A method for routine characterisation of shelterbelts

S. Nelmes, R.E. Belcher, C.J. Wood*

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

Received 27 September 1999; received in revised form 11 September 2000; accepted 14 September 2000

Abstract

This paper describes a working method of assessing the shelter quality of a wind-break, hedge or shelterbelt by a single field measurement, using portable equipment, deployed by an operative with minimal training on any day when the wind is suitable. The automated measurement yields a single characterisation parameter used to access an “expert system” database of information quantifying the benefit to plants or animals of various species.

Because shelter depends not just on wind-break porosity but also on other local terrain features affecting the shear and turbulence in the upstream wind, the characterisation measurement is defined to include not only the mean wind speed but also the turbulence. Thus, the assessment of a farm hedge views the shelter benefit, not just of the hedge in isolation, but of the hedge as found within its own local surroundings.

The routine measurement requires the simultaneous deployment of two anemometers connected to a pre-programmed data logger. One anemometer is sited upstream of the shelter barrier and one downstream. Both are at a distance \( h \) from the nearest shelterbelt face and at a height of 0.4\( h \), where \( h \) is the nominal height of the shelterbelt.

The method is established by a combination of field and wind tunnel measurements. In the field, the shelter parameter has been measured for a hawthorn hedge and the flow downstream has been explored extensively. In the wind tunnel, a wind-break model has been constructed to reproduce the same shelter-parameter value, and the downstream flow compared extensively with the full-scale observations. Thus validated, the range of wind tunnel study has been extended to include other wind-break models and wind flow simulations giving a range of shelter parameters. The research was sponsored by, and the exploitation rights are the property of, Woodland Improvement and Conservation, of Huntley, Gloucestershire. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Shelterbelts; Wind-break model; Characterisation parameter

1. Introduction

Hedges and belts of trees exist not only as land boundaries. They also shelter crops from physical damage or growth-inhibiting stress due to wind, and protect livestock from chill. Questions concerning the quality of wind shelter depend in part upon what is being sheltered, but invariably these questions focus upon the extent to which the wind speed and/or gustiness are reduced and upon the ground area protected. Beyond that, judgements of shelter quality tend to become subjective, depending upon the experience and sometimes the prejudices of the observer.

Measuring wind speed reduction over an area of ground is not easy and is rarely undertaken. Instead, evaluations of shelter are frequently discussed in terms of the visual appearance of density or porosity of the shelterbelt itself (e.g. Perera, 1981; Loeffler et al.,...
However, judging the appearance of foliage distribution is subjective and even measurements of physical form, however painstaking, must be correlated with other measurements before they can be used as indicators of the performance of the hedge in modifying the wind. For a comprehensive review of research in this area, see Heisler and Dewalle (1988).

The present paper continues the search for a simple measurement to characterise shelter performance. It starts from the proposition that measuring physical shape and structure will not solve the problem. Rather, the only hope of characterising aerodynamic performance is by means of a measurement that is itself aerodynamic.

An early example of such aerodynamic characterisation is the mean velocity deficit at the point of minimum mean velocity, proposed by Bean et al. (1975) and used by Wilson (1985). However, to measure this particular descriptor requires an extensive survey of the flow in the sheltered region, and it is more appropriate to regard it as part of the assessment of general shelter benefit rather than as a characterisation. This recognition is implicit in the demonstration by Wilson that the greatest mean velocity deficit ratio could be correlated, at least for one upstream wind structure with a fundamental aerodynamic characteristic, namely the resistance coefficient of the porous material forming the barrier.

The resistance coefficient is the defining aerodynamic characteristic of any porous material. To measure it requires that a panel of the material be fitted to completely obstruct an air duct, so that the pressure drop can be determined as a ratio with the dynamic pressure of the duct flow. Quite obviously, such a measurement is impossible for shelter systems comprising growing trees and Wilson (1985) was reduced once again to suggesting an empirical formula based on observed physical porosity.

However, the objection to the use of resistance coefficient for shelterbelt characterisation is not that it is not practical to measure it, but specifically because it is a property of the material alone. To use it for characterisation takes no account of the fact that the shelter afforded by a given hedge will also depend significantly on the scale and intensity of turbulence in the wind where it is planted.

