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A METHOD FOR CATEGORIZING SHELTERBELT POROSITY

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ABSTRACT

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Porosity is recognized as the most important single parameter describing shelterbelts. However, porosity is a very difficult variable to measure or define. This paper describes a method for categorizing wind breaks in terms of porosity the wind sees, using only measured minimum leeward-wind velocity.

Wind velocities at a height of 1.4 m were measured behind shelterbelts of different porosity. A double row of hardwood trees (high porosity), a medium porosity mixed stand, and a dense pine stand (low porosity) were used. Wind velocity declined to a minimum at 1—4 tree-heights leeward of the trees and then gradually increased to open-field velocity. The field data show that the wind measurements could be made at any height without affecting relative reduction in velocity. The data indicate that the minimum relative wind velocity behind the shelterbelt could be used as an index to compare the porosities of different shelterbelts.

Comparisons were made to Dyunin's analysis for surface-wind velocities leeward of uniformly porous barriers. The analysis indicates that tree-stand porosity is the dominant parameter governing the wind reduction obtained, while the range of sheltering is controlled by the amount of local turbulence and the turbulence present in the atmosphere beforehand.

INTRODUCTION

Wind breaks have been used many years for crop protection, soil erosion, and increased snow deposition. Numerous studies describe the effect of wind breaks on various atmospheric parameters such as temperature, evaporation, wind velocity, water-vapor content, and carbon dioxide concentration. But no suitable method has been found to compare the results of tests using different wind breaks. As mentioned in the abstract, porosity is recognized as the most important single parameter describing shelterbelts. However, porosity is a very difficult variable to measure or define. This paper describes a method for categorizing wind breaks in terms of porosity the wind sees, using only measured minimum leeward-wind velocity.

We have made several basic assumptions. First, the influence of surface roughness and ground friction have been neglected. This assumption is justified later using field data. Second, wind penetration through tree wind breaks is pictured to be due mostly to the jetting of air around the tree trunks between ground surface and tree crown level.

To analytically describe the behavior of the wind, we utilized Dyunin's (1964) solutions for wind velocity near the ground behind porous barriers. The resultant theoretical predictions are compared with measured wind-velocity patterns leeward of three tree stands of distinctly different porosity.

THEORY FOR WIND FLOW BEHIND POROUS BARRIERS

Wind flow leeward of porous barriers may be broken down into three different flow regimes (Fig. 1) (Dyunin, 1964). In the first flow regime, the jetting of many individual air jets occur through the openings of a porous barrier. Within a short distance leeward of the barrier, the jets merge to mark the beginning of the second flow regime. The third flow regime develops when air flow over the barrier begins to impart some of its greater momentum to the flow field behind the barrier. The lowest leeward-wind velocity occurs just before the air flow over the barrier influences the flow field and begins to increase the surface-wind velocity.

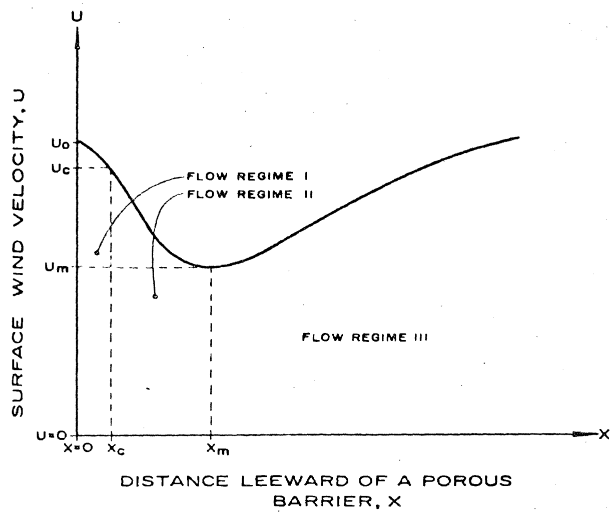

Fig. 1. The three flow regimes behind a porous barrier.

