four-foot elevation leeward velocity reduction curves for three single-row shelterbelts. Photographs show front (upper) and end (lower) views of each belt. Table indicates effectiveness index, height of dominant species, and tree-species composition.

belts J and M, and 7-row belt N were shown to have a very low effectiveness per row of trees.

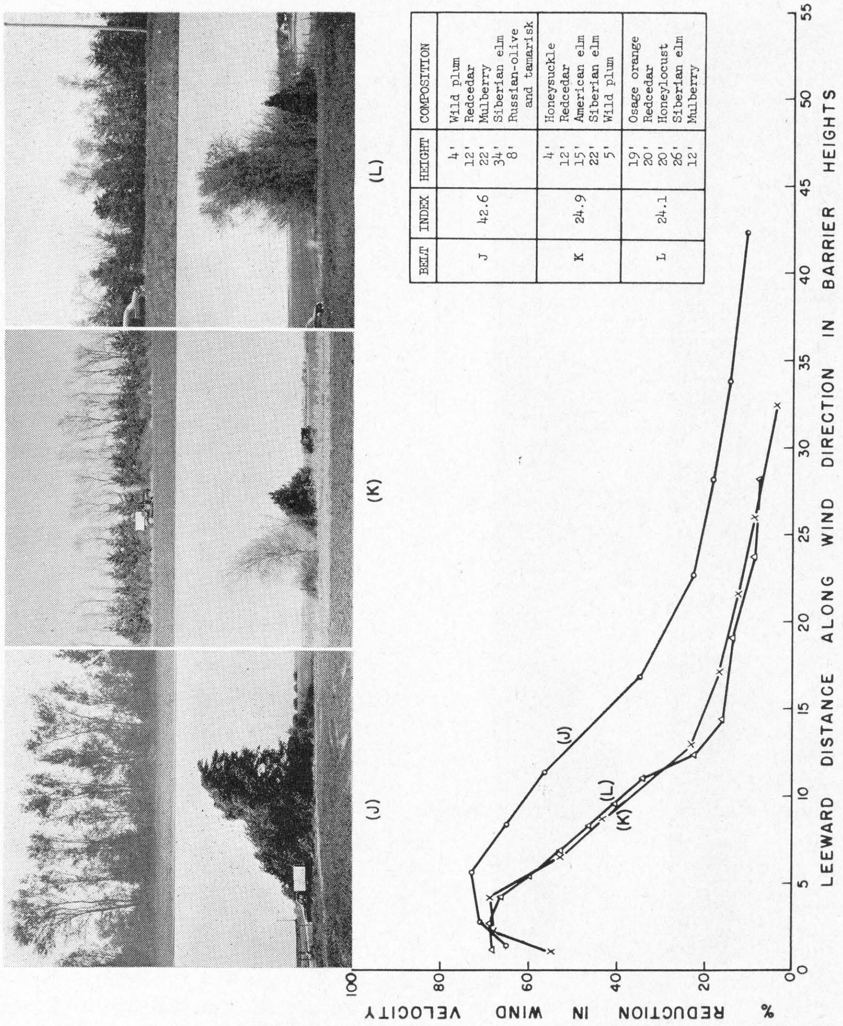
Species Comparisons.—The relative wind velocity reduction efficiency of several different tree species can be obtained from the summer condition 1-row belt data in Table 2. In terms of the effectiveness index, Osage-orange was most effective fol-



BELT	INDEX	HEIGHT	COMPOSITION
G	55.9	13' 13'	Mulberry Mulberry
H	30.8	6' 16' 16'	Honeysuckle Redcedar Redcedar
I	44.5	15' 18' 25'	Green ash American elm Siberian elm

Fig. 5.—Four-foot elevation leeward velocity reduction curves for a 2-row and two 3-row shelterbelts. Photographs show front (upper) and end (lower) views of each belt. Table indicates effectiveness index, height of dominant species, and tree-species composition.

lowed in order by arborvitae, Siberian elm, cottonwood, and jack pine. The velocity-reduction curves (Figures 3 and 4) show that the Osage-orange was particularly effective in reducing wind in the zone from 5 to 15 H leeward. Jack pine had a relatively low maximum velocity reduction (Figure 3) and was not very effective beyond 15 H leeward.