A more appropriate approach to characterisation by pressure loss was attempted by Schmidt et al. (1995) who measured, at ground level, the pressure difference across a live hedge in the wind. This is discussed below, but the aim in the present paper remains to achieve a velocity-based aerodynamic characterisation. Thus, we seek to define a single characterisation parameter which (a) is based on velocity measurements close upstream and downstream of any porous barrier, (b) is related by unique and sensitive correlations with all the essential shelter benefits, (c) allows for different upstream wind turbulence and velocity profiles, and (d) can be measured quickly and easily in the field by an operative with minimal training, using cheap, portable pre-programmed equipment.

2. Defining a characterisation parameter

2.1. Description of the flow

It is important that the definition of the proposed parameter should not be arbitrarily empirical but should be firmly related to relevant flow mechanisms, so that it can be understood and justified. Therefore, we approach the definition with a discussion of the salient features of a shelterbelt flow field.

Fig. 1 shows a schematic diagram of porous barrier in the wind. Some of the flow passes through the barrier relatively slowly, whilst the remainder is deflected over the top with a local increase of speed. Downstream of the barrier, a mixing layer divides the two flows. It grows from a point near the top of the barrier until it meets the ground downstream. As recognised by Plate (1971), and Judd et al. (1996), this mixing layer is the dominant feature of the flow.

Below the mixing layer, the reduced velocity $U_2$ is approximately invariant with height. Bean et al. (1975) have pointed this out, and it may be shown by elementary one-dimensional analysis that such smoothing is an expected feature of the flow downstream of any barrier of uniform resistance. In the present context, this region close to the ground and close to the hedge is a convenient place for a downstream velocity measurement because the uniformity means that precise positioning of the anemometer is not critical. Beyond the point of first contact between the shear layer and the ground, the perturbations to the velocity and turbulence profiles decay until the undisturbed flow is restored.
2.2. Terms in the momentum equation

The flow features discussed above are of course governed by the equations of momentum and continuity. Others have written these equations for various control volumes surrounding a porous barrier in the wind, and have sought to assess the relative magnitudes of the various terms. Most have been concerned to omit those that are negligible in order to achieve a simplified analysis for a particular calculation, e.g. Seginer (1972), who sought to estimate the drag on the barrier. However, the present objective is not to perform any calculation but merely to review the terms in the momentum equation whilst considering what velocity measurement for characterisation might be physically meaningful in reflecting the local physical effects of a porous barrier in a turbulent wind.

For this discussion, we choose a slightly unusual control volume ABCDE as shown in Fig. 2. The sloping upper face CD is chosen deliberately to be below the lower limit of the shear layer so that turbulent momentum transfer on it is low. Nevertheless, we do not ignore it but write the momentum equation for ABCDE in the form:

\[
\int_A^B p \, dy + \int_C^D p \, dy - \int_E^D p \, dy - D - \int_A^E \tau \, dx
\]

\[
= \rho \int_E^D (U_x^2 + U_z^2) \, dy - \rho \int_A^B (U_x^2 + U_z^2) \, dy
\]

\[
+ \rho \int_B^C (U_x U_z + U_z U_x) \, dx + \rho \int_C^D (U_x U_z + U_z U_x) \, dx
\]

\[
- \rho \int_C^D (U_x^2 + U_z^2) \, dy
\]

(1)

In this equation, \( D \) is the drag force on the barrier, \( \tau(x, t) \) the shear stress on the ground, \( p(x, y, t) \) the local pressure, and \( (U(x, y) + u(x, y, t)) \) and \( (W(x, y) + w(x, y, t)) \) the instantaneous local horizontal and vertical velocity components, respectively, \( U(x, y) \) and \( W(x, y) \) being mean values.

We now consider the magnitudes of some of these terms and discuss the practical convenience or otherwise of making related measurements, having regard to the objective stated above, of simplicity for an unskilled operative.

Fig. 1. Schematic diagram of flow behind a porous barrier.

Fig. 2. Control volume for momentum analysis.
We reject measurements related to Reynolds stress-type turbulent momentum exchange because the simultaneous recording of two fluctuating velocity components would require two-component anemometers that are expensive and require elaborate calibration.

Shear stress measurements on the ground are equally impracticable. The forces involved are very small and any delicate balance installed at ground level would be vulnerable to damage and dirt.