The "surface-wind velocity" for theoretical calculations is based on the velocity at height $z = 0$. In the actual or field situation, the velocity at $z = 0$ is zero due to surface friction effects. In this case the term "surface-wind velocity" denotes the wind velocity within several meters of the ground. We will show that the actual height of measurement is not important when the velocity is normalized by the open-field wind velocity at the same height.

The "penetration velocity" through a porous barrier is not the velocity through the openings of the barrier, but is rather the average velocity just leeward of the porous barrier if the flow were evenly distributed. The minimum surface-wind velocity at the boundary between regimes II and III approaches the penetration velocity.

Theoretical Results

Dyunin (1964) has solved the appropriate equations for the flow behind a uniformly porous slat-like barrier of height H. We will not repeat his theory here, but will simply present his final equations in a non-dimensional form. Velocities are normalized by the velocity well upwind of the barrier, U_0, that is the free-stream velocity. Heights are normalized by the height of the barrier H, and downwind distance x is normalized by $H/2a$ where a is an empirical constant.

Dyunin stated that empirical evidence shows the penetration velocity U_i to be solely a function of the porosity P, i.e.:

$$U_i/U_0 = 0.2P\,(1 + 4P) \tag{1}$$

where $P = c/(c + d)$ and c is the width of opening and $c + d$ the spacing of the openings.

His solutions for the axial velocity of an individual jet, U_c, at the downwind distance, x_c, where regimes I and II join are:

$$\left(\frac{U_c}{U_0}\right)^2 = \operatorname{erf}\left(\frac{1.5\,U_i/U_0}{1-U_i/U_0}\right) \tag{2}$$

$$\frac{2a\,x_c}{H} = \frac{1}{3}\left(\frac{c+d}{H}\right)\left(1-\frac{U_i}{U_0}\right) \tag{3}$$

In flow regime II, Dyunin used a relation from Gran Olsson in which the axial velocity of each jet, U_j, decays as a function of $1/x$. This leads to:

$$\frac{U_j}{U_0} = \frac{U_i}{U_0} + \frac{x_c}{x}\left(\frac{U_c}{U_0} - \frac{U_i}{U_0}\right) \tag{4}$$

in which U_j declines from U_c toward the penetration velocity as x increases.

In flow regime III, Dyunin superimposed the velocity of the air coming over the barrier, which was also assumed to behave like a jet, on the air coming through the barrier. Integration or summing the contributions of each jet flow from zero to infinity — noting that above some height H_k the velocity is

$U = U_0$ (Fig.2) — and applying continuity of mass in the region from $z = 0$ to $z = H_k$ yields:

$$\left(\frac{U}{U_0}\right)^2 = (h^2 - 1)\,\mathrm{erf}\left[\left(\frac{H_k}{H}\right)\left(\frac{H}{2ax}\right)\right] + \left(\frac{U_i^2}{U_0^{\,2}} - h^2\right)\mathrm{erf}\left(\frac{H}{2ax}\right) + 1.0 \tag{5}$$

where:

$$h = \frac{H_k/H - U_i/U_0}{H_k/H - 1.0} \tag{6}$$

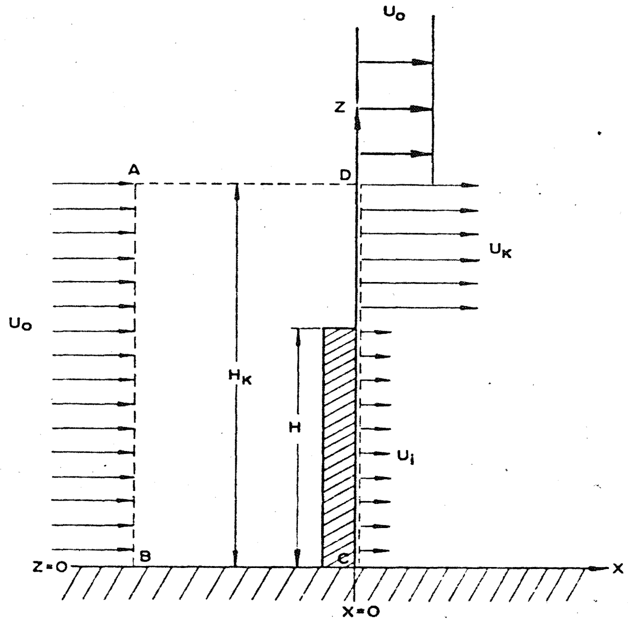

Fig.2. Idealized, frictionless wind flow through a uniformly porous barrier.