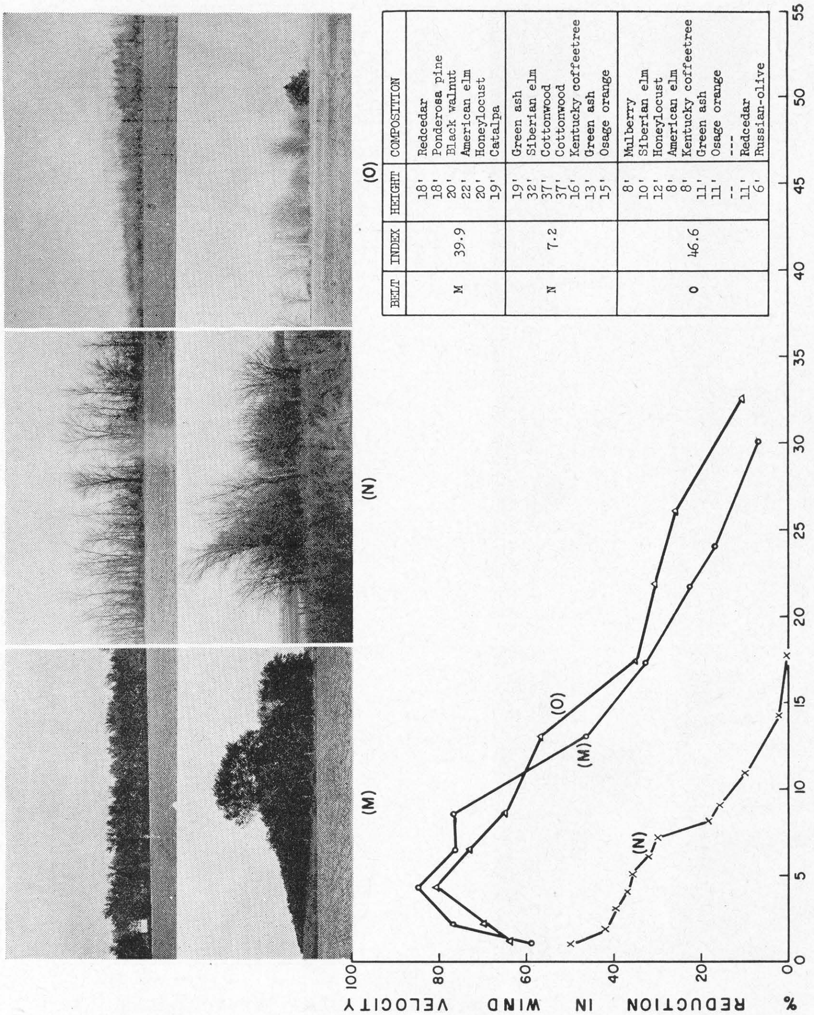


BELT	INDEX	HEIGHT	COMPOSITION
J	42.6	4' 12' 22' 34' 8'	Wild plum Redcedar Mulberry Siberian elm Russian-olive and tamarisk
K	24.9	4' 12' 15' 22' 5'	Honeysuckle Redcedar American elm Siberian elm Wild plum
L	24.1	19' 20' 20' 26' 12'	Osage orange Redcedar Honeylocust Siberian elm Mulberry

Fig. 6.—Four-foot elevation leeward velocity reduction curves for three 5-row shelterbelts. Photographs show front (upper) and end (lower) views of each belt. Table indicates effectiveness index, height of dominant species, and tree-species composition.

Wind-Erosion-Protected Zones

Figures 8 and 9 show velocity ratio curves for 10 of the shelterbelts that had bare fallow, thin-growing wheat, or other vegetation not more than 3 inches high lying leeward. Table 3, based on Figures 8, 9, and 2, presents data on leeward distances that would have wind velocity reduced below the average



BELT	INDEX	HEIGHT	COMPOSITION
M	39.9	18'	Redcedar
		18'	Ponderosa pine
		20'	Black walnut
		22'	American elm
		20'	Honeylocust
		19'	Catalpa
N	7.2	19'	Green ash
		32'	Siberian elm
		37'	Cottonwood
		37'	Cottonwood
		16'	Kentucky coffeetree
		13'	Green ash
		15'	Osage orange
O	46.6	8'	Mulberry
		10'	Siberian elm
		12'	Honeylocust
		8'	American elm
		8'	Kentucky coffeetree
		11'	Green ash
		11'	Osage orange
		--	---
		11'	Redcedar
		6'	Russian-olive

Fig. 7.—Four-foot elevation leeward velocity reduction curves for 6-, 7-, and 10-row shelterbelts. Photographs show front (upper) and end (lower) views of each belt. Table indicates effectiveness index, height of dominant species, and tree-species composition.

Table 3.—Wind-erosion-protected zones in terms of maximum leeward H distance at which wind velocity is held below 14 miles per hour at 1 foot above ground, when wind velocity at 50-foot height ranges from 30 to 70 miles per hour.