Local pressure measurements do provide a possible way to characterise a wind-break and Schmidt et al. (1995) have reported successfully the mean static pressure difference at ground-level between the upstream and downstream sides. However, the minimum equipment for such measurements is two pressure transducers requiring calibration with at least one anemometer to measure the wind speed. Also, pressure measurements are sensitive to local flow perturbations near the point of measurement, e.g. due to non-flat ground surface.

Having rejected pressure measurements, attention is focussed on the major horizontal momentum terms on the upstream and downstream control volume boundaries AB and ED. These terms are both in the form \( U^2 \frac{CN}{u^2} \), showing that in a turbulent wind the momentum change caused by the barrier should not be evaluated from changes in mean velocity alone.

2.3. Definition of a characterisation parameter

Other investigators, notably Wilson (1985), have achieved good correlations of some shelter properties with simple characterisation ratios using mean velocity alone. Nevertheless, in the present approach, which seeks to take into account not only barriers of different flow resistance but also sites where winds have significantly different gust structure, we defend a measurement which includes a recognition of differences in upstream turbulence.

Modern light, small anemometers respond rapidly to gusts and modern data loggers can be programmed to sample at high frequency and also to perform the necessary data processing. Consequently, there is no problem in including the time-varying velocity terms in a simple automated measurement.

Thus, we choose to define a velocity ratio parameter \( s \) as a downstream-to-upstream ratio of total turbulent kinetic energy in the horizontal wind speed component. The square root merely yields a convenient scale of variation over the expected range of barrier porosity:

\[
s = \sqrt{\frac{[U^2 + \bar{u}^2]_{ED}}{[U^2 + \bar{u}^2]_{AB}}} \tag{2}
\]

For routine assessments, we wish to limit the velocity measurement procedure to a single location upstream and a single location downstream. The location of the two measurement points remains to be decided.

Downstream of the barrier it is expected that the flow region below the shear layer the flow will be relatively uniform so there is an argument for choosing a location between E and D (Fig. 2). In contrast, there is no obvious location for a representative upstream measurement. The upstream mean velocity increases with height, and is also reduced on close approach to the barrier, so it is necessary to define a precise measurement location. This is a matter that is best resolved after wind tunnel trials (see Section 3.4).

The most important point to be resolved in the trials is whether \( s \) does what it is designed to do. Firstly, it is necessary to show that a given barrier will yield different values of \( s \) for different turbulence amplitudes and frequencies in the upstream wind. Secondly and crucially, it must be discovered whether the various properties of the sheltered flow downstream will correlate well with \( s \) alone, irrespective of the combination of barrier and wind turbulence that \( s \) represents. Only then the parameter can be considered suitable for use as the basis of an expert system database of shelter.

3. Wind tunnel experiments

3.1. Wind flow modelling

The boundary layer wind tunnel at Oxford University has been described by Greenway and Wood (1977). It has a working section 4 m wide by 2 m high with a 12 m length for the controlled development of velocity and turbulence profiles using a combination of grid-generated turbulence and arrays of floor roughness elements.

Using these devices, three different simulations of the atmospheric boundary layers were generated. To
validate these, gust frequency spectra and profiles of horizontal mean velocity and turbulence intensity were compared with full-scale wind data published by ESDU International Ltd. (data items 82026, 83045, 84011, 85020).

In the ESDU correlations, the essential characteristics of the wind are presented as functions of a single ground roughness length $z_0$. This length is the free constant in the logarithmic function relating the wind speed $u(z)$ at any height $z$ to a reference speed $u(z_{ref})$ at a chosen reference height $z_{ref}$:

$$\frac{u(z)}{u(z_{ref})} = \frac{\ln z - \ln z_0}{\ln z_{ref} - \ln z_0}$$

(3)

The constant $z_0$ has values established by fitting the function to measured mean wind speed data within the lowest 30–50 m over uniform flat terrain. These values are also correlated by ESDU with the intensity and frequency spectrum of turbulence and are shown to be strongly related to the category of terrain (e.g. town, country, etc.).

The ESDU correlations allow the three wind tunnel boundary layers to be compared with full-scale data and identified simply by determining the scale factor and value of $z_0$ for best fit. Included in the assessment were not only mean velocity profiles but also turbulence intensity profiles and gust frequency spectra, to ensure that the entire structure of each simulated boundary layer was reasonable at the declared scale. The wind tunnel flows, hereafter identified as “flow 1”, “flow 2” and “flow 3”, are described below:

1. $z_0 = 0.3$ m, equivalent to dense woodland or domestic housing, scale 1:75.
2. $z_0 = 0.07$ m, equivalent to farmland with scattered trees and hedges, scale 1:75.
3. $z_0 = 0.1$ m, equivalent to farmland with scattered trees and hedges, scale 1:200.