This equation shows U increasing from the penetration velocity to the free-stream velocity as x increases (Figs.3 and 4). The distance x_m, where flow regimes II and III meet, can be found from equating eqs.4 and 5.

The parameter $(c + d)$ influences the axial jet velocity, U_j, but not the penetration velocity, U_i. The effect of this parameter is small by the time the jets are nearly fully merged (Fig.3). The parameter H_k/H represents the non-dimensional boundary layer thickness of the flow over the barrier; its effect is not large as long as it is greater than about 4. The effects of $(c + d)/H$ and H_k/H are larger as P is larger, but they are small in the range of minimum velocity.

The theory indicates that the individual jets have almost fully merged so that U_j is nearly equal to the penetration velocity, U_i, before flow over the

top of the barrier begins to have an effect (Figs.3 and 4). The minimum axial jet velocity is always close to the penetration velocity; it thus is little affected by variation in $(c + d)/H$ or H_k/H and depends almost completely on the porosity, P, alone. Hence, porosity becomes the controlling factor for the amount of wind reduction behind the barrier.

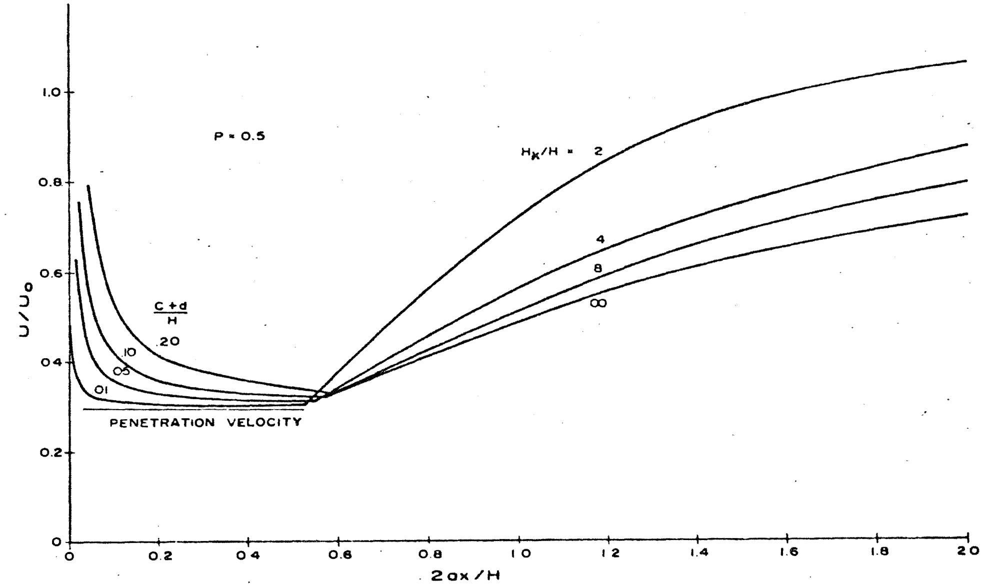

Fig.3. Effect of barrier geometry on theoretical wind velocity reduction.

