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Wind Tunnel Studies of Shelterbelt Models[1]

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This study was initiated with two purposes in mind: (1) to obtain quantitative measurements of the protective effects of the number of rows of trees and shrubs within a shelterbelt, and (2) to obtain information on their design and orientation with respect to wind direction.

A single row of trees that would attain a uniform height and retain branches to the ground would, in theory, perform many of the functions expected of a shelterbelt and occupy the least area. Certain factors, however, such as attacks of insects, fungi, unforseen soil and soil moisture conditions, ice, lightning, and livestock have tended to render the single-row field shelterbelt impractical. Single-row shelterbelts are not necessarily out of the picture as illustrated by successful osage orange plantings in south central Kansas. There is need, however, for additional trial and observation to ascertain their desirability or adaptability with respect to species and location.

Shelterbelts with 10, 7, 5, 4, 3, and 2 rows have been recommended. Wide belts have the advantage of providing both early and late protection due to the several species of trees and shrubs ordinarily planted. They also provide the so-called forest condition, woodlots, and a habitat for propagation and self-preservation of the trees within the shelterbelt. It is for these reasons that 10-row shelterbelts have been used generally. A disadvantage of wide belts is their utilization of considerable land area which could otherwise be used for agricultural crops.

Investigators have reached varying conclusions concerning the number of rows a shelterbelt should contain. A pamphlet entitled "Tree Windbreaks for the Southern Plains" (*3*) recommends that the majority of shelterbelts be planned with 3 or 4 permanent rows. Bates (*1*) indicates that the wide windbreak's value for field protection is not as great as that of a narrow one containing fewer rows. An S.C.S. handbook for farm planners (*2*) does not consider that the 5-row, or even the 7-row, belt meets all requirements of a "dual purpose" planting as well as does the 10-row belt.

Several little-understood aspects of the shelterbelt problem exist. This study is concerned primarily with the aerodynamic features. Certain characteristics of the shelterbelt such as orientation with respect to wind direction, number of rows of trees and shrubs, and overall design in terms of air flow and conditions of protection in the vicinity of the belt may be evaluated in principle by the use of models. The study of model shelterbelts ignores silvicultural problems but provides controlled conditions of height, spacing, and other factors. Such conditions are somewhat theoretical and do not usually occur in the field.

Procedure

This experiment was conducted in a wind tunnel described previously (*5*). The working section used for the study consisted of a 12-foot horizontal length beginning at a point 40 feet downwind from the fan. The top of the tunnel for the experimental section was constructed to facilitate horizontal movement of a staff of Pitot tubes throughout the 12-foot length. The floor of the tunnel consisted of gravel of size range $> 1/6$ and $< 1/4$ inch. A turbulent boundary layer several inches in depth was developed beyond the 40-foot point.

The model shelterbelts used in the tunnel experiments were fabricated from cedar boughs placed in short lengths of ¼-inch aluminum tubing. The "trees" were oriented in a series of holes drilled in a 20- x 36-inch plywood base. Eight rows of larger "trees" and two rows of "shrubs" were prepared. They could be moved in any manner desired and 10-, 7-, and 5-row belts were assembled. The scale used for the models was 1 inch to 5 feet. Thus, in terms of the prototype condition, the lowest shrub in a 10-row belt was 7.5 feet, the tallest tree was 30 feet, and the remainder of the trees were graduated upward in 2.5-foot increments from 7.5 feet to 30 feet. Spacing between the rows was 2 inches on the model, corresponding to 10 feet for field conditions. Spacing within the rows for the trees was also 2 inches, or 10 feet. Spacing within the rows for the shrubs was 1 inch, or 5 feet. This spacing provided 36 trees and shrubs in a 10-row belt, 27 trees and shrubs in a 7-row belt, and 21 trees and shrubs in a 5-row belt for each unit H^2 length of belt. Two different 10-row belt designs were constructed. Each of these was reversed with respect to wind direction, making four different conditions pertaining to a 10-row belt. Seven- and 5-row belts were also tested using a single wind direction orientation for each. The various designs and orientations used in the study are shown in side view in Figure 1.