Although the flows are thus shown to be realistic, it must be emphasised that the purpose here is not to restrict the experiments to particular scales, but simply to create three significantly different flows in order to examine the general sensitivity of shelter to upstream wind structure. To avoid misunderstanding of this point, the comparisons with full-scale target flows are not shown here. The three wind tunnel flows are merely described by mean velocity and turbulence profiles as measured. These are shown in Figs. 3 and 4. The scatter in the data is a normal consequence of practical constraints on sampling time with fluctuating signals.

Fig. 3. Mean velocity profiles of three wind tunnel flows ($U$ is the horizontal mean wind speed).
3.2. Permeable barrier models

To represent a range of shelterbelts exposed to these flows, a total of 13 different barriers of porous material was fixed across the full width of the tunnel. These were formed from various materials, including wire gauze and “horsehair” matting but mainly perforated sheet metal with various hole sizes to give varying porosity. Most of the barriers were 100 mm high but a few 200 mm strips were also used. These might be considered to represent shelterbelts of height 7.5 and 15 m at 1:75 scale, or 20 and 40 m at 1:200, but it is emphasised again that scale modelling is not the objective, apart from showing that the range is realistic. The intended outcome of the present work is a generalised correlation between $s$ and a range of practical shelter benefits that is valid irrespective of barrier height or wind flow environment.

The models were set perpendicular to the wind direction, but some were also rotated on the wind tunnel turntable to examine the effect of flow angle. The variation in most of the important shelter parameters is small for a $30^\circ$ range on either side of the perpendicular and the effect of angle is not discussed further here.

3.3. Wind tunnel velocity measurements

To measure velocity components in the wind tunnel, a Dantec two-component fibre-optic laser–Doppler anemometer (LDA) was used. This system projects two pairs of intersecting laser beams from a remote miniature optical head, linked to the laser projection and detection systems by a fibre-optic cable. Doppler frequency detection was done by two Dantec burst spectrum analysers with post-processing software also supplied by Dantec. To use the LDA, the airflow in the wind tunnel was seeded with atomised droplets of glycerine solution.

Throughout all experiments, the nominal speed $U_{\text{tun}}$ in the wind tunnel was monitored continuously using a pitot–static tube positioned well away from the model. All other measured velocity components from the LDA are expressed initially as ratios with the simultaneous value of $U_{\text{tun}}$ in order to eliminate the arbitrary choice of tunnel speed.

3.4. Points of measurement for $s$

The first wind tunnel tests were designed to determine the best upstream and downstream locations for the measurement mean and r.m.s. velocities for the determination of $s$ (Eq. (2)).

For each barrier of height $h$, measurements of longitudinal and vertical velocity were made with the LDA on a finely spaced ($0.2h \times 0.2h$) grid of points extending from $2h$ upstream to $2h$ downstream of the barrier plane, and from ground level up to a height of $1.6h$. 

Fig. 4. Turbulence intensity profiles of the three wind tunnel flows.
These measurements revealed the extent of local upstream influence of the barrier and also of the shear layer and the relatively uniform wake region below it. This information facilitated the choice of a downstream measurement point that was (a) within the uniform wake, (b) far enough from the barrier to avoid small-scale local influences of non-uniform porosity, and (c) high enough to avoid local influences of uneven ground. Because the uniform region is tapered (see Fig. 2), these requirements are to some extent in conflict.

For the upstream measurement point the position constraints are less complicated. Although at first sight, it might appear ideal to choose a location well clear of the upstream influence of the barrier, there is in fact no requirement implied by Eq. (1) or Fig. 2 that the control volume boundary AB should be in undisturbed flow. Therefore, we may allow the practical consideration of avoiding unnecessary intrusion into adjacent crop space, whilst ensuring only that the ratio \( s \) between upstream and downstream measurements is sensitive to barrier porosity and gives a clear correlation with other shelter benefits. Following these trials, measuring positions for \( s \) were chosen to be 1\( h \) upstream and downstream of the nearest barrier face, and 0.4\( h \) above ground.