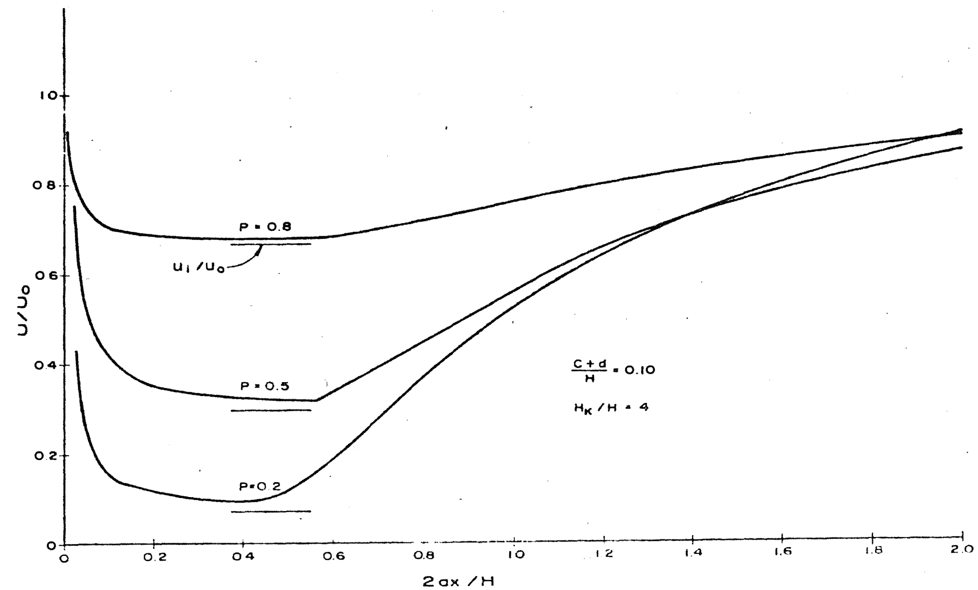

Fig.4. Theoretical wind velocity reduction.

The location of the minimum axial jet velocity, x_m, depends very little on $(c + d)/H$, H_k/H, or P and is essentially fixed at about $2ax_m/H = 0.5$ (Fig.4). Thus, the height of the stand, H, and the empirical constant, a, which is related to the turbulence characteristics of the wind, control the range of sheltering.

EXPERIMENTAL METHOD

Wind velocities were measured at a height of 1.4 m behind three tree stands of different porosity. Leeward-wind velocities were measured simultaneously by four Casella anemometers connected to one central counter. The open-field wind velocity at the 1.4 m-height was obtained during the same time interval by a manually operated Casella anemometer located several tree heights in front of the trees.

Vertical profiles of wind velocity were also obtained at several locations behind the medium and low-porosity stands with a set of four Thornwaite anemometers. At the same time, the open-field wind velocity was measured at a height of 1.4 m with a Casella anemometer.

All wind velocities were measured over 15-min intervals. The prevailing wind direction was approximately perpendicular to each tree stand. The height of each tree stand was estimated from the ground. Distances behind the tree stands were measured from the outer edge of the leeward trees which formed the stand.

Data for the low-porosity tree stand was obtained with the open-field wind velocity at 1.4 m varying from 4.8 to 6.6 m/sec. Wind patterns behind the medium-porous tree stand were measured with an open-field wind velocity between 3.4 and 5.8 m/sec. The open-field wind velocity varied from 2.9 to 4.4 m/sec for the highly porous hardwood stand with no leaves and from 1.9 to 3.9 m/sec with leaves on the trees.

The high-porosity stand we studied consisted of two rows of hardwood trees approximately 10 m apart — separated by a narrow country road. The taller trees were about 12 m in height and had diameters on the order of 25 cm. There was also a dense understory or hedgerow of shorter stems of 2—5 cm diameter. The length of the stand was roughly 100 m. Velocity measurements were taken during March with no leaves on the trees and during June with the trees in full foliage.

The stand of medium porosity was mixed white pine and hardwoods. Velocity measurements were taken during the early spring when no leaves were on the hardwoods and undergrowth in the stand. The average height of the stand was about 18 m; its depth or width was about 40 m; and its length was approximately 150 m. At about the 12-m height, the pine trees' crowns became thick.