			Leeward distance fully protected from wind erosion when				
			1-foot elevation wind velocity in mph is				
			17	23	29	34	40
			50-foot elevation wind velocity in mph is				
	Belt	Season	30	40	50	60	70
			H	H	H	H	H
A	1-row Osage-orange	Winter	19.5	12.0	5.2	1.7	0
K	5-row honeysuckle, cedar, Amer. elm, Sib. elm, olive	Winter	12.7	9.2	6.3	5.8	3.3
O	10-row cedar (1), deciduous (9)	Winter	24.5	15.0	13.0	11.5	10.5
E	1-row Sib. elm	Summer	16.5	9.5	7.0	1.0	0
G	2-row mulberry	Summer	33.0	18.0	15.6	12.5	6.5
H	3-row cedar (2), honeysuckle	Summer	28.5	11.0	6.0	5.5	5.4
J	5-row plum, cedar, mulberry, Sib. elm, olive	Summer	20.8	15.0	11.2	9.6	8.5
M	6-row cedar, Ponderosa pine, walnut, Amer. elm, locust, catalpa	Summer	21.0	15.0	11.4	9.7	8.4
D	1-row Osage-orange	Summer	24.5	14.0	11.5	4.7	1.0
F	1-row cottonwood	Summer	12.5	8.0	2.2	0	0

ultimate threshold of 14 miles per hour at the 1-foot height, thus preventing potential soil movement by wind.

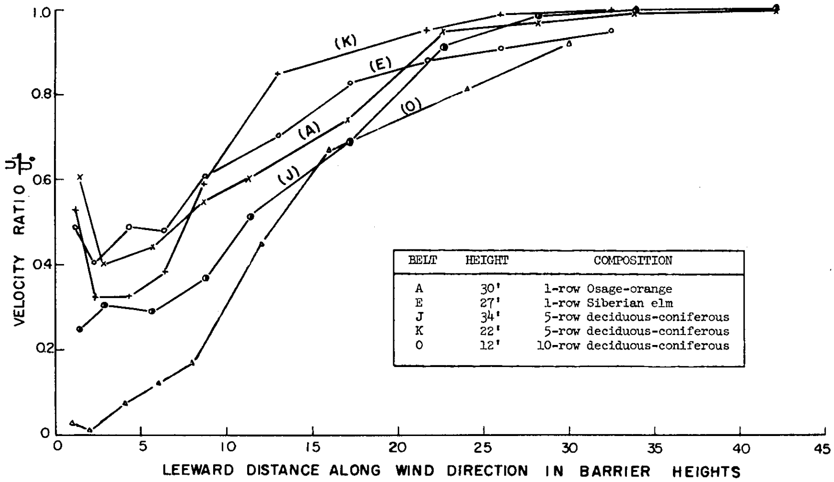
Of the three winter belts, 10-row belt O provided the longest protected distance for all levels of wind velocity (Table 3). Belt K, a 5-row winter belt, was less effective at the lower wind speeds than the defoliated 1-row Osage-orange (belt A) but was more effective at higher wind speeds. Winter belt A provided little or no protection when wind speeds exceeded 50 miles per hour.

Of the seven summer belts, 2-row mulberry, belt G, provided the longest protected distance for all levels of wind velocity except 70 miles per hour (Table 3). Summer belts J and M also provided good protection at all velocity levels. Summer belts E and F were relatively ineffective in controlling wind erosion at wind speeds exceeding 50 miles per hour at the 50-foot height.

Estimated Influence 15 Years After Planting

Barrier influence in terms of expected protected distances 15 years after planting on four different soil sites is presented in Tables 4 and 5. The protected distances were found by multiplying the expected height of the dominant tree 15 years after planting as reported by Read (8), see Table 6, by the corresponding H values given in Table 3.

Examination of Tables 4 and 5 shows that expected protected distances vary with the level of open wind velocity and with site conditions. Belts J, O, and F, in that order, provide the greatest length of protection 15 years after planting on site-condition class A-1 if the open wind velocity is only 30 miles per hour; however, if the wind is blowing 50 miles per hour, belt F, the single-row cottonwood, is replaced in third place by 6-row belt M. Belts J, O, and E would be best on site condition class B-1 with 30-mile-per-hour winds, but with 50-mile-per-hour winds belt M would replace belt E in third place. Belts J, F, and E and J, M, and O should provide the most protection on class B-2 site conditions and belts J, O, and E and J, O, and M would be best on C-1 sites with open wind velocities of 30 and 50 miles per hour, respectively, measured at the 50-foot elevation. The barrier formed by a combination of plum, cedar, mulberry, green ash, and a Siberian elm as the dominant species, belt J, is shown most effective for all sites and all levels of wind velocity. The single-row cottonwood provided a relatively long protected distance on site classes A-1 and