### 3.5. Values of \( s \) from model tests

Having decided where to measure \( s \), and completed the measurements as in Table 1, the second set of experiments was concerned with correlating the value of \( s \) with the relevant flow properties over the entire sheltered area downstream of the model. For this survey, streamwise and vertical velocity components were measured at 96 points mainly in the downstream wake. The grid of measurements was defined in each case by \( z/h = (0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 4.0) \), \( x/h = (-1.0, 0.5, 1.2, 3.4, 5.6, 8.10, 15.20) \). Vertical heights \( z \) were measured from the ground, and streamwise positions \( x \) from the nearest face of the barrier.

The flow properties examined include both longitudinal and vertical mean velocity components as well as standard deviation of these components representing turbulence. The third probability moment (skewness) has some relevance to the generation of shear stress and mass transfer. Finally, the mean of the instantaneous \( uw \) product represents turbulent transfer of momentum or of heat, moisture or transpired gases.

Using all of the barrier/wind-flow combinations in Table 1, the variation with \( s \) was assessed for each of the seven flow properties noted above, at each of the 96 measuring points. This was done in each of the 672 cases by postulating a simple linear relationship between \( s \) and each flow property, and finding the best straight line by linear regression.

### Table 1

<table>
<thead>
<tr>
<th>Barrier description</th>
<th>( h ) (mm)</th>
<th>Flow 1</th>
<th>Flow 2</th>
<th>Flow 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 mm perforations</td>
<td>100</td>
<td>0.61</td>
<td>0.74</td>
<td>0.63</td>
</tr>
<tr>
<td>2 mm perforations</td>
<td>100</td>
<td>0.42</td>
<td>0.42</td>
<td>0.44</td>
</tr>
<tr>
<td>3 mm perforations</td>
<td>100</td>
<td>0.43</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>5 mm perforations</td>
<td>100</td>
<td>0.43</td>
<td>0.47</td>
<td>0.50</td>
</tr>
<tr>
<td>6 mm perforations</td>
<td>100</td>
<td>0.52</td>
<td>0.55</td>
<td>0.51</td>
</tr>
<tr>
<td>12 mm perforations</td>
<td>100</td>
<td>0.53</td>
<td>0.76</td>
<td>0.77</td>
</tr>
<tr>
<td>Wire mesh box</td>
<td>100</td>
<td>0.92</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Horsehair 45 mm thick</td>
<td>100</td>
<td>0.30</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td>12 + 6 mm</td>
<td>100</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 + 3 mm</td>
<td>100</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 mm + horsehair</td>
<td>100</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horsehair in box</td>
<td>100</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double height, 2 mm</td>
<td>200</td>
<td>0.57</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Double height, 12 mm</td>
<td>200</td>
<td>0.83</td>
<td>0.87</td>
<td></td>
</tr>
</tbody>
</table>

### 3.6. Correlation of shelter properties with \( s \)

Having decided where to measure \( s \), and completed the measurements as in Table 1, the second set of experiments was concerned with correlating the value of \( s \) with the relevant flow properties over the entire sheltered area downstream of the model. For this survey, streamwise and vertical velocity components were measured at 96 points mainly in the downstream wake. The grid of measurements was defined in each case by \( z/h = (0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 4.0) \), \( x/h = (-1.0, 0.5, 1.2, 3.4, 5.6, 8.10, 15.20) \). Vertical heights \( z \) were measured from the ground, and streamwise positions \( x \) from the nearest face of the barrier.

The flow properties examined include both longitudinal and vertical mean velocity components as well as standard deviation of these components representing turbulence. The third probability moment (skewness) has some relevance to the generation of shear stress and mass transfer. Finally, the mean of the instantaneous \( uw \) product represents turbulent transfer of momentum or of heat, moisture or transpired gases.

Using all of the barrier/wind-flow combinations in Table 1, the variation with \( s \) was assessed for each of the seven flow properties noted above, at each of the 96 measuring points. This was done in each of the 672 cases by postulating a simple linear relationship between \( s \) and each flow property, and finding the best straight line by linear regression.
3.7. Test of linearity

It is intended that the proposed linear relationships shall be used to interpolate the available data and thus extend the application to any desired value of $s$. To justify this, the assumption of linearity was tested by examining the magnitude of the residuals from the regressions.