For the low-porosity tree stand, wind velocities were measured behind a stand of mature white pine. The pine stand had an average tree height of roughly 14 m and was 90 m in depth. The length of this belt was about 150 m, with the forest becoming wider beyond this at both ends.

Stem diameters were measured in all three stands to provide data for an estimate of stand porosity. The porosity estimate used for this study was by a method similar to one used by Federer (1971) for the shadow of tree stems. The results of this type of analysis for the tree stands of this study are as follows: highly porous, $P = 0.80$; medium porosity, $P = 0.47$; and low porosity $P = 0.27$ (Table I).

TABLE I

Stand characteristics from stem diameter measurements at 1.4-m height

	Porous	Medium	Dense
Stand width (m)	10.7	35.4	91.4
Length of measurement area, L (m)	61.0	61.0	30.5
Measurement area (m^2)	650	2,155	2,322
Number of stems per unit area (m^{-2})	0.1909	0.0854	0.0573
Quadratic mean stem diameter (m)	0.109	0.247	0.303
Fractional basal area	0.00178	0.00408	0.00414
Sum of diameters/L	0.222	0.745	1.323
Porosity	0.801	0.475	0.266

RESULTS AND DISCUSSION

The pattern of near-surface wind velocities behind a shelterbelt can be fairly well described by three dimensionless parameters. The field data are normalized by dividing velocities by the upwind or open-field speed, U_0, and by dividing downwind distance by shelterbelt height H. Then the parameters are the dimensionless minimum speed behind the belt, U_m/U_0, the location at which this minimum occurs, x_m/H, and the sheltering range, x_r/H. The sheltering range, x_r/H, describes the downwind distance over which a significan wind reduction exists. We here propose that it be defined as the value of x/H at which U/U_0 has recovered to 0.90.

Before discussing these parameters in detail, we first need to consider the effect of height at which the measurements were made on the results. The vertical wind-velocity profiles in the lee of the medium- and low-porosity stands were logarithmic near the ground. The data fit the equation:

$$U = \frac{U_*}{k} \ln \left(\frac{z}{z_0}\right) \tag{7}$$

very well, with no diabatic correction or zero-plane displacement. Here U is the speed at height z, U_* is the friction velocity, k is Von Karman's constant and z_0 is the roughness parameter. Linear-regression fitting gave estimated z_0

values for each profile, and these averaged to 0.87 cm for the medium-porous stand and 2.78 cm for the low-porosity stand.

Vertical profiles were not measured upwind of the stand, but if we assume that z_0 upwind is the same as downwind, it is possible to normalize all the data. Manipulation of the above equation leads to:

$$\frac{U_{zd}}{U_{zu}} = \frac{U_{zd}}{U_{1.4u}} \frac{\ln\left(\frac{1.4}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)} \quad (8)$$

where U_{zd} is the speed measured at height z downwind and $U_{1.4u}$ is the speed measured at 1.4-m height upwind. The data show that the relative reduction in wind speed by the stand is not strongly dependent on the height of measurement within several meters of the surface (Fig.5). The exception is at the 300-cm level at 1 H behind the dense stand. However, this peculiarity may be due to the influence of the tree crowns which became very thick at this height. This occurrence is an indication that the surface wind-jetting behavior developed theoretically by Dyunin and the wind patterns observed experimentally hold only for the layer of air between ground level and the height where tree crowns become thick.

Variations in wind direction were assumed to have caused negligible influence on the amount of sheltering measured. This is in agreement with Russian sources (Konstantinov and Struzer, 1969), which state that the prevailing wind may vary as much as 45° from being perpendicular to the shelterbelts without noticeably affecting their sheltering effect.

The magnitude of the wind velocity can influence the amount of sheltering. High-wind speeds increase the efficiency of low porosity and decrease the efficiency of more porous tree stands, while light- to medium-wind velocities have little effect on the amount of sheltering (Konstantinov and Struzer, 1969). Wind velocities in this study were light to medium, 1.8—6.6 m/sec; thus, wind-velocity variations were assumed to have negligible effect on the results. Porosity distribution of shelterbelts has been shown to influence leeward-wind velocity patterns to some degree (Gloyne, 1954).