Figure 2, showing two views of a 10-row design, demonstrates the orientation of a belt in the wind tunnel. All of the models were placed in the tunnel 42 feet downwind from the fan. The flow of air about each model was studied through use of horizontal velocity measurements and patterns of erosion in a sand surface to the lee of the belt. The equipment and procedure for these two measurements has been described previously (*4*).

Horizontal velocity measurements were made at 12 heights and

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[2]$H = 6$ inches in the model or 30 feet in the actual belt and is the tallest tree in a given belt.

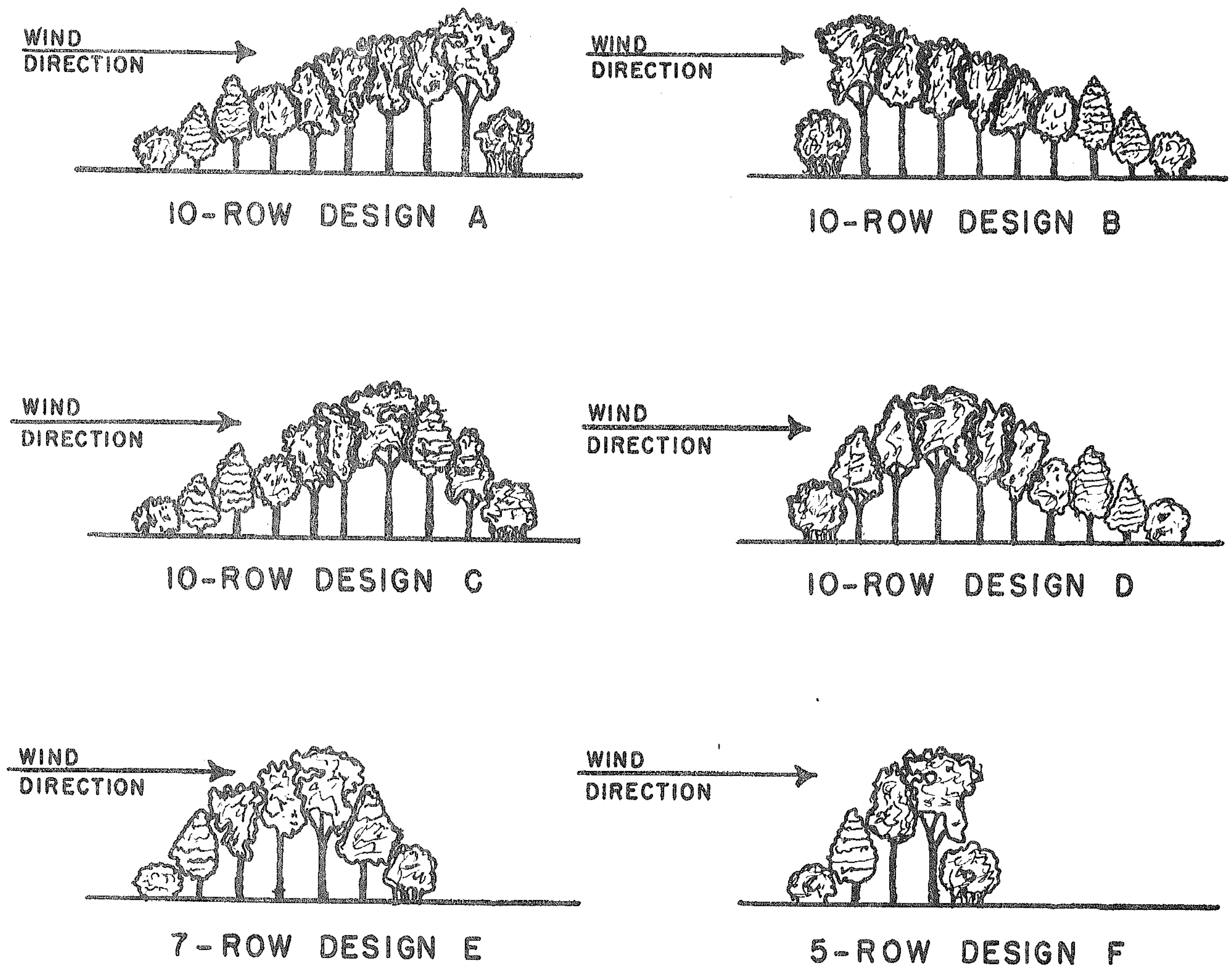


FIG. 1.—Sketches showing the wind orientation and number of rows of trees for the shelterbelt models used in this study.

