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Effects of windbreaks on airflow, microclimates and crop yields

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Abstract. The mechanisms by which a porous windbreak modifies airflow, microclimates and hence crop yields are addressed, based upon recent wind tunnel experiments, field observations and numerical modelling. This paper is thus an update to the excellent reviews in Brandle (1988). It shows how a turbulent mixing layer initiated at the top of the windbreak dominates the airflow behind a windbreak. This mixing layer spreads vertically as it moves downwind, growing at a rate determined by the turbulence in the approach flow and the windbreak's 'permeability'. The roughness of the terrain and land-cover upwind, windbreak height and porosity are thus the main controls on the amount and extent of shelter provided by a windbreak. The changes in temperature, humidity, heat and evaporation fluxes given these changes in turbulence are then described. Based on the turbulent mixing layer model, the highly sheltered 'quiet zone' will be typically warmer and more humid while further downwind in the 'wake zone', cooler and drier conditions would be expected. The careful experimental studies needed to verify these theoretical predictions have not yet been published. Shade is also shown to modify the heating in the quiet zone and, depending on the orientation of the windbreak, can offset the warming in the quiet zone. Lastly, the mechanisms affecting plant productivity are described in light of these airflow and microclimate changes. A major effect of a windbreak is to reduce the incidence of low frequency, high magnitude damage events such as sandblasting or lodging. Microclimate effects, however, do not always improve productivity. For example, while shelter may improve water-use efficiency in irrigated crops by increasing yields and reducing water-use, this may not be the case in dryland agriculture.

1. Introduction

Climate is the factor with the greatest impact upon agricultural productivity. It is therefore not surprising that the practise of intentional microclimate modification is as old as the practise of agriculture itself. In particular, windbreaks – by providing shade and shelter – have long been used as a tool to create a more benign and productive microclimate. Anecdotal and published evidence over the last 50 years suggests that windbreaks may significantly improve crop, pasture and animal productivity. Planting tree windbreaks is therefore seen as a way of ameliorating land degradation while maintaining, and even improving, agricultural productivity.

The main effect of a tree windbreak is to provide shelter – i.e. a windbreak alters the mean windspeed, wind direction and turbulence of the airflow. As a result, the surrounding aerial, plant and soil environments are modified because of changes to the following processes (see also Figure 1):

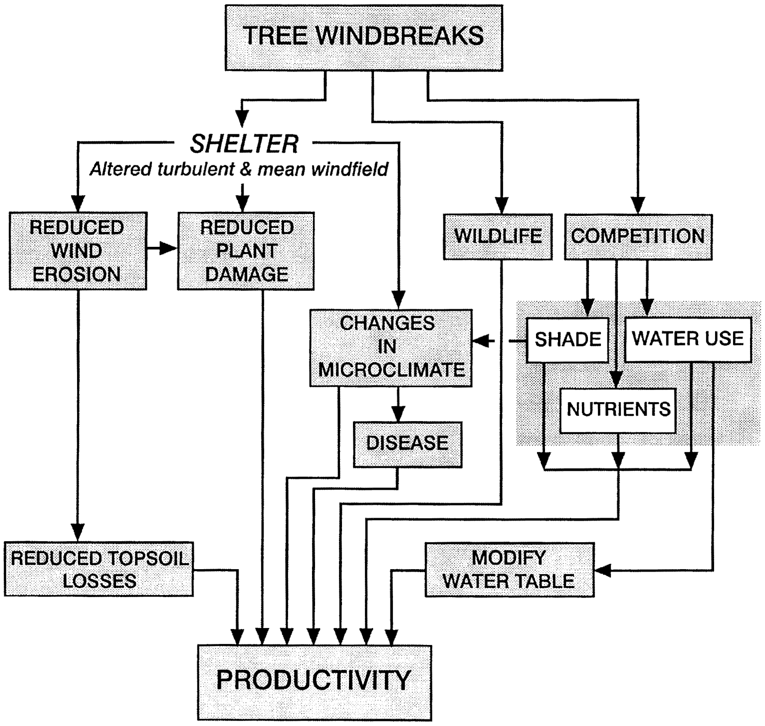


Figure 1. Mechanisms by which a windbreak affects microclimate and plant productivity.

- Direct mechanical effects of wind:
  - wind erosion – sandblasting; burial of seeds and seedlings; stripping of nutrients;
  - plant damage – fruit damage; lodging; leaf tearing and removal.
- Microclimate processes:
  - shading from direct solar radiation and trapping of longwave radiation;
  - turbulent exchanges of heat, water vapour and CO_2.
- Water and nutrient flows in the windbreak-crop/pasture-soil system:
  - competition for water and nutrients;
  - partitioning between soil and plant evaporation and its affect on seasonal water use efficiency.
- Ecological processes:
  - transport pathways for pollens, pollutants and pathogens are modified;
  - biodiversity creates opportunities for both competition and complementarity between components of the windbreak-crop/pasture-soil system;

Some of these mechanisms operate incrementally over time while others may occur only intermittently – although their impact can be catastrophic. Protection from low frequency, large magnitude weather events, such as crop lodging in a severe storm, is an *intermittent* windbreak effect. Soils that are warmer by day due to shelter, and lose less moisture through evaporation, can encourage early germination, plant growth and improve water use efficiency. This latter example illustrates a potential *incremental* effect of a windbreak that operates over the entire growing season. Economic benefits may flow in both examples, but the timing, magnitudes and reliability differ.

The task of quantifying the effect of any one of the above mechanisms, or identifying which are the most important for plant productivity, has yet to be fulfilled – despite decades of field experiments, observational studies and some modelling. The aim of this paper is to review our current understanding of each of these mechanisms and thus assess windbreak effects on the microclimate and ultimately plant productivity. The three main objectives are to:

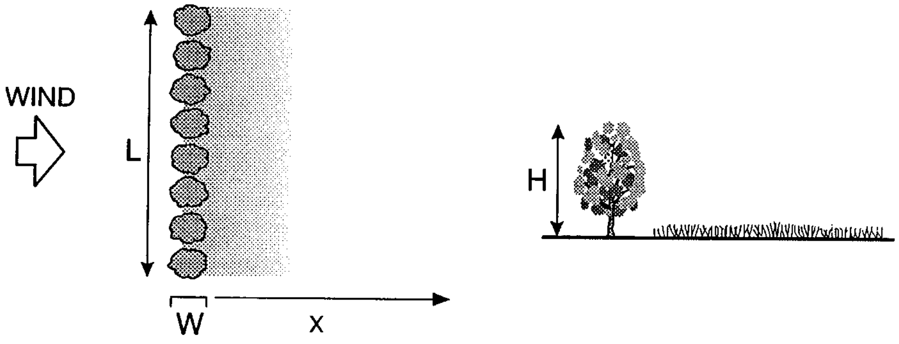
1. describe the processes by which a windbreak creates shelter through its effect upon the mean and turbulent airflow (Section 2);
2. assess the effect of shelter on microclimates and evaporation rates (Section 3);
3. review the effects of windbreaks on plant (not animal) productivity and describe how the mechanisms listed above may bring about such changes in productivity (Section 4).

For the purposes of this review, a windbreak is defined as a row (or several rows) of trees whose width is at least an order of magnitude less than its length. The term ‘single windbreak’ refers to a windbreak along a single axis of a paddock; ‘multiple windbreaks’ refers to successive parallel windbreaks and a ‘windbreak grid’ refers to a network of windbreaks completely surrounding a paddock (Figure 2). Windbreaks are assumed to be synonymous with shelterbelts and only tree or shrub windbreaks are considered.

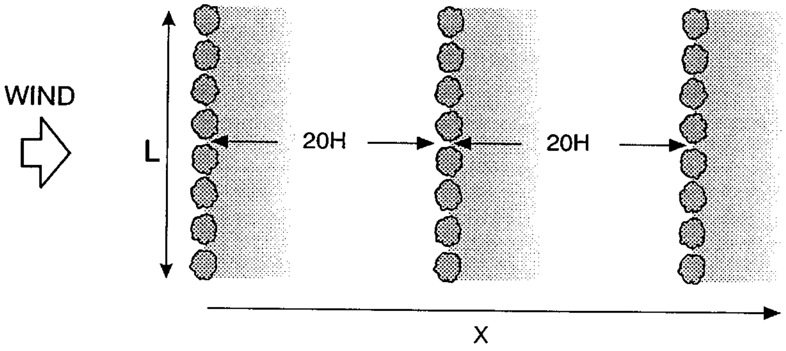
2. The aerial environment around a windbreak

2.1. *Airflow regions around a single windbreak*

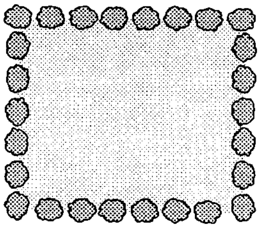
Windbreaks present a porous obstacle to the approaching airflow, forcing air to flow through the windbreak at a reduced speed and accelerate over the top. Windbreaks thus slow the airflow and provide shelter for some distance downwind. The way that windspeed and turbulent flow are modified by the windbreak will determine its shelter efficiency (Wang and Takle, 1997). The perturbation to the pressure field, the mean wind velocity and the turbulence that results from flow through a porous windbreak underpins almost all the subsequent windbreak effects. It is therefore appropriate to begin by briefly describing the basic airflow pattern around a windbreak and the resulting distinct airflow regions or zones. These airflow regions, plus vertical profiles of mean windspeed, around a porous windbreak are illustrated in Figure 3 from Judd et al. (1996). Other examples of similar descriptions of these



a Single windbreak



b Multiple Windbreaks



c Windbreak Grid

Figure 2. Windbreak definitions: layout and dimensions.

aerodynamically distinct airflow zones can be found in Jensen (1954), Caborn (1957), Plate (1971) and Raine and Stevenson (1977).