The results of this study show the expected decline of wind speed with increasing distance behind the shelterbelt until some minimum is reached, followed by a slow increase in velocity toward the free-stream speed (Fig.6). Qualitatively, our data are similar to results of Nageli (Plate, 1971) and Russian sources (Gloyne, 1954), but there are quantitative differences.

The sheltering ranges in Gloyne's and Nageli's data vary from 18—26 (Table II). Our data do not go downwind enough to obtain the range directly, but extrapolating the data gives x_r/H on the order of 7 except for the porous, leafless stand (Table II). Dyunin's analysis predicts that $2ax/H$ is about 2 when U/U_0 = 0.9. Using Dyunin's value of a = 0.055, this gives a theoretical range of about 18 in close agreement with the Gloyne and Nageli values. The reason that our measured sheltering ranges are so low is not known, but may be related to some topographic variation and additional trees farther downwind at our sites. Also, our open-field wind velocity was usually measured 2—3 tree heights in front of the tree stands. According to Nageli and Gloyne, the open-field wind velocity this close to shelterbelts would have already been reduced by as much as 10—15%. Thus, our results may show less wind reduction than actually occurred.

Nageli concluded that shelterbelts having medium porosity had at least 20% longer sheltering ranges than either very low-porosity or very porous shelterbelts (TableII). Dyunin's analysis predicts surprisingly little variation in x_r/H with porosity, but agrees with the experimental data that the range