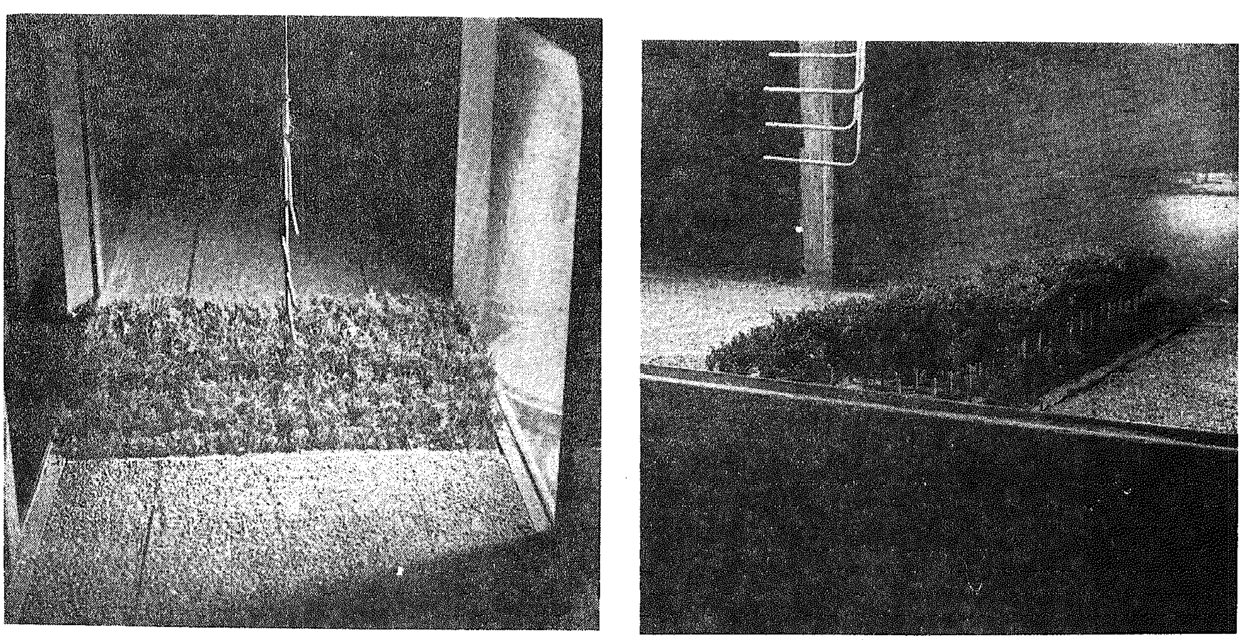
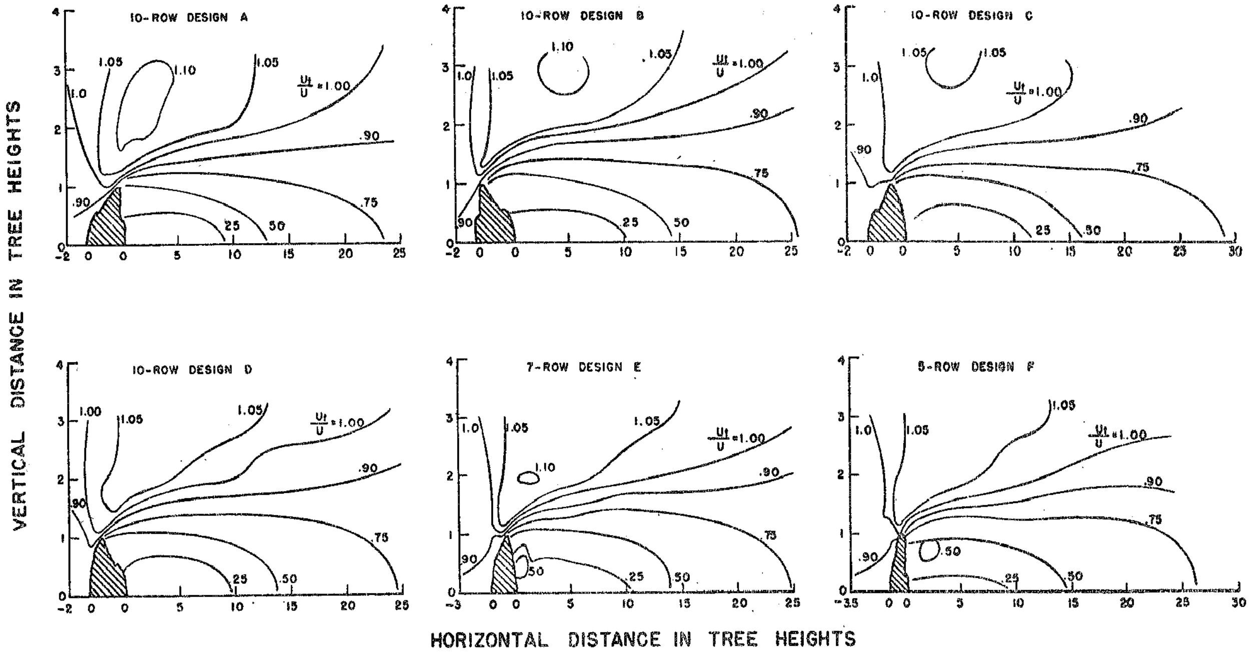