BELT	HEIGHT	COMPOSITION
A	30'	1-row Osage-orange
E	27'	1-row Siberian elm
J	34'	5-row deciduous-coniferous
K	22'	5-row deciduous-coniferous
O	12'	10-row deciduous-coniferous

Fig. 8.—One-foot elevation velocity ratios U_L/U_o obtained leeward of five narrow field shelterbelts. (U_L is the average leeward velocity and U_o is the average open field velocity for the same time period and elevation.)

Table 4.—Expected distances fully protected from wind erosion by shelterbelts 15 years after planting on site conditions A-1 and B-1.[1]

	Belt	Season	Leeward distance fully protected when wind velocity ranges from 30 to 70 mph at 50-foot height									
			Site A-1					Site B-1				
			30	40	50	60	70	30	40	50	60	70
			Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
A	1-row Osage-orange	Winter	293	180	78	26	0	234	144	62	20	0
K	5-row honeysuckle, cedar, Amer. elm, Sib. elm, olive	Winter	432	313	214	197	112	419	304	208	191	109
O	10-row cedar (1), deciduous (9)	Winter	588	360	312	276	252	613	375	325	288	263
E	1-row Sib. elm	Summer	561	323	238	34	0	545	314	231	33	0
G	2-row mulberry	Summer	528	288	250	200	104	495	270	234	188	98
H	3-row cedar (2), honeysuckle	Summer	428	165	90	83	81	399	154	84	77	76
J	5-row plum, cedar, mulberry, Sib. elm, olive	Summer	707	510	381	326	289	686	495	370	317	281
M	6-row cedar, Ponderosa pine, walnut, Amer. elm, locust, catalpa	Summer	462	330	251	213	185	525	375	285	243	210
D	1-row Osage-orange	Summer	368	210	173	71	15	294	168	138	56	12
F	1-row cottonwood	Summer	587	376	103	0	0	Not adapted				

[1] See footnote of Table 6 for description of site conditions.

Table 5.—Expected distances fully protected from wind erosion by shelterbelts 15 years after planting on site conditions B-2 and C-1.[1]

			Leeward distance fully protected when wind velocity ranges from 30 to 70 mph at 50-foot height									
			Site B-2					Site C-1				
	Belt	Season	30	40	50	60	70	30	40	50	60	70
			Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
A	1-row Osage-orange	Winter	254	144	62	20	0	254	144	62	20	0
K	5-row honeysuckle, cedar, Amer. elm, Sib. elm, olive	Winter	394	285	195	180	102	305	221	151	139	79
O	10-row cedar (1), deciduous (9)	Winter	441	270	234	207	189	466	285	247	219	200
E	1-row Sib. elm	Summer	512	295	217	31	0	396	228	168	24	0
G	2-row mulberry	Summer	429	234	203	163	85	363	198	172	138	72
H	3-row cedar (2), honeysuckle (1)	Summer	371	143	78	72	70	342	132	72	66	65
J	5-row plum, cedar, mulberry, Sib. elm, olive	Summer	645	465	347	298	264	499	360	269	230	204
M	6-row cedar, Ponderosa pine, walnut, Amer. elm, locust, catalpa	Summer	441	315	239	204	176	357	255	194	165	143
D	1-row Osage-orange	Summer	294	168	138	56	12	294	168	138	56	12
F	1-row cottonwood	Summer	600	288	79	0	0	——Not adapted——				

[1] See footnote of Table 6 for description of site conditions.

Table 6.—Expected 15-year tree height on four broad site conditions in Kansas and Nebraska.[1]

Tree species	Site condition[2] A-1	B-1	B-2	C-1
	Feet	Feet	Feet	Feet
Eastern redcedar	15	14	13	12
Ponderosa pine	15	14	14	12
Osage-orange	15	12	12	12
Russian mulberry	16	15	13	11
Green ash	21	22	18	17
American elm	22	25	21	17
Honeylocust	24	25	18	19
Siberian elm	34	33	31	24
Cottonwood	47	not adapted	36	not adapted