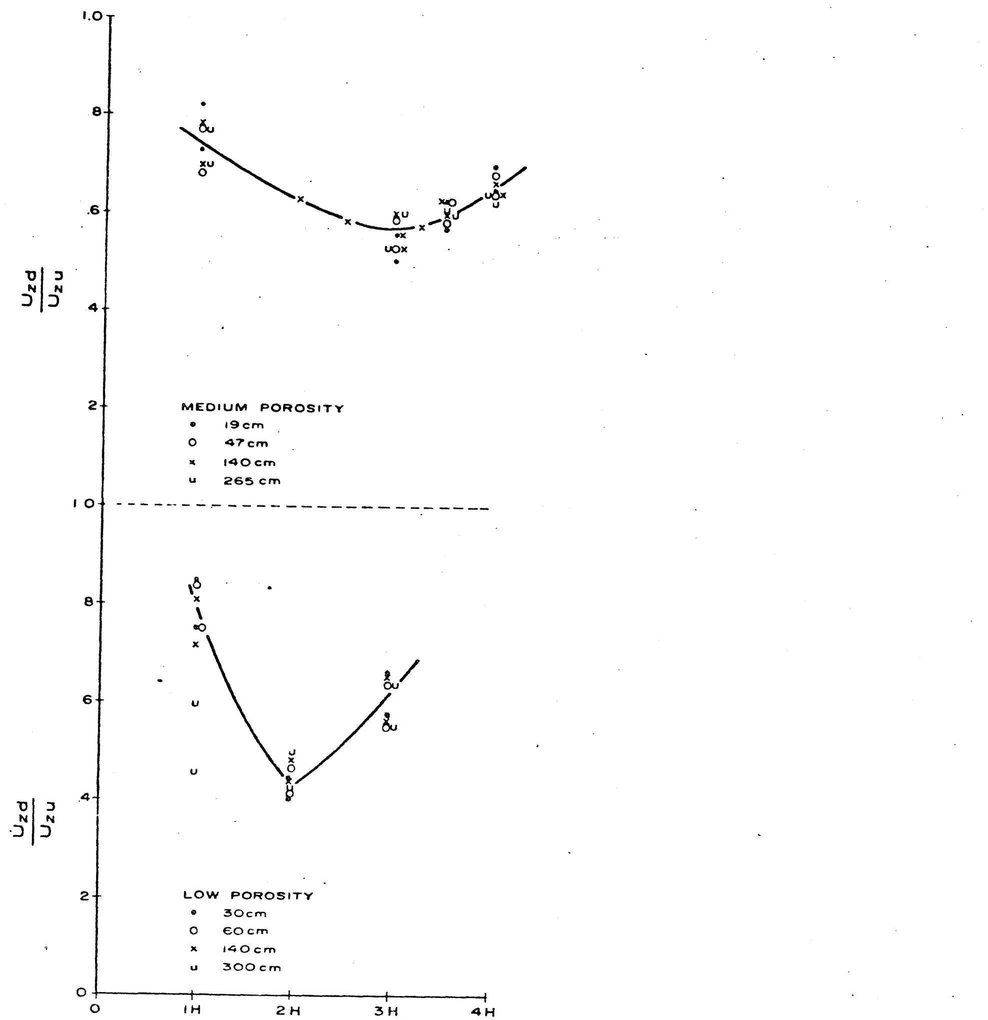

Fig.5. Non-dimensional velocities at different heights for medium- and low-porosity stands.

is larger with intermediate porosities (Fig.4). At the very high porosity of our leafless stand, the sheltering range was very small; but it increased rapidly with the growth of leaves (Fig.6).

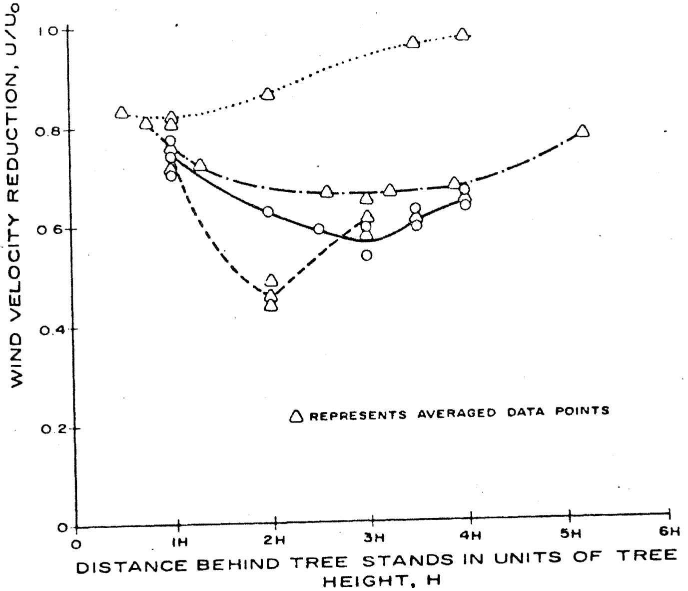

Fig.6. Sheltering effect for tree stands of different porosities in New Hampshire. Point line = low-porosity tree stand without leaves; dash-point line = low-porosity tree stand with leaves; full line = medium-porosity tree stand; dash line = low-porosity tree stand.

Wind speed behind our three tree stands decreased to a minimum relative velocity, at x_m/H of 1–3.5 (Fig.6). Values from Gloyne's and Nageli's data range from 2.2–7.0 (Table II). All the field data imply that x_m/H is somewhat larger at medium porosities, and less for very porous or very low-porosity stands. This behavior is the same as for the sheltering range, but the differences in the values of x_m/H are much larger than in the values of x_r/H.

Dyunin's analysis states that $2ax_m/H$ is nearly independent of porosity, declining from 0.55 to 0.45 as P decreases from 0.8 to 0.2 (Fig.4). If the theory is correct, then field variations in x_m/H must be primarily due to variation in a. Dyunin states that a is approximately constant at a value of 0.055, but if we assume $2ax_m/H = 0.5$, then the field measurements of x_m/H require a to vary from 0.036 to 0.357 (Table II). Exactly what determines the empirical constant a is not known. Shelterbelt porosity distribution, local ground roughness, and turbulence in the atmospheric boundary layer could all influence the value of a. Perhaps the greatest cause for observed differences was the nature of the ground surface. Ground roughness greatly effects the wind-velocity profiles near the ground (Plate, 1971). However, the character of the land terrain can induce local turbulence of very different intensity. Thus, the land upwind of shelterbelts could markedly affect the