In most of the wake region, the residuals are very small and it is therefore reasonable to assume a linear dependency of shelter flow parameters upon $s$. The worst non-linearity is in the mixing layer downstream of and close to the barrier top edge (see Fig. 1). The reason is that the vertical gradients of flow properties here are very steep and the mixing layer itself is moved vertically by changes in barrier porosity and upstream flow turbulence. Fortunately, this region close to the top of the barrier is of relatively little practical importance since species requiring shelter are more likely to be found near the ground and further downstream.

3.8. Use of linear regression functions to interpolate shelter data

The benefit of postulating a linear relationship between each shelter-flow property and $s$ is that it facilitates interpolation of measured data. This permits a simple estimation of shelter quality for hedges or barriers not actually tested.

To demonstrate the accuracy of this process, one of the wind tunnel models listed in Table 1 has been selected. This is the horsehair barrier in wind flow No. 1 for which $s = 0.3$.

The discrete points in Figs. 5–8 show directly measured values of two mean velocity components and two turbulence components. In each case, profiles of the measured values are plotted against height at three downstream locations.

For comparison with these discrete points, representing direct measurement when $s = 0.3$, continuous curves are drawn. The continuous curves are estimated from the entire data set including all $s$ values (Table 1) interpolated to $s = 0.3$ using the linear regression functions discussed above.

It would be tedious to comment on every detail of the comparisons. However, it will not be surprising that, whatever the flow property, the maxima and minima are underestimated by the averaging process so
that the excursions of the directly measured data points are greater.

Whilst good agreement in the longitudinal mean velocity profiles (Fig. 5) is an obvious criterion of success, it is gratifying to find that the interpolation method gives a similar quality of prediction for vertical velocities and for both components of turbulence (Figs. 6–8). Other satisfactory comparisons not shown here include skewness and Reynolds stress reported in detail by Nelmes (1999).
4. Field experiments

4.1. Site and instrumentation

The experimental shelterbelt was a 3.2 m high, trimmed hedge of hawthorn located at Collin’s Farm, Fritford, 10 miles southwest of Oxford (51°40.5’N, 1°22.5’W 70 m ASL). The hedge separates two-level cultivated fields and is aligned normal to winds from 290°. For winds from this direction, the upwind field provides an uninterrupted fetch of 0.6 km. Beyond this, the terrain is farmland with fields, hedges, a few buildings and small copses of trees.

The main tests were conducted between 28 November 1998 and 28 February 1999. Further tests to examine the mixing layer were conducted during March and April 1999.

Table 2
List of field instruments

<table>
<thead>
<tr>
<th>No.</th>
<th>Instrument</th>
<th>Manufacturer</th>
<th>Dist. const. (m)</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Cup anemometers, A100L2</td>
<td>Vector Instruments, Rhyl, N. Wales</td>
<td>2.3</td>
<td>A\textsubscript{V}</td>
</tr>
<tr>
<td>3</td>
<td>Cup anemometers, DWR-205O</td>
<td>Didcot Instruments, Didcot, Oxon</td>
<td>4.5</td>
<td>A\textsubscript{D}</td>
</tr>
<tr>
<td>1</td>
<td>Tachogenerator anemometer, DWR-205G</td>
<td>Didcot Instruments, Didcot, Oxon</td>
<td>&gt;4.5</td>
<td>A\textsubscript{T}</td>
</tr>
<tr>
<td>2</td>
<td>Direction vanes, DWD 105</td>
<td>Didcot Instruments, Didcot, Oxon</td>
<td></td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>Data logger, DL3000</td>
<td>Delta-T Devices, Cambridge</td>
<td></td>
<td>L1</td>
</tr>
<tr>
<td>1</td>
<td>Data logger, Delta-T</td>
<td>Delta-T Devices, Cambridge</td>
<td></td>
<td>L2</td>
</tr>
</tbody>
</table>
when it was strong enough to be due to significant meteorological events and not due to local thermal activity.

To achieve this control, a trigger circuit was used to monitor the mast 1 wind speed and direction continuously and to power the data logger and the other anemometers only when the 10 min-average wind direction and speed were, respectively, within 30° perpendicular to the hedge and greater than 4 m s\(^{-1}\). Once initiated, the duration of data sampling was 10 min at 0.2 or 0.5 Hz. These sampling frequencies were limited by logger capability.