The following description assumes that the atmosphere is neutrally stratified, i.e. there are no buoyancy effects, which requires fairly strong winds and minimal surface heating. The windbreak's structure is characterised by its height (*H*); width and length (*W* and *L*) and permeability. This latter is

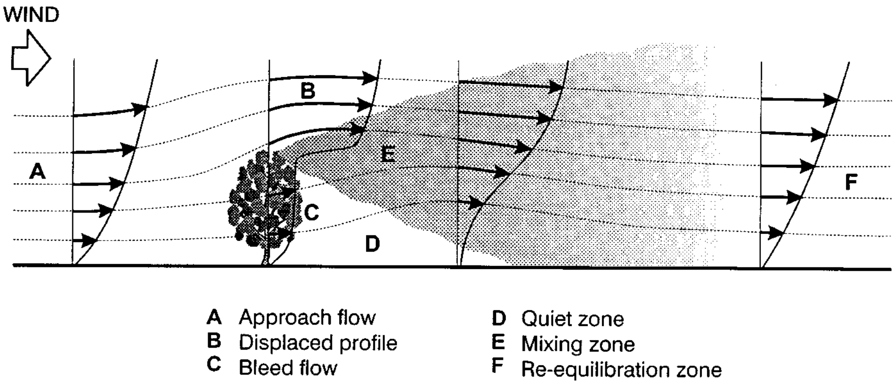


Figure 3. Schematic of airflow regimes around a single windbreak, oriented normal to the flow, in neutral atmospheric conditions. Shown are hypothetical vertical profiles of mean horizontal windspeed and streamlines.
Source: after Judd et al. (1996).

quantified by the porosity (ϕ) which is essentially the fraction of open spaces making up the windbreak. A windbreak with $\phi = 0.1$ is an example of a very low porosity windbreak and would be very impermeable. The following windbreak structure is assumed: $L > 20H$, $H > W$, the approaching wind direction is normal to the windbreak's long axis and there is no vertical or lateral variation in the windbreak's porosity. Distance downwind of the windbreak is denoted as X and height as Z (see also Figure 2).

The *approach flow or profile* (Figure 3) is determined by atmospheric stability – windspeed increases logarithmically with height when the atmosphere is neutral – and the aerodynamic roughness of the surface over which the approaching air has flowed. About five windbreak heights upwind of the windbreak ($X = -5H$), the air in the layer below the top of the windbreak ($Z = H$) begins to slow and diverge. Some air continues on to flow through the porous windbreak creating a region of *bleed flow* immediately to the lee. The velocity of the bleed flow is reduced because of the drag exerted by the vegetation in the windbreak.

Most of the air, where the amount depends on the porosity, actually flows over the top of the windbreak as illustrated by the streamline deflection in Figure 3. Continuity demands that this convergence above the windbreak be matched by an increase in windspeed. A layer of air with consistently enhanced wind velocities therefore extends at least $1.5H$ above the windbreak (McNaughton, 1988). The characteristic 'kink' in the *displaced wind profile* shown in Figure 3 results from this combination of reduced windspeed below, and increased windspeed above, the top of the windbreak. The region of displaced air, plus the slowed diverging air immediately upwind of the windbreak, has been referred to as a *displacement zone* (Oke, 1987).

A sheltered area, the *quiet zone*, is formed in the lee of the windbreak. It has a roughly triangular shape where the boundaries are formed by the windbreak itself, the ground surface, and a line sloping downwards and downwind from the top of the windbreak intersecting the ground between 3 and 8*H* (Figure 3). The minimum windspeed (U_{min}) occurs in the quiet zone, its downwind position moving closer to the windbreak with decreasing porosity and as $Z \rightarrow H$ (see below). The turbulence of the air in the quiet zone is mostly influenced by the bleed flow (McNaughton, 1988) and hence aspects of the windbreak's morphology such as its vertical structure, leaf density etc. The dimensions and turbulent characteristics of the quiet zone are also influenced by the airflow approaching the windbreak – these effects are described later. The turbulent eddies in the bleed flow and quiet zone are typically smaller and less energetic than those upwind. If the windbreak is very dense ($\phi \leq\ \approx 0.3$, Perera, 1981; Schwartz et al., 1995; Wang and Takle, 1996), the flow in the quiet zone can reverse direction to form a recirculating eddy.

Above and downwind of the quiet zone is a turbulent layer of air called the *mixing* layer which eventually ($X \gg 10H$) merges into an *equilibration zone* where the upwind profile is re-established. The mixing layer grows downwards from a thin layer initiated at the top of the windbreak, where the wind profile is inflected (Figure 3), and intersects the ground surface at about 5*H* downwind – marking the limit of the quiet zone. This region of turbulent air, downwind of the quiet zone, is typically referred to as the *wake* zone.

2.2. *Mean and turbulent velocity fields*

This perturbed airflow pattern determines the subsequent changes in heating, evaporation, transpiration and microclimate in the areas upwind and downwind of a windbreak. The results from field observations, a recent wind tunnel experiment and numerical modelling are used to illustrate important features of the mean and turbulent velocity fields.

Vertical profiles of windspeed measured at several locations up and downwind of a medium porosity windbreak are shown in Figure 4. These profiles are from the wind tunnel experiment of Judd et al. (1996) where wire gauze was used to represent a porous windbreak. A model plant canopy that

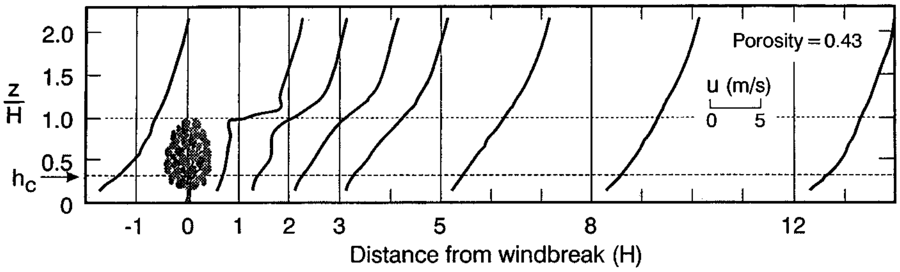


Figure 4. Vertical profiles of average horizontal windspeed at varying locations around a single, medium porosity windbreak.
Source: after Judd et al. (1996).

mimicked the interaction of a tall, flexible crop with the airflow surrounded this model windbreak. The resulting approach wind profile is typical of what might be seen over an extensive, uniform wheat crop. It is a considerable improvement over many early wind tunnel studies that used smooth floors to represent the land surface (e.g. Caborn, 1957).

The profiles in Figure 4 can be compared with Bradley and Mulhearn's (1983) velocity profiles measured around a shelter fence (ϕ = 50%) placed in a bare field (Figure 5). The similar form of the wind profiles is evidence of the ability of the wind tunnel to replicate flows around a windbreak. Both the wind tunnel (Figure 4) and field (Figure 5) data show a sizeable wind shear (change in windspeed with height) at the top of the windbreak. This results from three factors: (1) the accelerating flow over the top of the windbreak; (2) lower windspeeds immediately behind the windbreak and (3) some acceleration through the plant canopy at the base of the windbreak (seen in the wind tunnel data only). These effects combine to virtually eliminate any gradient in the bleed flow, i.e. the windspeed in the layer between the top of the crop (h_c) and H is almost constant with height. This accentuates the wind shear at the top of the windbreak and yields the characteristic inflection in the wind profile described earlier. Profiles measured at locations further downstream of the windbreak show that the inflection diminishes in size as it moves downwind, until eventually the upstream wind profile is re-established.