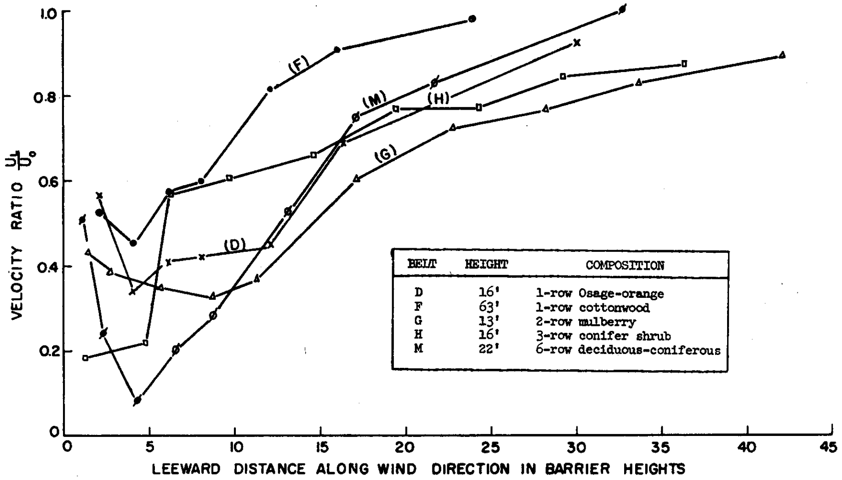
1. Based on data in Appendix tables of Read, R. A. 1957. "The Great Plains Shelterbelt in 1954." Neb. Agr. Expt. Sta. Bul. 441, Great Plains Agricultural Council Pub. 16.

2. The following descriptions are briefed from the bulletin:

Site A-1:	River and stream valley lowlands of deep, permeable loam soils, less than 20 feet to water table.
Site B-1:	Upland medium to deep silt loams, more than 30 feet to water table.
Site B-2:	Upland medium to deep sandy soils, more than 30 feet to water table.
Site C-1:	Upland shallow to medium silt loams underlain by tight silty clays, more than 30 feet to water table.

B-2 with open wind velocities up to 40 miles per hour but was not effective with higher wind velocities and was not adapted to B-1 and C-1 sites. Here it should be noted that the most effective belt, J, was measured in a foliated condition. Its effectiveness in winter would probably be reduced to that of belt K, a comparable belt; thus, the 5-row belt would move to second place following the 10-row belt O, during the defoliated season.

The least expected protection for all soil sites is shown by belts A, H, D, and F. The poor ratings of belts A and D, single rows of Osage-orange in winter and summer condition, respectively, can be credited to too much porosity and the slow growth expectancy of the Osage-orange. Belt F, a single-row cottonwood, was too porous to be effective at high wind velocities when measured in a foliated condition; therefore, it would be even less effective under winter conditions. The poor rating of belt H can be credited to the slow growth expectancy of redcedar and to the fact that it provided too dense a barrier without extended leeward reduction in velocity.



BELT	HEIGHT	COMPOSITION
D	16'	1-row Osage-orange
F	63'	1-row cottonwood
G	13'	2-row mulberry
H	16'	3-row conifer shrub
M	22'	6-row deciduous-coniferous

Fig. 9.—One-foot elevation velocity ratios U_L/U_o obtained leeward of five narrow field shelterbelts. (U_L is the average leeward velocity and U_o is the average open field velocity for the same time period and elevation.)

DISCUSSION AND CONCLUSIONS

The data presented in this publication demonstrate that such factors as potential rate of growth of the various tree species, choice and orientation of species within the belt, and the level of wind velocity have considerable influence on the actual and potential protection expected from a shelterbelt. The importance of these factors makes some discussion appear appropriate.

An examination of the rank of the shelterbelts in terms of the effectiveness index shows that the top three summer condition belts are a 2-row, a 3-row, and a 5-row, and the three best winter belts are a 10-row, and 5-row, or a 1-row Osage-orange. This indicates that it is not so much the number of rows as it is the porosity or density of the barrier formed that governs the effectiveness of a shelterbelt. The data further show that there may be some practical limits which determine the fewest number of rows needed in a shelterbelt. For example, the single-row barriers tested here, particularly those in a foliated condition, were about as effective as wider belts; they also were most effective in terms of effectiveness index per row and certainly such belts would be most desirable for economical use of agricultural land. Field experience in Canada and in the Northern Plains of the U.S. has also indicated that single-row belts can be used and maintained as wind barriers in those areas. However, where climatic conditions do not favor species effective as single barriers it may not be possible to meet the year-round porosity requirements and the very important necessity for tree survival to insure a continuous barrier with a single row of trees. Here, wider belts of two to five rows may provide a more effective barrier and more insurance against gaps due to loss of trees.