FIG. 2.—Side and top views of one of the 10-row model shelterbelts oriented in the wind tunnel.

FIG. 3.—Velocity ratios $\frac{U_t}{U_c}$ obtained in the vicinity of six shelterbelts of varying design.



23 locations in the air flow. A constant wind velocity of 31 mph. was maintained at an elevation of 2 H above the trees. Velocity profiles were obtained by plotting the dimensionless ratios $\frac{z}{H}$ and $\frac{U_t}{U_c}$, where

z = elevation above datum
H = height of the tallest tree in the belt
U_t = velocity in tunnel with shelterbelt in position
U_c = velocity at corresponding point in a clear tunnel

Vertical and horizontal distances on the profile maps are shown in terms of tree heights, H. The ratios, when plotted on the maps, indicate the changes in velocity attributed to each of the belts. This type of analysis describes the flow in a zone extending from an elevation of 0.1 H to 3.1 H vertically and from 2 H windward to approximately 23 H leeward of the belts horizontally.

The method of shear patterns has been described in detail previously (*4*); therefore, only a brief summary will be given here. It is based on the concept that the velocity ratio $\frac{u}{u_o}$ is related to levels of shear as follows,

$$\frac{u}{u_o} = \sqrt{\frac{\tau}{\tau_o}}$$

where u_o is the threshold velocity for a given erodible material in a clear tunnel, u is a velocity of known magnitude greater than the threshold also measured in a clear tunnel, τ_o is the threshold shear, and τ is a shear of known magnitude greater than the threshold. Dune sand of size 0.30-0.42 mm. was used as an experimental vehicle. Four levels of wind, each yielding values of $\frac{u}{u_o} > 1$, were passed over the trees and sand, and the boundary of sand remaining at the end of each test denoted the approximate location at which the belt reduced the shear at bed level to τ_o. This is the equivalent of reducing the value of $\frac{u}{u_o}$ to unity at the same location. This reduction is termed the effective velocity reduction. Expressed as a percent it is:

$$\text{Effective velocity reduction} = \frac{100\left(\frac{u}{u_o} - 1\right)}{\frac{u}{u_o}} = 100\left(1 - \frac{u_o}{u}\right)$$

When the data obtained in this manner are plotted, they yield dimensionless curves which describe the effect of the wind on the ground to the lee of each of the belts. Benefits may be expressed in terms of apparent limits of influence, effective percent velocity reductions at any distance from the belt, effectiveness per tree, and indexes of protection (area under curve), irrespective of the velocity of the wind.