Figure 6 presents a different view of the effect of a windbreak on windspeed and hence shelter. Rather than plotting a sequence of vertical wind profiles (where windspeed is plotted against height above ground), Figure 6 shows how the mean windspeed measured at one height (below 0.5H) varies with distance upwind and downwind of the windbreak. Note that the windspeeds are expressed as a percentage of the upwind windspeed. The series of

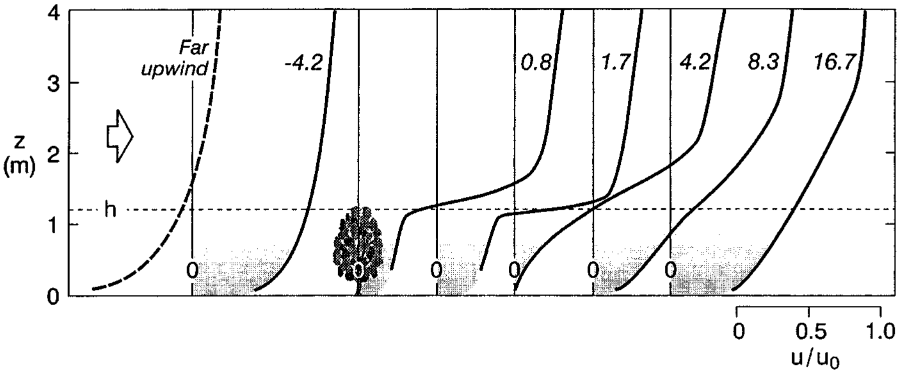


Figure 5. Profiles of average horizontal windspeed measured around a single, medium porosity windbreak. The scale for the windspeed profiles is normalised – U is the actual windspeed measured at various heights (Z) and downwind locations (marked beside each profile, in windbreak heights) and U_0 is the upwind windspeed measured at Z = 4 m.
Source: after Bradley and Mulhearn (1983).

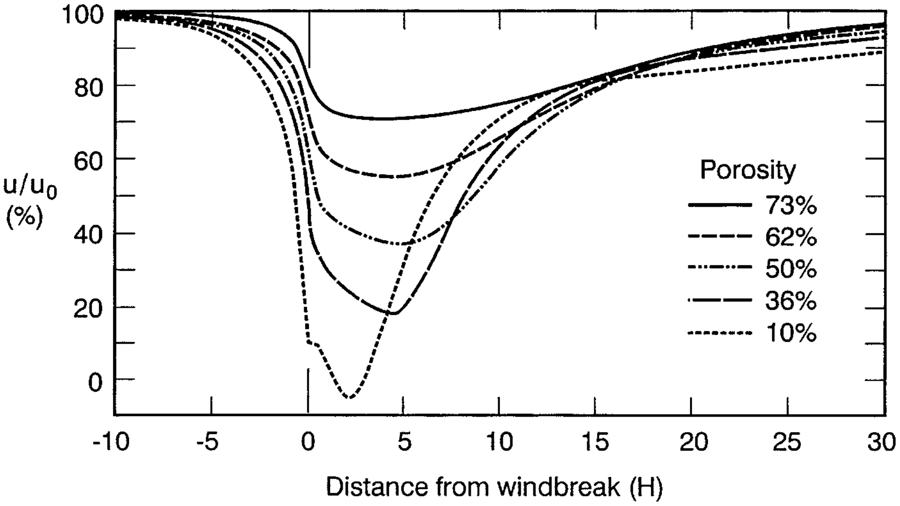


Figure 6. Spatial variation of average horizontal windspeed for windbreaks with varying porosity. Height of windspeed was not specified, but it is less than 0.5*H*.
Source: after Wang and Takle (1997).

curves represent a range in windbreak porosity (described below) and is from the numerical modelling study of Wang and Takle (1997). The important features to note here are a slight windspeed reduction ahead of the windbreak extending to –5*H*; maximum windspeed reduction between $X = 2$ and 8*H* (depending on windbreak porosity); 80% recovery of the upwind windspeed at about 20*H* and incomplete recovery at 30*H*. This means that the zone extending from about 5*H* upwind to at least 20*H* downwind is sheltered from the wind.

Further downstream in the wake zone ($X > 3H$) the combination of faster windspeeds in the layer between h_c and 1.5*H*, and slower windspeeds above, yields a new equilibrium wind profile. This happens by about 6*H* downwind of the windbreak for the upper air layers, but there is still acceleration in the lower layers beyond 12*H* as seen, for example, in the profiles in Figure 5.

The description so far has focused solely on the reduction in mean windspeed by a porous windbreak, but the airflow's turbulence is affected too. Because turbulence transfers water vapour and heat in the atmosphere, it is through changes to both the mean and turbulent flow that a windbreak modifies water use and microclimate. Figure 7 illustrates the variance of the horizontal windspeed (σ_u^2) which is a measure of the turbulence in the flow. It shows a highly turbulent, thin layer of air coincident with the top of the windbreak. This layer spreads vertically with distance downstream, and is quite distinct from the zone of reduced turbulence in the area defined as the quiet zone. Recent studies have shown that this turbulent layer shares many features with a plane turbulent mixing layer (Zhuang and Wilson, 1994; Judd

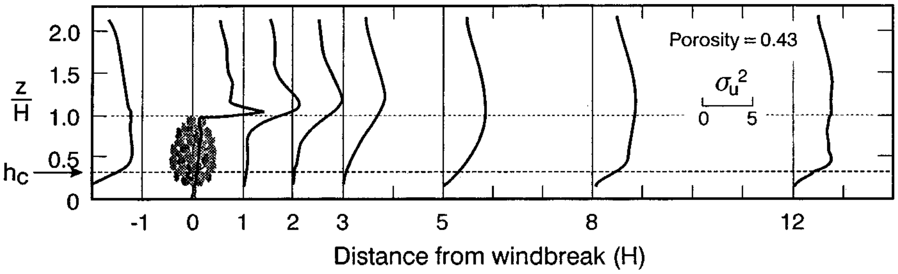


Figure 7. Vertical profiles of σ_u^2 (variance of horizontal windspeed, units are $m^2 s^{-2}$) at various locations surrounding the same model windbreak used in Figure 4.
Source: after Judd et al. (1996).

et al., 1996) which arises when two flows with differing velocities are allowed to merge. The mixing layer is created by the strong wind shear seen in the wind profiles (recall Figure 4) at the top of the windbreak. Its presence is indicated by the 'nose' in the profile of σ_u^2 leeward of the windbreak, at $Z = H$, in Figure 7. This zone of increased turbulence, seen as a relative increase in σ_u^2, spreads outwards and attenuates with distance downwind of the windbreak. Eventually the mixing layer intersects the canopy at around $X = 3H$. The mixing layer is important in re-establishing the upwind wind profile by mixing down the faster flowing air from aloft (i.e. above H) into the air layers closer to the surface. This downward transport of faster flowing air is defined as a downward flux of the air's momentum.

Where the mixing layer intersects the surface downwind (about $3H$ in Judd et al., 4–$8H$ in Wang and Takle, 1997), enhanced turbulence can potentially increase the vertical transport flux of heat, water vapour and any other entity (referred to as scalars) released at the surface. Judd et al. (1996) did not observe a large *increase* in the turbulent momentum flux, unfortunately there are no analogous published measurements of scalar fluxes.

2.3. *Effects of windbreak structure on shelter*

Is there a windbreak structure that creates optimum shelter? This is a question that has driven much of the windbreak research over the last 30 years. Given that 'effective shelter' refers not just to reducing windspeed, but also to the area over which this windspeed reduction occurs, there are many ways to quantify 'shelter'. The most commonly used measures of shelter are:

- U/U_0 (or $[U_0 - U]/U_0$) – the ratio (*or difference*) between the windspeed measured near the windbreak (U) and an upwind reference speed (U_0). These two windspeeds should both be measured at the same height above, and fairly close to, the plant canopy ($Z < 0.5H$);
- U_{min} – the minimum downwind windspeed;
- X_{min} – the downwind distance to U_{min};

- X_S – the distance over which $U/U_0 < c$ where c is an arbitrary factor – often 0.7 or 0.8.

Note that changes in turbulence are never considered in these definitions of shelter – although they should be.

The shelter provided by a windbreak of sufficient length to assume two-dimensional flow ($L > 20H$), and whose width is of the same order as its height, is primarily determined by the drag of the windbreak and the growth of the turbulent mixing layer. These both depend on the following structural features of the windbreak and atmosphere:

- *Windbreak height:* This is the point where the turbulent mixing layer is initiated and determines the size of the sheltered area (i.e. X_S).
- *Windbreak porosity:* The major factor determining the amount of shelter (U/U_0, $U_{\min}$) as well as $X_{\min}$ and wind shear. Numerical simulations (Wang and Takle, 1997) found that the size of the quiet zone was also influenced by the porosity. Porosity depends mostly on the windbreak's morphology and width, but it may also vary with wind speed and direction. Although the two are not the same, the optical porosity does provide an adequate estimate of the windbreak's 'aerodynamic' porosity for relatively thin windbreaks (e.g. Bean et al., 1975).
- *Turbulence of the approach flow:* This influences the rate of spread of the turbulent mixing layer and hence the size of the sheltered area (X_S and the quiet zone). It is determined both by the upwind surface roughness, i.e. land cover and topography, and the atmospheric stability.

As McNaughton (1988) comments, all of these aspects have to be considered when comparing data collected under a range of conditions. Differences in these features may account for apparently conflicting results from different studies.