The importance of height of the dominant tree species within a given shelterbelt is emphasized by results of this study. For example, the 2-row mulberry had a high effectiveness index and a relatively long length of protection in belt height, H units, but this belt was only 13 feet high. Simple arithmetic shows that even if this belt affords protection to 30 H, that is still only 390 feet of protected field length. The effect of height is perhaps more evident in the 15-year expected influence analysis where the single-row cottonwood, because of its fast growing characteristics, has the potential of protecting a greater length of field than does a belt containing a very slow growing species such as redcedar. This is true despite cottonwood not producing so dense and so efficient a barrier in terms of unit height as does redcedar.

The data also show that shelterbelts may be too dense as well as too porous. Several of the shelterbelts measured, particularly those containing coniferous tree rows, over-reduce the wind velocity. The amount of reduction required would vary with the function of the belt, i.e., what it is protecting, and with the levels of wind velocity expected in a given region. For wind erosion control in Kansas and Nebraska it appears that a 60-percent reduction would be a tolerable maximum. Such a reduction would be sufficient to reduce 50-mile-per-hour, 50-foot elevation winds to the average ultimate 14-mile-per-hour velocity at the 1-foot height required for initiation of soil movement. According to Zingg (16) winds of 50 miles per hour lasting 1 hour can be expected at Dodge City, Kansas, only once in 6.5 years and those of 3-hour duration only once in 8 years.

Previous research (14) in Kansas has also shown that excessive reduction in wind velocity to the leeward of shelterbelts causes air stagnation with a marked decrease in turbulent mixing and heat exchange accompanied by increases of temperature of as much as 10 to 12°F. Although research data are limited, there is an indication that such drastic changes in microclimate to the leeward of the belt increase transpiration rates of plants which, in hot climates, can inhibit growth. Farmers in Kansas are cognizant of these effects and many have thinned wide, dense plantings (Figure 10). The man who owned this shelterbelt indicated that its density inhibited plant growth, created an ideal environment for insect activity, and

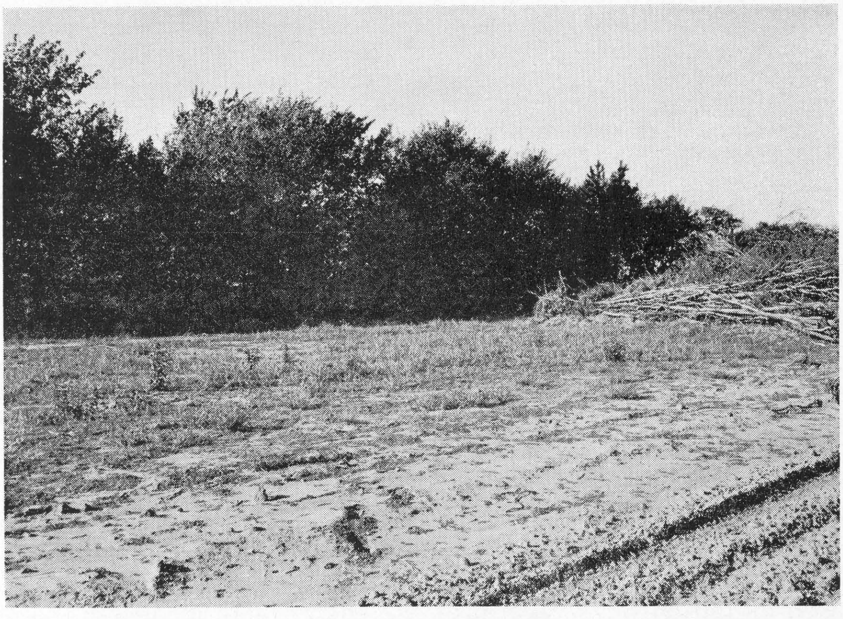


Fig. 10.—An example of removing tree rows to increase the porosity of a shelterbelt. Three rows were removed from this original 7-row belt, leaving a pine, a mulberry, a redcedar, and a shrub row, in that order, front to back as pictured.

caused a more rapid decay of residues which he was trying to maintain on his field to control wind erosion and to conserve moisture. All of this indicates that the shelterbelt should be planned with both the minimum and maximum reduction capabilities in mind. There is some difference of opinion as to what constitutes ideal belt porosity. This study has indicated that a belt having moderate porosity in the crown with slightly more porosity near the ground such as that obtained with a 2-row mulberry in summer (see photograph Figure 3) would be ideal for maximum protective efficiency. Previous wind tunnel research (13) has indicated this to be desirable; however, Caborn (3) has indicated that a barrier of moderate porosity from ground to crown might have maximum effectiveness.