Results

Horizontal Velocity Measurements—0.1 H to 3.1 H Elevation

The effect of each of the belts on the horizontal velocity of air flow is shown in Figure 3. Consideration of the zone above the trees indicates that a shelterbelt of design 10-row-A creates the largest area of increase in velocity (ratio equals 1.10) at locations close to the belt. Design 10-row-B also shows a small area of 1.10 increase in velocity but it is located farther to the lee of the belt. The 7-row-E design gives a very small area of 1.10 increase, and the remaining three designs show a maximum increase of 1.05. Designs 7-row-E and 5-row-F show the effects of lessened density and the consequent jetting of air through the trees by the pools of only 50% reduction found immediately aft of the belts.

The effect of each of the six belts at an elevation of 0.1 H is summarized in the following short table. The shelterbelts are ranked in order of their effectiveness in creating 25 and 50 percent reductions in wind velocity. Percentage reductions in wind velocity are equal to $100\ (1 - \frac{U_t}{U_c})$.

Type of Shelterbelt (Number of rows and letter designation)	Distance to 0.1 H to: 75% reduction	50% reduction	25% reduction
10-Row-C	11.5 H	16.1 H	29.0 H
5-Row-F	9.1 H	14.5 H	26.4 H
10-Row-B	10.2 H	14.3 H	25.5 H
7-Row-E	10.3 H	13.9 H	24.8 H
10-Row-D	9.6 H	13.8 H	24.5 H
10-Row-A	9.3 H	12.8 H	23.4 H

Effects on Surface—By Method of Shear Patterns

The effect of each of the shelterbelt designs on the ground surface to the lee of the belt, as determined from shear or erosion patterns in sand, is shown in Figure 4. The dashed portion of the curves indicates extrapolation to determine points of maximum effective velocity reduction. The curves for all of the 10-row designs show maximum reductions occurring in close proximity to the leeward row. This decreases gradually with increasing distance from the belt. The curves representing conditions near the belts of 7-row-E and 5-row-F designs differ from those derived for the 10-row arrangements. This is due to their greater porosity. Air jetting through the trees causes erosion to occur immediately to their leeward. The point of maximum reduction is located approximately 2 H aft of the belts. It will also be noted that the 5-row arrangement gives a slightly greater maximum than the 7-row belt. A summary of pertinent data from Figure 4 is given in Table 1. The data are presented in the order of the belt's effectiveness as measured by the "index of protection."

Discussion of Results

Differences in protective features between some of the belts are small. Definite conclusions regarding their relative merits should be made only with reservation in these instances. Form and density are interrelated in their effects, and clear-cut separations of the influences of each factor cannot be made at the present time. While not all the results are understood clearly, certain real differences seem to exist.

Evaluation of the effectiveness of different designs is dependent upon the elevation above the ground level in which one is interested. Horizontal velocity measurements cannot measure the condition at the ground level. They do, however, show conditions at levels ranging from 0.1 H to 3.1 H. This zone would be of primary importance in considering protection to farm buildings, livestock, orchards, or crops. The horizontal velocity measurements indicate the following comparative influences of the various belts in the zone 0.1 H to 3.1 H.

1. A 10-row shelterbelt of design C, where the wind approaches the slope of the belt as shown in Figure 1, gives maximum protection in terms of distances to 25 and 50 percent reductions at 0.1 H. It does not create ás large a zone of accelerated flow above and to the aft of the shelterbelts as do several