TABLE II

Stand porosities and sheltering

Reference	Stand character	U_m/U_0	Apparent p	Visual p	x_m/H	Apparent a	x_r/H*
Very porous:							
This work	porous, leafless	0.82	0.90	0.80	1.0	0.250	2.5
Nageli	deciduous, leafless	0.63	0.77		2.2	0.113	16
Porous:							
This work	porous, leaved	0.66	0.79	0.80	2.8	0.089	7
Gloyne	open	0.58	0.73		4.2	0.060	19
Nageli	loose	0.38	0.58		3.2	0.078	17
Medium porous:							
This work	medium porous	0.56	0.72	0.48	3.0	0.083	8
Gloyne	open below medium above	0.21	0.40		7.0	0.036	26
Nageli	medium porous	0.33	0.50		4.0	0.062	21
Low porosity:							
This work	low porosity	0.46	0.64	0.27	2.0	0.125	7
Gloyne	medium porous below low porosity above	0.16	0.34		4.0	0.062	20
Nageli	very low porosity	0.16	0.34		0.7	0.357	13

* Values for Gloyne and this work estimated by extrapolation.

turbulence present in the surface wind leeward of the tree stands. The general character of the atmospheric boundary layer could also account for some of the observed sheltering differences (Van der Linde, 1962; Rutter, 1968). Generally, winds over hilly areas are more turbulent and have less velocity than coastal and plain winds. It would appear from this that the reason for the lower values of x_m/H obtained by the authors is higher turbulence as indicated by higher values of a.

In our data and that of Gloyne and Nageli, U_m/U_0 declines as the shelterbelt becomes more dense (Table II). In Dyunin's analysis, the minimum relative wind velocity, U_m/U_0, is very close to the penetration velocity, U_i/U_0, which is determined solely by the porosity as given in eq.1. If this is true, then U_m/U_0 is an index to the porosity and can be calculated from the measured U_m/U_0 assuming $U_m = U_i$. This is an important conclusion since it could represent a standard way of representing and comparing all data from many diverse types of shelterbelts and eliminates the verbal characterization which is a very subjective description. The porosity calculated in this manner is the apparent porosity of the stand as seen by the wind field which in itself is the characteristic desired for any comparative study. For our stands, we can compare this with the visual porosity of the stem space as given in Table I (Table II). Agreement is good for the high-porosity stand, but is poor for the medium- and low-porosity stands. However, the agreement is not expected to be high since the wind will always seek the path producing the least pressure drop or the highest porosity, which cannot be measured from knowledge of tree stems and spaces. The two approaches to measuring stand porosity do not give the same values although the ordering of stands in both cases agrees with the crude verbal characterization of the stand. As can be seen, verbal characterization is unsatisfactory for comparing the results of different workers, since the "medium" categories of Gloyne, Nageli and the stands we examined have U_m/U_0 ranging from 0.21 to 0.56 (Table II).

CONCLUSION

If it can be assumed, as indicated by Dyunin's analysis, that porosity is the governing factor for the maximum wind reduction (minimum wind velocity leeward), two important conclusions can be drawn. They are:

(1) From a measurement of the minimum wind velocity behind a barrier, the porosity of the shelterbelt can be obtained which could be used as a standard for comparison of the characteristics of the many diverse shelterbelts rather than a subjective verbal characterization.

(2) From a measurement of the range of sheltering, an estimate of the turbulent wind characteristics is possible. Further verification of the effects of local surface conditions, porosity distribution of tree stands and atmospheric boundary-layer behavior must be made before leeward flow patterns are fully understood. Without this knowledge, the role of shelterbelt porosity on turbulence and hence the range of sheltering cannot be accurately evaluated. The need for a more detailed analytical procedure is also indicated.

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