While it should be emphasized that the zones of wind erosion protection are computed and not measured, they are based on the average ultimate threshold velocities required to initiate soil movement and it is believed they provide a fairly reliable indication of the protection the belts will provide. It is important to note, however, that the distances given are measured along the direction of the wind at the center of the belt's length. Since the area of protection to the leeward of an isolated barrier is parabolic, with the vertex located at the farthest distance from the belt, it follows that a relatively small area would be protected from erosion at the extreme leeward distances. This indicates the need and importance of a complete barrier system designed to provide not only extended protection across fields but also protection from crosswinds.

The spacing intervals for a supplemental belt system must be determined from considerations of the growth rate of different tree species, the porosity of the belt as it is related to the winter and summer conditions, and the general level of wind velocity for different geographic regions. Some of this information is given in Tables 4 and 5. For example, if a system is designed to provide protection from a 30-mile-per-hour wind at the 50-foot elevation 15 years after planting, Tables 4 and 5 show that 5-row plantings similar to belt J with a Siberian elm as the dominant tree could be spaced at 707- and 499-foot intervals on A-1 and C-1 soil sites, respectively. However, if the system were designed for 50-mile-per-hour winds, the spacing interval for this same type of belt would be cut to 381 and 269 feet, respectively, for A-1 and C-1 soil sites. On the other hand, if the system were designed to protect while in winter condition, Tables 4 and 5 show that 5-row belt K, measured in winter condition and also having a Siberian elm as the dominant species, could be planted at about 432-foot intervals on A-1 sites and at 305-foot intervals on C-1 sites under conditions of a 30-mile-per-hour wind measured at the 50-foot elevation. If the design wind velocity were 50 miles per hour at the 50-foot height, then the spacing interval for this winter condition would be cut to 214 and 151 feet, respectively, for A-1 and C-1 soil sites.

From these computations it is apparent that a complete system should be designed on a basis of growth potential of the dominant species, a consideration of whether protection will be desired when the trees are foliated or defoliated, and the general level of wind velocity for different geographic regions. If belts are planted in Kansas and Nebraska to provide protection from wind erosion, the system should be designed for the winter condition because about 90 percent of the wind erosion occurs when the trees are defoliated. The spacing intervals determined here under design conditions of 30 miles per hour at the 50-foot elevation are in fair agreement with the 400 and 600 feet indicated for the Northern Plains (7) and the standard spacing of 440 to 660 feet for single-row caragana systems in the dry subhumid area of Canada (10). However, the spacing intervals indicated here for winter conditions and 50-mile-per-hour winds are considerably less, particularly on the poorer soil sites, than the Canadian and Northern Plains recommendations. Design conditions were not specified for those recommendations; however, since experience has shown them to be effective, and since examples worked out here using 30-mile-per-hour velocities give comparable results it appears that 50-mile-per-hour velocities are too high for use in designing field systems in Canada and the Northern Plains. In Kansas and Nebraska where the general level of wind velocity is higher than in the Northern Plains, 40- to 50-mile-per-hour design velocities would probably provide the most effective belt system. Wind records for a given geographic region should be carefully studied, however, before choosing a design velocity for any shelterbelt system.

SUMMARY

Wind velocity data were taken in the open and to the leeward of 15 field shelterbelts to determine their effectiveness in reducing wind velocities.

Results are presented in terms of velocity-reduction curves, effectiveness indexes, indicated wind-erosion-protected zones, and an estimated extent of influence 15 years after planting which is based on the rate of growth of the dominant tree species on different soil-site conditions.

The results showed that it is not so much the number of rows as it is the porosity or density of the barrier formed that governs the effectiveness of a shelterbelt. For example, some single-row belts were more effective than some 3-, 5-, and 7-row belts and conversely some 5- and 10-row belts were more effective than single or 3-row belts. Of the belts tested, the three most effective ones in the summer were a 2-row mulberry, a 3-row all deciduous, and a 5-row deciduous-coniferous combination. The three best belts in the winter were a 10-row deciduous-coniferous, a 5-row deciduous-coniferous, and a single-row Osage-orange hedge. Single-row barriers had a high effectiveness index per row of trees—an important attribute if economical use of land and cost are to be considered.

A relative comparison of the velocity-reduction efficiency of several different tree species, made from the summer condition single-row belt effectiveness index data, showed the Osage-orange to be most effective followed in order by arborvitae, Siberian elm, cottonwood, and jack pine.