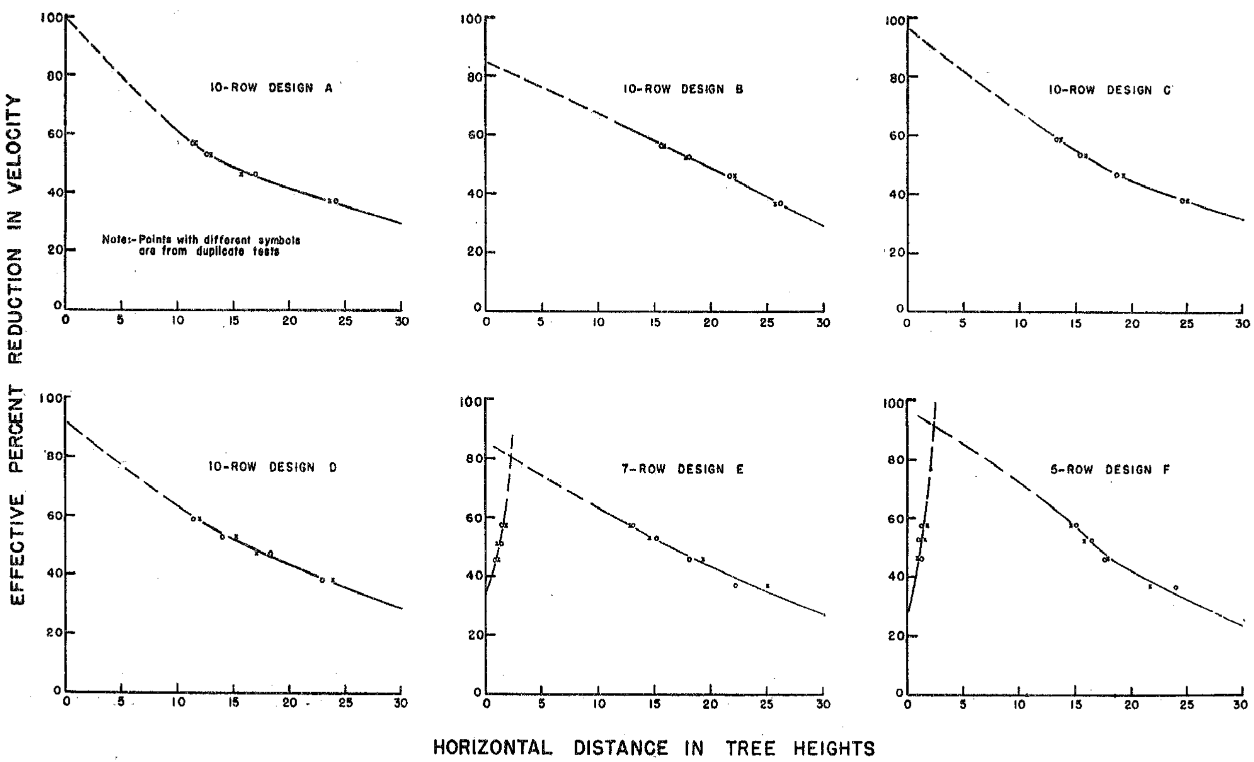


FIG. 4.—Dimensionless curves showing effective velocity reductions at the bed level to the lee of shelterbelts. Values obtained from erosions patterns in sand placed on floor of wind tunnel.

TABLE 1.—A SUMMARY OF VELOCITY REDUCTIONS, APPARENT ZONES OF INFLUENCE, NET ZONES OF EFFECTIVE VELOCITY REDUCTION, INDEXES OF PROTECTION, AND EFFECTIVENESS PER TREE FROM FIGURE 4

Type of windbreak (Number of rows and letter designation)	Approximate maximum effective velocity reduction and distance to lee of windbreak: Distance	Reduction	Apparent limit of zone of influence[1]	Zone of effective velocity reduction[2] Net distance: 50%	25%	Index of protection (area under curve)	Effectiveness per tree[3] per unit H length of belt
	H units	*%*	*H units*	*H units*	*H units*		
10-Row-C	0	96.0	57.5	17.0	35.5	22.4	0.62
10-Row-A	0	100.0	54.0	14.0	34.0	20.0	.56
10-Row-B	0	85.0	47.0	19.4	32.3	19.8	.55
10-Row-D	0	91.0	53.0	16.0	31.5	19.5	.53
5-Row-F	2.4	92.0	46.0	15.7	27.8	18.3	.87
7-Row-E	2.4	80.0	50.0	15.3	30.5	18.1	.67

[1]Apparent limit of zone of influence = Point of zero effective velocity reduction as determined by extrapolation of the curves of Figure 4.

[2]Zone of effective velocity reduction = Net distance to points of 25% and 50% reduction after allowance for zones of lesser reduction caused by jetting of air through the trees.

[3]Effectiveness per tree $= \frac{\text{Index of protection}}{\text{Number of trees per unit H length of belt}}$

of the other designs. It should be noted that if this same design is turned around so that the wind approaches from the opposite direction (design D) it ranks fifth in effectiveness. This would indicate that a consideration of the direction of the prevailing winds for a given area would be of importance. A shelterbelt of design C is the conventional 10-row shelterbelt recommended in the Farm Planner's Handbook (*2*).