The effect of porosity on shelter is clearly seen in the profiles of normalised windspeed differences $[U_0 - U]/U_0$ pictured in Figure 8 (from Judd et al., 1996) and the spatial change of U/U_0 in Figure 6 (from Wang and Takle, 1997). Both these figures show that wind speed reduction is greater downwind of a low, rather than a high, porosity windbreak. Figure 6 also illustrates that $X_{\min}$ moves closer to the windbreak with decreasing porosity and shows the presence of recirculation, where U/U_0 becomes negative, behind the 10% porosity windbreak.

Many older windbreak studies have argued that increased turbulence in the lee of a low porosity windbreak leads to a more rapid return to upwind windspeeds. Based mostly on the observations of Naegeli (1946), this led to the recommendation that a medium porosity ($\phi \approx 0.4$) windbreak is optimal for maximising both windspeed reduction and sheltered area. Unfortunately Naegeli's data sets are a composite from several field sites with a variety of upwind conditions and windbreak configurations. Heisler and DeWalle (1988) note that one of Naegeli's data sets is actually from a multiple windbreak

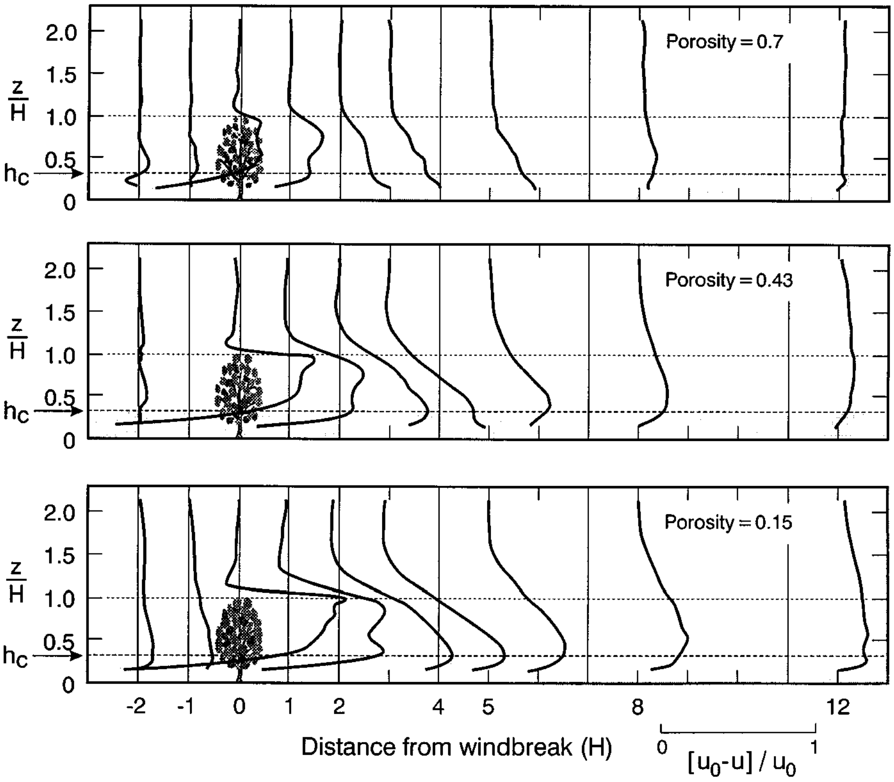


Figure 8. Effect of porosity on reduction in mean windspeed. Note that this is plotted as the normalised difference between the measured windspeed upwind (U_0) and that measured at each station (U), i.e. $[U_0 - U]/U_0$. This means that the more the curve deviates from the axis origin, the greater the wind speed reduction.
Source: after Judd et al. (1996).

array. We know from Judd et al. (1996) that the turbulent mixing layer will grow faster behind such an array (see below). These, and other confounding factors, mean that past interpretations of Naegeli's results overstate the link between porosity and sheltered area, as also noted by Heisler and de Walle (1988). Close inspection of results from other field measurements (e.g. Caborn, 1957) fail to reveal any large differences in the sheltered area for low and high porosity windbreaks. Furthermore, wind tunnel studies such as Jensen (1974), Raine and Stevenson (1977) and Judd et al. (1996) do not find large reductions in X_S behind low porosity windbreaks.

Wang and Takle's (1997) numerical simulations (recall Figure 6) show that the sheltered area (X_S) does not significantly differ between windbreaks with 10% and 50% porosity. Indeed their modelling simulations provide detailed insight into the processes driving the rate of recovery of the upwind windspeed. Behind dense windbreaks, as seen in Figure 6, the rate of recovery is faster in the lee (X = 0–10H) and slower from 10–30H in part as a result of differences in the size and shape of the pressure gradient perturbation behind high and low porosity windbreaks. They conclude that low porosity windbreaks are only slightly less effective than medium porosity windbreaks.

In summary, porosity affects $U_{\min}$ and $X_{\min}$ but, except for very dense windbreaks ($\phi < 0.1$), has a small effect on X_S. Such dense windbreaks, which cause flow separation and high intensity turbulence downwind, are not needed to achieve a shelter effect.

Judd et al.'s (1996) measurements around single and multiple windbreaks revealed the importance of the turbulence in the approach airflow. They found that adding windbreaks upwind created a more turbulent approach flow giving, in effect, a greater slope to the rate of spread of the turbulent mixing layer which therefore intersects the plant canopy sooner. As a result, the quiet zone only extended to 1.8H in the multiple windbreak array and the amount of *local* shelter was decreased. Multiple windbreaks also created a *non-local* shelter effect because the extra drag of the windbreak array lowered the upwind mean velocity. Because this non-local shelter effect more than compensated for the decrease in local shelter, windspeeds were still lower in the quiet zone of a multiple windbreak array than behind a single windbreak

2.4. *Effects of oblique flow on velocity fields and shelter*

Although windbreaks are typically oriented normal to what is believed to be the prevailing wind direction, there will obviously always be periods when the wind blows at an oblique angle to the windbreak. It is therefore important to consider what effect these oblique flows will have on shelter. A reduction in $U_{\min}$, X_S and a shift in $X_{\min}$ will accompany the shift to oblique flow (see Figure 9) for one or all of the following reasons:

- distances downwind, relative to the windbreak, are changed because of the oblique flow path, and the possible refraction of the flow as it passes obliquely through the windbreak (Mulhearn and Bradley, 1977 and Figure 9a, b);
- the aerodynamic porosity in vegetative windbreaks typically decreases as the flow direction (α) shifts from normal ($\alpha = 0°$) to oblique simply because the path length through the break is increased;
- flow around the windbreak ends encroaches on the sheltered area. In Figure 9c, sites located up to 10H downwind of a windbreak (whose length is 40H) are protected from winds approaching the windbreak at an angle of 60°, but sites beyond 10H are not. At 20H, protection is only received for winds blowing at 45° to the windbreak;
- frictional effects will reduce windspeeds even when the flow is parallel to the windbreak (e.g. Caborn, 1957).

Most of the literature suggests that X_S decreases and $X_{\min}$ moves closer to the windbreak as the approach flow becomes more oblique (e.g. the results of

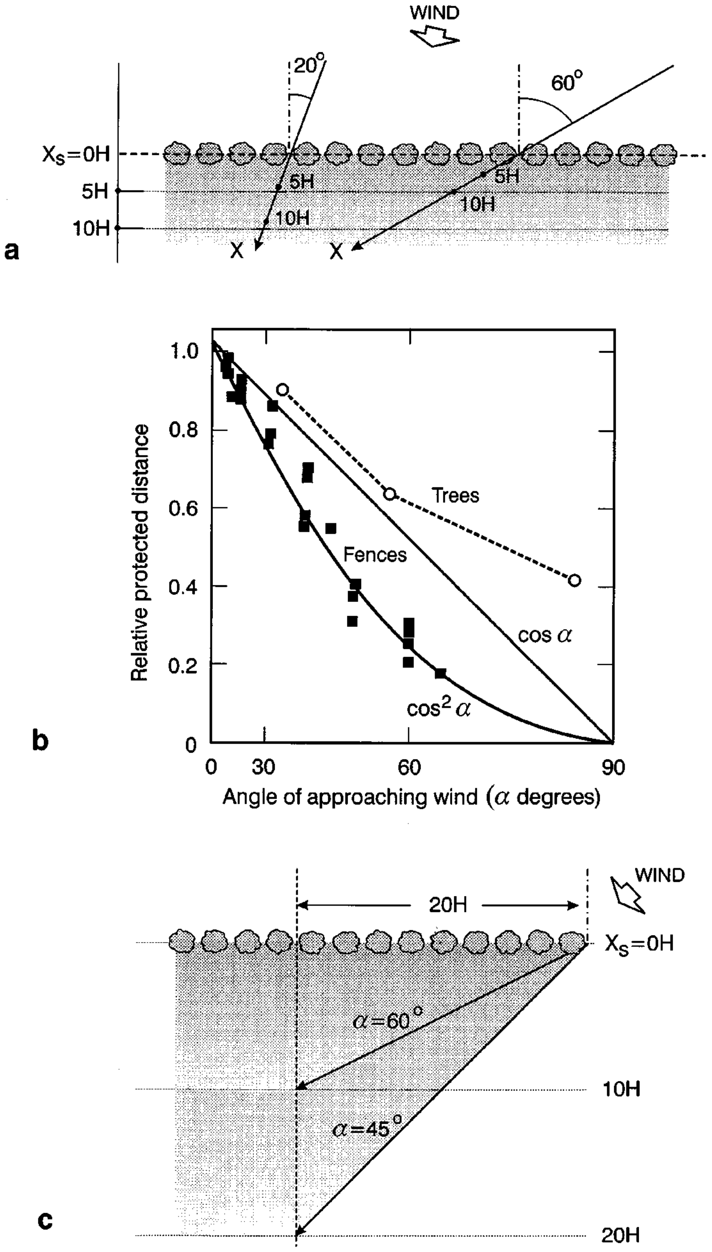


Figure 9. Effect of upwind wind direction on shelter: (a) variation of relative protected distance (= X_S/X in (b)) with flow direction where 0° is normal to windbreak; (b) schematic showing how the relative protected distance is determined – X_S is the distance downwind from the windbreak for normal flow and X is distance downwind along wind's path; (c) illustrates how flow around the ends of a windbreak can reduce the size of the sheltered area.
Source: after Heisler and de Walle (1988).