Leeward distances which would be fully protected from soil erosion by wind were shown to vary from a maximum equal to 33 times the belt height for a 2-row foliated mulberry with a 30-mile-per-hour, 50-foot elevation wind velocity to zero for 1-row defoliated Osage-orange hedges and 1-row foliated Siberian elm barriers when the wind reached 70 miles per hour. For a 40-mile-per-hour velocity at a 50-foot elevation, the maximum protected length in terms of barrier heights, H, was 18 H for 2-row foliated mulberry. The minimum was 8 H for a 1-row foliated cottonwood belt. The average for 10 belts, some foliated and some not, was 12.8 H.

The 15-year expected extent of influence analysis showed that a 5-row foliated belt composed of plum, cedar, mulberry, green ash, and a Siberian elm could be expected to provide the longest distance fully protected from wind erosion on all four soil-site conditions evaluated and for levels of wind velocity ranging from 30 to 70 miles per hour measured at the 50-foot elevation. For winter conditions, a 10-row deciduous-coniferous combination provided the longest protected length. A single-row foliated cottonwood because of its more rapid rate of growth would provide the third longest extent of influence on soil sites to which it is adapted and under conditions of wind velocity less than 40 miles per hour. Shelterbelts composed entirely of coniferous species were generally found too dense and too slow-growing to provide an ideal wind barrier. However, their use, if properly spaced or trimmed to provide porosity near the ground, is indicated in combination with deciduous trees.

Data given for distances protected from wind erosion and for growth potential of trees were used in conjunction with different levels of open wind velocity to demonstrate how the required planting interval for a system of shelterbelts can be determined. Examples were workd out for two different soil sites for a summer and a winter condition, 5-row deciduous-coniferous combination having a Siberian elm as the dominant species. The spacing interval was shown to vary from 151 feet for the winter belt on C-1 (shallow upland) soil sites with 50-mile-per-hour, 50-foot elevation winds to 707 feet for the summer belt on A-1 (river valleys) sites with 30-mile-per-hour, 50-foot elevation winds.

REFERENCES

1. Baltaxe, R. Shelter planting practice. The Royal Scottish Forestry Society **15**(1):17-32, 1961.
2. Boylshev, N. N., and Solov'yev. Soil investigation methods on State farms organized on virgin soil. Soviet Soil Science **4**:388-396, 1958.
3. Caborn, J. M. The dependence of the shelter effect of shelterbelts on their structure. Paper SP/63/VII-V.K. Fifth World Forestry Congress, pp. 2, 3, 1960.
4. Chepil, W. S., and Milne, R. A. Wind erosion of soil in relation to size and nature of the exposed area. Sci. Agr. **21**:479-487, 1941.
5. Chepil, W. S. Wind erosion control with shelterbelts in North China. Agron. Jour. **41**:127-129, 1949.
6. Ferber, A. E. Windbreaks in conservation farming. U.S. Dept. of Agr., Soil Conserv. Service Misc. Pub. No. 759, 22 pp., illus., 1958.
7. George, E. J. Shelterbelts for the Northern Great Plains. U.S. Dept. of Agr. Farmers' Bul. No. 2109, 16 pp., illus., 1957.
8. Read, R. A. The Great Plains shelterbelt in 1954. Nebr. Agr. Expt. Sta. Bul. 441. Great Plains Agricultural Council Pub. 16, 126 pp., illus., 1957.
9. Staple, W. J., and Lehane, J. J. The influence of field shelterbelts on wind velocity, evaporation, soil moisture, and crop yield. Canadian Jour. of Agri. Sci. **35**:440-453, 1955.
10. Staple, W. J. Vegetative management and shelterbelts in evaporation control. Paper presented at Second Canadian Hydrology Symposium, 1961.
11. Woodruff, N. P., and Zingg., A. W. Wind tunnel studies of fundamental problems related to windbreaks. U.S. Dept. of Agr. SCS-TP-112, 1952.
12. Woodruff, N. P., and Zingg, A. W. Wind tunnel studies of shelterbelt models. Jour. of Forestry **51**(3):173-178, 1953.
13. Woodruff, N. P. Shelterbelt and surface barrier effects on wind velocities, evaporation, house heating, snowdrifting. Kansas Agr. Expt. Sta. Tech. Bul. 77, 1954.
14. Woodruff, N. P., Read, R. A., and Chepil, W. S. Influence of a field windbreak on summer wind movement and air temperature. Kansas Agr. Expt. Sta. Tech. Bul. 100, 1959.
15. Zingg, A. W., Chepil, W. S., and Woodruff, N. P. Analysis of wind erosion phenomena in Roosevelt and Curry counties, New Mexico. (Published by Region VI, Soil Conservation Service, Albuquerque, New Mexico) M436, May 1953.
16. Zingg, A. W. The intensity-frequency of Kansas winds. U.S. Dept. Agr. SCS-TP-88, 1950.