2. A shelterbelt of design A, which is an alternate 10-row design in the handbook, ranks sixth, or last, in effectiveness if the wind approaches the slope of the belt, or it ranks third if the tall trees are placed to the windward as in design B (Fig. 1).

3. The 5-row-F belt ranks second in comparison to the other designs. It does not cause as high a zone of accelerated flow as do some of the belts. However, it shows a zone of rather low velocity reduction near the belt due to less density and consequent jetting of air between the trees.

4. The 7-row belt, design E, ranks fourth in order. Apparently, it offers little advantage over the 5-row belt.

Surface protection to the lee of a shelterbelt is important with respect to erosion of soil by wind and for protection of very small plants. The method of shear patterns gives a good indication of the degree of protection at the ground surface. Table 1, which summarizes these results, indicates the following:

1. A 10-row shelterbelt of design C ranks first with respect to "apparent limit of zone of influence." net zone of effective 25% reductions in velocity, and index of protection.

2. A belt of 10-row design A apparently offers maximum reductions near the belt and ranks second with respect to index of protection and apparent limit of zone of influence.

3. 10-row design B and 10-row design D are quite similar as measured by the index of protection. However, 10-row D apparently has a zone of influence greater in length than does 10-row-B.

4. 7-row design E has a longer zone of influence than 5-row design F. Both designs rank nearly the same in terms of index of protection but are substantially less effective than the 10-row shelterbelts in this respect.

5. The greatest effectiveness per tree planted is shown for the 5-row shelterbelt, followed by the 7-row, 10-row design C, 10-row design A, 10-row design B, and 10-row design D.

In summing up the overall effectiveness of the various belts as exemplified by both methods of study, it appears that the maximum protection is obtained from a 10-row belt of design C (Fig. 2). This is true at both surface and higher elevations. Selection of a second choice would depend upon which elevation was being considered. A 10-row belt of design A appears desirable if surface protection is the main objective; however, if protection at points above the ground is needed, 10-row design B would be preferred. If the woodlot and self-propagation features can be ignored, and a species of trees can be planted to withstand the attacks of insects and diseases, the 5-row belt would be an excellent design. This belt ranks fairly well for ground protection and very well at higher elevations; its effectiveness per tree is high; and the overall protection for the amount of land utilized is the greatest of those tested. The 7-row belt, which is a compromise between a 5- and a 10-row belt, apparently has little advantage over the 5-row belt other than the opportunity for planting more fast-growing species due to the availability of more rows.

A study of this type raises certain questions and problems which should be noted. Probably the most important is that of applying wind tunnel results directly to atmospheric conditions. This is a speculative approach and depends for its validity upon the applicability of the Reynolds number in depicting similarity of flow patterns. Direct application of this parameter to the atmosphere is somewhat problematic for conditions of turbulence associated with the lapse rates of temperatures often present under atmospheric conditions.

Other limitations involved in a study of this type have been discussed previously (*4*).

Summary

Wind tunnel studies were conducted to obtain information on the following two phases of the shelterbelt problem: (1) the effect of the number of rows within a shelterbelt, and (2) the general design and orientation of shelterbelts with respect to the direction of the prevailing winds. Models of a 5-row, 7-row, and two different designs and two orientations of a 10-row shelterbelt were used in a wind tunnel to obtain this information.

The influence of the shelterbelt both at the ground surface and at elevations extending to three times the height of the tallest trees is given. Pitot tube measurements of horizontal velocity, velocity profile maps and shear or erosion patterns in sand are employed to describe the flow about the shelterbelts.

The different shelterbelts are ranked according to their effectiveness in reducing the velocity at the ground surface and at elevations above the surface. A 10-row shelterbelt of conventional design was found to be the most effective at both levels. The alternate designs of 10-row belts were less effective or were variable in their effectiveness, with some designs showing relatively more effectiveness at higher elevations than at the surface. The 5- and 7-row shelterbelts were found to offer nearly as much protection as the 10-row designs.

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