Nord, 1991; Cleugh unpublished data). Heisler and DeWalle (1988) show that the relative protected distance varies with [$\cos^2 \alpha$] for artificial barriers and [$\cos \alpha$] for natural windbreaks (McMahon, 1990; Brenner et al., 1995, Figure 9(b)). With the exception of Nord's results, these relationships indicate that shelter effects for approach angles within 20° of normal do not vary widely (Jacobs, 1984; van Eimern, 1964 and Brenner et al., 1995).

Mulhearn and Bradley's (1977) experiment points to the importance of maintaining large windbreak length to height ratios in oblique flows. While they found that windspeed reductions were not significantly affected by oblique flow for medium porosity ($\phi = 0.43$) fences with $L > 40H$, this was not the case for dense ($\phi = 0.2$), short fences ($L = 11H$) where shelter was significantly reduced during oblique flow. Furthermore, the turbulent momentum fluxes, in contrast to the mean velocities, were much more sensitive to windbreak orientation – regardless of the porosity or L/H.

2.5. *Summary*

The mean and turbulent airflow around a porous windbreak, oriented normal to the flow, is described. The reduction in windspeed as air flows over a windbreak leads to the development of several distinct flow regions. These include a quiet zone immediately to the lee of a windbreak where windspeeds are reduced, a zone of faster-moving air above the windbreak and a mixing layer where the windspeeds begin to return to their upwind values but where the air's turbulence is enhanced. This mixing layer is initiated at the top of the windbreak, where the windspeed change is the greatest, and grows with distance downwind of the windbreak. It intersects the ground surface at about $5H$ downwind.

The mixing layer, with its enhanced turbulence, has an important effect on microclimates and water-use because these are determined by the turbulent exchange of heat and water between the land surface and atmosphere. The next two sections detail these processes, and their ultimate effect on yields.

It is difficult to prescribe a windbreak design that optimises shelter – in part because the term 'shelter' has many meanings. Nonetheless, windbreak height and the turbulence in the approaching airflow are the main factors influencing the distance over which windspeeds are reduced, while windbreak porosity is the critical factor determining the amount of windspeed reduction. There is little difference in the size of the sheltered area downwind of porous and dense windbreaks, in contrast to the findings and interpretations of earlier studies.

In contrast to this picture for the mean and turbulent airflow, our understanding of windbreak effects on turbulent exchanges of heat and water vapour, and the way that these effects are changed with oblique flow, are much more poorly understood.

3. Microclimates around windbreaks

3.1. *The effect of shelter on turbulent fluxes; temperature and humidity*

What are the effects of these changes in airflow on the microclimate and the amount of heating and evaporation from surfaces downwind of a windbreak? Unfortunately, there have been far fewer studies of the turbulent fluxes of heat, water vapour and CO_2 behind windbreaks compared to studies of the mean and turbulent airflow. Especially, there are no published wind tunnel studies analogous to that of Judd et al. (1996), and very few numerical simulations, to provide clear insight. The following discussion relies upon the excellent review by McNaughton (1988) and introduces new work done since.

Airflow studies have shown that turbulence, the mechanism for exchanging heat, water vapour (i.e. evaporation) and CO_2 between the land surface and the atmosphere, is reduced in the quiet zone and enhanced in the wake zone behind a porous windbreak. This means that turbulent transfer should be less efficient in the quiet zone and more efficient in the wake zone. By convention, turbulent fluxes are considered to be positive when transfer is directed away from the surface and into the atmosphere. So by day, when the turbulent sensible heat flux (Q_H) is positive and the absorbed radiation is fairly uniform with distance downwind of the windbreak, near-surface air temperatures in the quiet zone would be expected to be larger than those upwind because of the 'less efficient' turbulent transport of heat. At night, when Q_H is typically negative, this effect would lead to cooler near-surface air temperatures in the quiet zone.

Similarly, we might expect air temperatures in the wake zone to be lower by day, and higher by night, than those in the quiet zone. Concentrations of other entities emitted from the land surface – water vapour is the most obvious example – would be expected to show similar spatial patterns, as illustrated in Figure 10. Plant canopies absorb CO_2 by day and so the near-surface quiet zone air may be depleted of CO_2 during daylight hours. The pattern just described assumes that the 'sources' of these entities have a uniform spatial distribution.

Some of the studies reviewed by McNaughton (1988), and more recent field measurements, have found elevated temperatures and humidities in the sheltered quiet zone by day in support of the theory. For example, McAneney et al. (1990) found that maximum air temperatures measured within kiwifruit orchards in NZ increased over time in accord with the increasing height of the surrounding windbreaks. The studies of Brown and Rosenberg (1972) and Wang and Klaasen (1995) found enhanced air temperatures in the sheltered zone, but not the expected cooling at night. Air temperatures were increased by 1.8 °C, and humidity by 4 hPa, in Brown and Rosenberg's (1972) measurements over sheltered sugar beets in Nebraska. Unfortunately the data do not extend much beyond $8H$ and are thus unable to shed any light on the pattern of scalar concentrations in the wake zone.

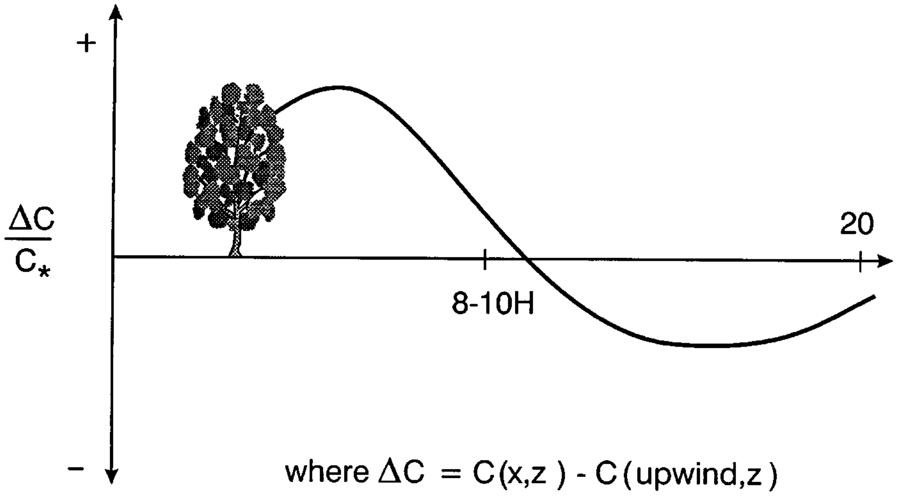


Figure 10. Hypothetical spatial distribution of changes in a scalar concentration (*C*) whose source is at the ground surface and is spatially uniform upwind and downwind of a windbreak. Scalar concentrations have been normalised by C^* (= Flux of C/u_0^* where u_0^* is the upwind shear stress – a measure of the airflow's turbulence and surface roughness upwind) to account for differences in radiation and windspeed.
Source: after McNaughton (1988).

Brenner et al.'s (1995) measurements of air temperatures and water vapour concentrations matched the theoretical pattern in Figure 10 although the upwind and downwind data seem to have been measured at different heights. Like many of these observational studies, the spatial variation of the heat fluxes downwind of the windbreak was not addressed. Early results from the numerical modelling studies of Patton et al. (1996) also reveal increased scalar concentrations in the quiet zone (X = 1–5H, below $Z = H$) but no marked decrease in scalar concentration for $X > 5H$.

The few studies measuring CO_2 concentrations have observed slightly reduced concentrations in the quiet zone by day (e.g. Caborn, 1957) and elevated concentrations at night. Brown and Rosenberg (1972) found that the daytime reductions in CO_2 concentration were not significant and certainly would not affect photosynthetic activity. They concluded that, in terms of plant responses, shelter affected humidity more than CO_2.