4.2. s-value for test hedge

For the test hedge in winter condition, the average value of \(s\) was 0.46 with standard deviation 0.05. This was calculated by Eq. (2) using anemometer measurements on masts 3 and 4 and the average was over more than 100 independent test runs. For comparison, the range of values in the wind tunnel was from 0.2 to 0.95.

To assess the effect of calculating \(s\) from omnidirectional wind speeds from cup anemometers rather than true normal velocity components, the values of \(s\) from a selection of test runs were compared with corresponding values calculated using instantaneous streamwise velocity components from the two sonic anemometers at the same locations. This is discussed in detail by Nelmes (1999). The agreement was within \pm 0.02.

4.3. Comparison of field data with wind tunnel data for shelter quality

By virtue of the interpolation procedure for wind tunnel data, it is possible to compare any measured feature of the sheltered wake behind the test hedge with the corresponding parameter measured in the wind tunnel and interpolated for the same \(s\) value. As an example, we consider in Figs. 10 and 11 the ratio \(U/U_0\) of sheltered to unsheltered horizontal mean wind speed at heights of 0.5\(h\) and \(h\), showing the variation with horizontal distance from the hedge. To illustrate the sensitivity of the comparison, field velocity distributions are shown (for \(s = 0.46\)) compared with a range of \(s\)-interpolated wind tunnel data (\(s = 0.4, 0.45\) and 0.5).

In making these comparisons, it should be noted that while the wind tunnel comparison is between the same measurement locations with the hedge present and removed, the field comparisons are necessarily with mean velocities at an undisturbed upstream location.

5. A database of shelter quality

An aerodynamic characterisation parameter \(s\) is proposed which can be measured in the field by a simple automated test using two anemometers and a pre-programmed data logger. The parameter is a ratio of momentum-like velocity terms between specified locations downstream and upstream of any permeable shelter barrier.

Wind tunnel tests, validated where possible by comparison with full-scale trials, have provided sufficient data to allow the value of \(s\) (Eq. (2)) to be used as a
correlation for variations in shelter as defined by the improvement in those flow parameters that are significant in describing wind damage and loss of heat or moisture.

That being so, the final outcome of the present research is to assemble the wind tunnel data into a database of shelter quality, accessed through a single value of $s$, measurable on a scale from 0 (solid
barrier) to 1 (no barrier) on any shelter barrier exposed to any wind environment.

The database has the capacity for extension as new data becomes available. The current version incorporates reduction ratios for mean and r.m.s. horizontal velocities for a barrier of height \( h \), and is applicable for locations within the downstream region \( 0 < z < h, 0 < x < 20h \). These are the primary shelter descriptors, but other flow properties, also correlated with \( s \), may be incorporated.

Also included in the database are meteorological wind speed probability tables for a selection of UK locations. These are designed to yield statistical information on the unsheltered reference wind speed \( U_0 \). Thus, the database provides a shelter assessment, not merely as a change from an arbitrary unsheltered environment, but as a probabilistic prediction of actual wind conditions in the sheltered region.

Finally, to complete the assessment in terms of tangible shelter benefits, the database incorporates empirical information on the shelter requirements of particular plant or animal species.

6. Concluding remarks

The outcome of this project is not merely the information described here, but includes the supply of a usable knowledge-based shelter assessment package. Using a simple data logger linked to two cup anemometers on short portable masts, an operative with rudimentary training may, on a suitable day with strong wind from an appropriate direction, make an automated two-point wind speed survey on any hedge or other shelter barrier and then on a laptop computer:

1. Enter the resulting measurement of \( s \).
2. Choose from a menu list of geographical locations (at present limited to within the UK).
3. Choose from a menu of animal or plant species to be protected.

Read from the database output an application-specific shelter quality assessment for the hedge or barrier that has just been surveyed, including the influence of local meteorological statistics.

The database is open to further development in that additional sites may be added at any time, information on wind-shelter requirements may be enhanced and new species may be included. Finally, of course, improvements may be made to the algorithms, at present linear, relating wind characteristics in the sheltered region to the characterisation parameter \( s \).

Acknowledgements

The authors have been encouraged by the enthusiastic interest taken by Mr. John Davies of Woodland Improvement and Conservation Ltd. and hope that the use of the shelter assessment technique proposed here will enhance the work of that company in providing high quality advice to landowners desiring to optimise the environmental benefits of tree-planting for shelter.

References