3.2. *Evaporation and heat fluxes*

Windbreaks are believed to reduce evaporative water losses from surfaces downwind, and thus conserve soil moisture, based on the notion that increased shelter from wind reduces evaporation. This arises from studies using either open water evaporation pans, or well-watered plants, behind windbreaks. Such studies are limited in two ways.

Firstly, they focus upon the relationship between windspeed and evaporation only. The previous discussion illustrated that the turbulent mixing layer, which reduces turbulent transfer in the quiet zone and potentially enhances scalar transport in the wake zone, dominates the turbulent flow behind a windbreak. Windspeed is thus only a part of the process by which windbreaks modify evaporation and water-use of soil and plants growing downwind. A complete analysis should also consider the modified turbulent transport of scalars in the quiet and wake zones, but there are no published measurements to provide this analysis.

Secondly, these studies reveal little about how actual soil and plant evaporation are modified by shelter, where actual evaporation is defined as the loss of water from plants and soil. Both leaves and soil have some internal resistance to water movement and simple relationships between windspeed and open water evaporation are therefore inappropriate. Stomata regulate the exchange of CO_2 and water vapour in plants. This stomatal regulation is quantified via the stomatal resistance (r_s) which varies in response to plant physiological and environmental factors such as light, temperature and moisture stress.

The Penman Monteith equation can be used to examine the sensitivity of evaporation to windspeed and thus, acknowledging the limitations mentioned above, provides an analysis of the way that a windbreak may modify evaporation and water use. The Penman Monteith equation (see Nuberg, this volume) is a physically-based and theoretically sound description of evaporation for plant canopies as well as bare soil. This analysis reveals that the sensitivity of evaporation to changes in windspeed depends on whether the actual evaporation rate (Q_E) is larger or smaller than the evaporation rate given by the following equation:

$$Q_{E\mathrm{eq}} = \frac{\varepsilon}{\varepsilon + 1} A$$

where[1] ε depends on temperature and A is the available energy ($Q^* - Q_G$ where Q^* is the net all-wave radiation and Q_G is the flow of heat into the soil). This evaporation rate is usually referred to as ‘equilibrium evaporation’ ($Q_{E\mathrm{eq}}$) because it is the evaporation from a well-watered crop or pasture, which is flat and extends for many kilometres in all directions. $Q_{E\mathrm{eq}}$ depends on radiation and temperature only – if the actual evaporation equals this equilibrium rate then it does not vary with changes in windspeed or stomatal resistance.

Reducing windspeed will reduce actual evaporation only if it exceeds the equilibrium evaporation rate. Such a situation, where $Q_E > Q_{E\mathrm{eq}}$, might happen when moisture is freely available, e.g. if the soil or plant canopy is wet from rain or irrigation and r_s is close to 0. This is what is traditionally referred to as potential evaporation. Actual evaporation can also be larger than $Q_{E\mathrm{eq}}$ when $r_s > 0$ if the atmosphere is very dry and surface moisture is available. Persistently low humidity levels over an actively evaporating surface can only be maintained by a continuous supply of dry air from upwind – this is dry air advection. In both of these situations, a reduction in windspeed will reduce evaporation.

If moisture is not freely available at the surface ($r_s > 0$) and in the absence of dry air advection, actual evaporation is typically less than the equilibrium rate (i.e. $Q_E < Q_{E\mathrm{eq}}$). In this situation, reducing windspeed can potentially *increase* evaporation, as demonstrated in Figure 11a and b.

Figure 11a illustrates a 'family' of curves, calculated using the Penman Monteith equation, which show the effect of increasing windspeed on evaporation (normalised by the available energy, A). Each curve is for a specific stomatal resistance, where 0 s/m represents a wet canopy; 50 s/m is typical for a crop well supplied with water and 500 s/m would be a very dry canopy indeed. The way that evaporation (Q_E) changes with changing windspeed (U) depends on stomatal resistance. The uppermost curve, where r_s is 0 s/m, shows that Q_E increases as U increases, while the lowest two curves show Q_E decreasing with increasing U. The evaporation rate that is independent of windspeed changes (i.e. $\partial Q_E/\partial U = 0$) corresponds to a stomatal resistance of about 50 s/m – this is referred to as $r_{s\mathrm{crit}}$ – and this evaporation rate is the equilibrium evaporation defined by the equation above. For plants whose stomatal resistance is less than $r_{s\mathrm{crit}}$ (i.e. the upper two curves in Figure 11a), a decrease in windspeed leads to a decrease in evaporation such that $\partial Q_E/\partial U$ is positive. Evaporation can *increase* with *decreasing* windspeed (i.e. $\partial Q_E/\partial U$ is negative) if stomatal resistances exceed 50 s/m, as indicated by the lower 2 curves. Note that each of the Q_E/U curves tend towards the equilibrium evaporation rate as $U \rightarrow 0$. This means that the effect of shelter, in terms of reduced windspeeds in the quiet zone, is to force evaporation closer to the equilibrium rate. Whether this represents an increase or decrease in evaporation depends on whether the evaporation rate *without* a windbreak is larger or smaller than equilibrium evaporation. Of course, this analysis specifies the stomatal resistance. As discussed both below, and in Section 4, if $Q_E < Q_{E\mathrm{eq}}$ in a real canopy, the increased demand accompanying a windspeed reduction may cause further stomatal closure, especially if soil water is severely restricted, and increased evaporation may not be observed.

Figure 11b is from Raupach (unpublished data) and goes a step further than Figure 11a. The same Penman Monteith equation is used, but Raupach extends the analysis to all surface roughness types whereas Figure 11a is for a crop only. In Figure 11b, the critical stomatal resistance ($r_{s\mathrm{crit}}$, the value of r_s when $\partial Q_E/\partial U = 0$) is plotted versus the surface roughness, thus showing the way that $r_{s\mathrm{crit}}$ varies across all surface roughness and surface wetness regimes for a particular climate (air temperature = 25 °C and relative humidity = 50%). There are two key points to be drawn from this figure:

1. Over very smooth surfaces (e.g. bare soil) $\partial Q_E/\partial U$ is positive for all moisture regimes, i.e. shelter will always *reduce* evaporation from low roughness surfaces.

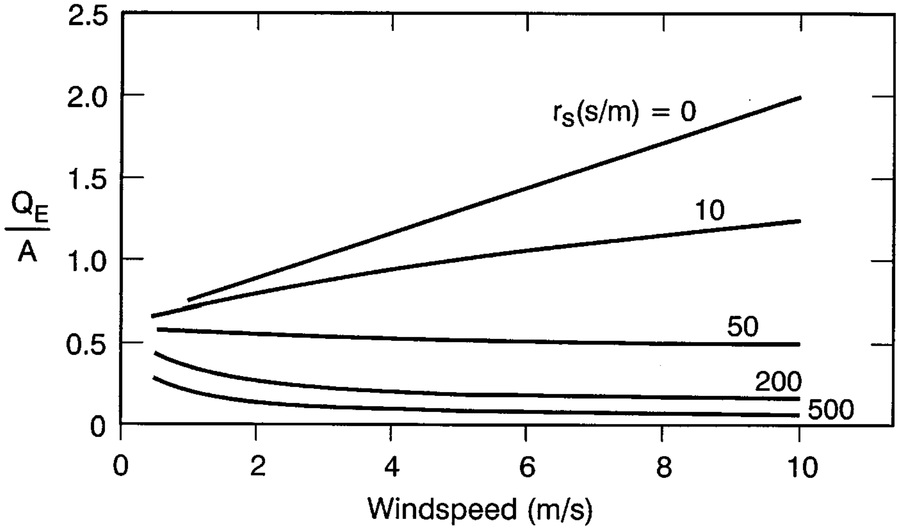


Figure 11a. Effect of windspeed on evaporation (Q_E), where evaporation is expressed as a fraction of the available energy (A = net radiation – soil heating).

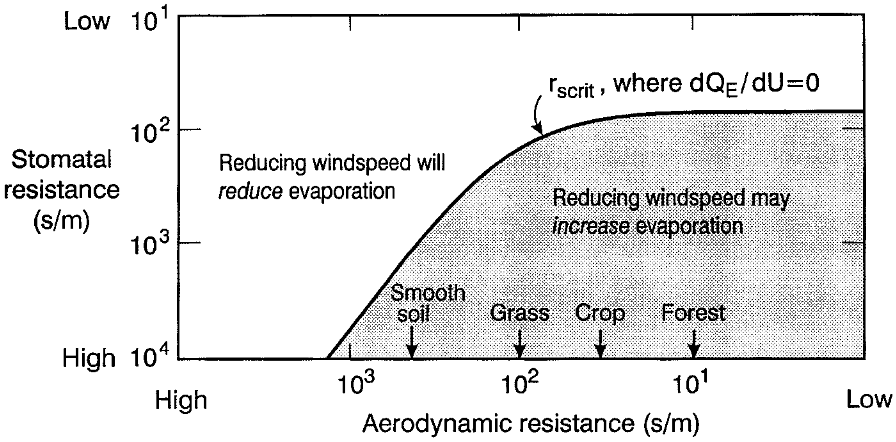


Figure 11b. Effect of surface roughness, expressed as the aerodynamic resistance, on the critical stomatal resistance where evaporation (Q_E) is insensitive to changing windspeed (U). The aerodynamic resistance is a measure of the surface roughness. For the same windspeed, this parameter will be smaller for a rough surface. Corresponding land cover types have been marked on the figure. Both (a) and (b) assume an air temperature of 25 °C and relative humidity of 50%.

Source: after Raupach (pers. comm.).

2. The critical stomatal resistance (r_{scrit}) for grass is 100 s/m; crops is 80 s/m; and forests is 70 s/m. If the actual stomatal resistance exceeds these critical values then $\partial Q_E/\partial U$ is negative, i.e. reducing windspeed via shelter will *increase* evaporation.

A different temperature or humidity would not alter this argument and findings, except r_{scrit} may change slightly. Thus for most agricultural landscapes – except bare soil – the relationship between windspeed and evaporation shown in Figure 11a holds. The physical explanation for this windspeed-evaporation relationship lies in the relative importance of plant temperature and turbulent transport in determining evaporation. Typically r_s is not negligible and plant leaves are therefore warmer than the atmosphere. The water vapour content within the leaf stomata is equivalent to the saturation vapour pressure[2] at the leaf temperature, which is greater than the vapour pressure of the air. This leaf-air humidity gradient drives the water vapour flux – the evaporation. A reduction in windspeed, and hence reduction in the transport of heat away from the leaf, raises the temperature of the leaves. This, in turn, increases the saturation vapour pressure within the leaves, strengthening the leaf-air vapour pressure gradient and increasing evaporation. The key point here is that when $r_s > r_{\mathrm{scrit}}$, it is the stomatal resistance that limits evaporation, not the turbulent transport. Thus the increase in leaf-air humidity gradient has a larger influence on the evaporation than the reduced transport of water vapour that arises from the lower windspeeds. Ignoring stomatal feedbacks, reduced windspeeds in the quiet zone will therefore only reduce evaporation when the vegetation is well supplied with water. Substantial reductions in evaporation can potentially be achieved in such circumstances because the windbreak also shelters the plant canopy from dry air advection (see McNaughton, 1988).

The situation for real crops growing in the quiet zone of a windbreak complicates the application of this theory. Plants growing in the quiet zone may germinate more quickly; grow larger leaves and have different stomatal resistances than unsheltered plants. For example, Brenner (1991) found that shelter increased the evaporation from unirrigated millet growing in the semi-arid Sahel by both reducing the stomatal resistance and so increasing the water loss per unit area, and by increasing the actual leaf area of the crop. Shading by the windbreak will further alter the spatial distribution of radiation and available energy. Indeed reduced available energy and photosynthetic radiation (see below) in the area shaded by a windbreak may reduce evaporative water losses and the onset of moisture stress. Such complexities illustrate why there is so little experimental data showing windbreak effects on crop water use per se.

There are a few carefully conducted studies that do confirm the relationship between windspeed and evaporation presented in Figure 11. Brown and Rosenberg (1971) measured evaporation from irrigated sugar beets, using techniques perhaps not best suited to flows behind windbreaks. They found that shelter slightly increased evaporation when the atmosphere was unstable (Q_H positive), and reduced evaporation when dry air advection dominated in the afternoon periods. They thus concluded that water use by a crop well supplied with water would not be significantly changed by shelter. While this result is generally accepted, it will not be the case if dry air advection persists throughout the day, as found by Miller et al. (1973). They took great care to eliminate feedbacks due to improved growth of plants grown in shelter. Under the strong dry air advective conditions in which they conducted their measurements, shelter reduced the downward flux of sensible heat, the stable lower atmosphere became unstable and evaporation was reduced. This is a classic example of the reductions in evaporation that can be achieved by shelter from dry air advection.

There are also a few studies measuring evaporation over unirrigated surfaces. Barker et al. (1989) found that evaporation rates and seasonal water-use in unirrigated cotton plants was increased by shelter. McAneney et al. (1992) directly measured evaporation from a kiwifruit vineyard surrounded by shelter. They found that the actual evaporation from the sheltered kiwifruit vines was larger than for the unsheltered vines because the effect of reducing windspeed was to move the actual evaporation rates closer to equilibrium evaporation. This confirmed the hypothesis from earlier studies by the same group (see e.g. Judd and McAneney, 1984) that shelter would force the actual evaporation towards an equilibrium rate.

3.3. *Summary*

Concentrations of entities with a ground level source, such as heat and water vapour, are likely to be altered as a result of the modified mean and turbulent airflow behind a windbreak. Higher daytime humidity, soil and air temperatures are thus expected, and often observed, in the quiet zone. The spatial pattern of these microclimate features further downwind, where the mixing layer intersects the ground surface, awaits more careful measurements. Physical reasoning predicts *reduced* scalar concentrations in this zone (recall Figure 10) as a result of more ‘efficient’ turbulent mixing. This would mean slightly cooler and less humid conditions by day at around 8*H*, but further research is needed to confirm these predictions.

The effect of the windbreak on plant and soil evaporation is very complex. Using physical relationships between windspeed and evaporation we show that shelter can either increase or decrease evaporation rates depending on soil and plant water status and the prevailing weather conditions. Thus any effects of shelter on water-use in the quiet zone (ignoring root competition) are likely to be small when integrated over the entire growing season. The subsequent impact on yields and water-use efficiency may not be small, however, as described in the next section. These interpretations are based on relationships between windspeed and evaporation, not the physical process of turbulence that transports water vapour from the surface into the atmosphere. Given the turbulent airflow patterns seen around windbreaks (e.g. Figure 7), the windspeed analysis just described is likely to be appropriate for evaporation in the quiet zone while increased evaporation rates are possible in the wake zone.

4. Effects of windbreaks on crop yield

A large number of observational studies have shown that windbreaks improve plant growth and yields over a range of climate and soil regimes. Kort (1988); Lynch et al. (1980); Eastham et al. (1990); Baldwin (1988) and Norton (1988) and others demonstrate that field and forage crops, such as cereals and pasture, have mixed responses to shelter, while shelter generally improves yields in vegetables, speciality crops, orchards and vineyards. Maximum yield gains are typically found in the quiet zone, i.e. between 3 and 10*H*.

Sections 2 and 3 described the aerial environment and microclimate surrounding a windbreak. This Section addresses the mechanisms by which this modified environment, and hence windbreaks, affects crop growth and yields. Further discussions of the effect of windbreaks on yields are contained in the excellent review edited by Brandle and Hintz (1988), and papers in this Volume reviewing windbreak effects on temperate crop and pasture productivity (Nuberg and Bird, this volume).

Shelter from wind affects crop yields directly and indirectly. Protecting plants from direct mechanical damage is possibly as important as the indirect microclimate effects described in Section 3 and below. A reduction in leaf abrasion, tearing and stripping is likely to be an important reason for the improved productivity of many sheltered vegetable crops. Grace and Russell (1982) found that wind-induced leaf abrasion modified the stomatal resistance of individual leaves. Likewise, windbreaks potentially reduce the incidence of sandblasting at the seedling stage. Many studies also report larger leaves, more luxuriant growth and/or more rapid development of leaf area near to windbreaks (see Miller et al., 1995; Cleugh, this volume). Leaf area developed faster, and grew taller, in millet plants grown at 3*H* compared to unsheltered plants, and plants growing at 1*H* (Brenner, 1991). The increased biomass did not, however, translate into large gains in grain yield. Sun (1994) suggests that the 7% increase in yields found in a sheltered potato crop resulted from reduced leaf damage, stripping, abrasion and wind-borne pests. Stem and root lodging may also be reduced, especially in the quiet zone. A better understanding of the turbulent regime in the wake zone is required before the likelihood of lodging in that zone can be assessed, although Judd et al. (1996) did not find increased turbulence in the canopy at the point where the mixing layer contacted the canopy.

The modified mean and turbulent airflow can indirectly affect plant growth because of the changes in energy partitioning and microclimate that were described in Section 3. A single windbreak, a multiple array of windbreaks, and even a landscape with a fairly dense tree canopy, can ‘decouple’ the air in the quiet zone from that above the windbreaks, or the below-canopy air from the above-canopy air in the case of a tree canopy[3] The importance of this decoupling to the local microclimate around a windbreak then depends on the regional climate. If that is characterised by dry air advection then the microclimate within the quiet zone may be more benign – with reduced wind, higher temperatures, reduced evaporation rates and higher humidity levels. Whether this is beneficial or harmful to the sheltered plants depends on the species. In winter, the presence of slightly elevated air and soil temperatures and enhanced germination in the quiet zone may explain rapid increases in sheltered leaf area, such as seen by Aase and Skiddoway (1974). On the other hand, this decoupling can lead to soil and air temperatures which exceed the optimum for germination and growth, as found by Brenner et al. (1995). Although not described in any papers, this decoupling will create colder temperatures at night when warmer air aloft is prevented from mixing down into the sheltered quiet zone. Whether this cold air then ponds near the windbreak, or drains away will depend on the slope of the paddock.

Leaf stomatal resistances can also be modified by shelter-induced changes to the canopy temperature and humidity. Brenner et al. (1995) noted the importance of differentiating stomatal responses to shelter between irrigated and unirrigated plants. The effect of sheltering plants that are well supplied with water (i.e. r_s is small) appears to be increased humidity within the leaves and canopy, a consequent reduction in stomatal resistance and, providing CO_2 is non-limiting, enhanced photosynthetic activity (Brown and Rosenberg, 1970; Brenner, 1991).

Combining these results with an understanding of how windspeed affects evaporation (Section 3) enables the following comments to be made about the impact of shelter on water use and yield for real crops and pastures. These refer to the quiet zone only – where windspeeds are reduced. In the wake zone, where turbulent transfer is enhanced, there is considerable potential for water-use to be increased above the rates that would occur in the absence of shelter:

1. Excluding cases of dry air advection, sheltering a well-watered crop does not alter the amount of water used, but is likely to increase photosynthetic activity and hence water-use efficiency. Thus greater vegetative growth can occur, and possibly enhanced yields, without a significant change in water use.
2. In contrast, sheltering a crop where the water supply is restricted can lead to one or all of the following responses:
   - Evaporation may increase via changes to the crop energy balance as described earlier (recall Figure 11). In the unlikely event that stomatal resistance is unaltered as a result of these energy balance changes, assimilation may remain the same while water-use increases.
   - It is more likely that increases in canopy temperature and canopy-air humidity gradients will cause stomatal closure. As a result photosyn-

thetic activity and assimilation will be reduced while water-use will be slightly reduced or not change.
  - If shelter results in faster growth rates and increased biomass production, then evaporation may be increased because of greater leaf area.
3. Shelter can reduce soil evaporation rates when LAI is low. This may improve the soil water availability for the crop later in the season and thus improve seasonal water-use efficiency.

Shade from solar radiation directly affects plant growth because of the reduction in photosynthetically active radiation and indirectly because of its effects on soil and air temperatures and evaporation. Ludlow (1978) notes that shading reduces the growth rates of tropical and temperate pastures and that gaining access to light is one of the most important competitive advantages for plants. Shading, essentially competition for light, can thus have a real impact when the size of the farm holding is small as illustrated in Kohli et al. (1990) for *Eucalyptus* windbreaks in India.

An increase in diffuse radiation near the windbreak, and the resultant improved light transmission into plant canopies, is a mechanism that could *enhance* photosynthetic activity but no documented evidence was found with which to test this hypothesis.

The area shaded by a windbreak is easily determined from the geometry and leaf area density of the shading vegetation; its latitude and the time of day and year of interest (these determine the solar elevation). Figure 12 illustrates the area shaded by a windbreak (in the Southern hemisphere) oriented normal to the solar azimuth (i.e. approximately east-west) as a function of season (summer, winter and the equinox); time of day (0900, solar noon) and latitude. The calculations assume that the windbreak does not reflect or transmit solar radiation. While highly simplified, Figure 12 demonstrates that at mid latitudes the shaded area can extend well beyond the quiet zone in winter. For a windbreak oriented parallel to the solar azimuth (i.e. roughly north-south), the shaded area shifts from the paddocks to the west of the windbreak in the morning to those east of the windbreak in the afternoon.

Lowering soil and canopy temperatures via shading may limit growth, as in the case of Onyewotu et al. (1994), or simply offset some of the warming in the quiet zone. Given the results of Brenner et al. (1995), shade may be needed to prevent damagingly high soil and plant temperatures in tropical climates. Conversely, a crop shaded through mid morning may be still frost-covered when exposed to high intensity, direct-beam solar radiation at midday. Figure 12 shows that this might be expected for an autumn-planted cereal or legume crop in July and August. Finally, we should note that shading may decrease evaporation rates close to a windbreak and so reduce moisture losses from bare soil prior to germination and emergence as found by Wallace et al. (1991).

Windbreaks have thermal radiation effects too. As a result of the sky view effect, where the cold night sky is replaced by warmer trees, a windbreak

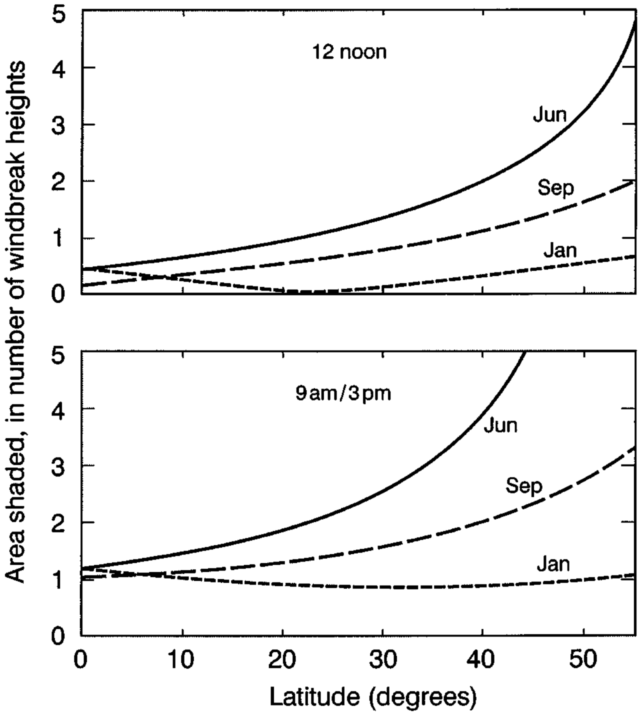


Figure 12. Model simulations of the area shaded by a windbreak as a function of latitude and time.
Source: from Abel et al. (1997).

can reduce thermal radiation losses from the surrounding crop out to about a distance of 1*H*. Eastham and Rose (1988) cited this slight reduction in frost incidence, near the windbreak, as an important affect on pasture productivity. The reduction in surface cooling that results from reduced thermal radiation losses out to about 1*H* is in contrast to the lower air temperatures that may occur over the entire quiet zone at night as a result of the decoupling described in Section 3.

There are two remaining mechanisms by which tree windbreaks modify the surrounding environment. These are mentioned briefly for completeness, however it is not the purpose of this review to comprehensively address them.

Below ground, the growth and productivity of the windbreak and sheltered plants depends on their relative root densities and rooting patterns. Tree roots can improve soil fertility by adding carbon, nitrogen (in the case of leguminous tree species), taking up leachable nutrients and maintaining soil biomass (Schroth and Zech, 1995). However, if the roots of the windbreak occupy the same soil volume as the sheltered crop, then competition for nutrients and water will almost certainly limit productivity. Allelopathy, where tree roots toxify the soil, is another mechanism whereby windbreaks may limit the productivity of adjacent vegetation (Onyewotu et. al., 1994). Onyewotu et al., 1994 found that root pruning substantially improved millet yields close to a *Eucalypt* windbreak where the millet and *Eucalypt* roots had similar depths.

Pests, pollen and pathogens all rely on the wind for transport. Thus providing shelter will modify the pathways for these around the crop environment. For example, if a pest or pathogen source area is some distance upwind of a sheltered crop then they will be preferentially deposited anywhere where the windspeed drops – usually immediately upwind or downwind of the windbreak. High humidity levels have been observed to exacerbate the incidence of fungal diseases in sheltered crops and reduce yields (Brenner, 1991). The increased biological diversity that potentially accompanies a well-designed windbreak may introduce natural predators to prey on pests and so reduce the need for pesticides.

5. Concluding comments

Above ground effects of windbreaks on the microclimate and crop growth begin with perturbations to the mean and turbulent airflow. This review has shown that the mean velocity field, for flow normal to a windbreak, is fairly well understood. Indeed, numerical model simulations (e.g. Wilson, 1985; Wang and Takle, 1995, 1996 and 1997; Patton et al., 1997) are able to capture features of the mean velocity field quite well. The challenge now is to use both these numerical modelling tools and carefully designed wind tunnel and field experiments to understand better the dynamics of the turbulent flow – including the effects of oblique flows. Wang and Takle's numerical study, which shed light on why medium-dense windbreaks are the most efficient, is an example of the role that numerical modelling can have. An even greater challenge is to develop a similar level of understanding for the mean and turbulent scalar concentration fields – i.e. humidity, temperature, CO_2 – using these same tools. Only then can windbreak effects on crop productivity be quantified and predicted.

Acknowledgements

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List of Main Symbols

H	windbreak height
W	windbreak width
L	windbreak length
ϕ	windbreak porosity
X	horizontal distance (usually downwind)
Z	height
U_{min}	minimum windspeed
U	windspeed
U_0	upwind, reference windspeed – not influenced by the windbreak
X_{min}	horizontal distance to location where Umin is observed
X_S	horizontal distance over which windspeeds have been reduced by
α	an arbitrary amount
	wind direction as flow approaches the windbreak
$Q* - Q_G$	available energy – $Q*$ is the net all-wave radiation while Q_G is the soil heat flux
A	available energy as defined above
Q_H	sensible heat flux
Q_E	latent heat flux – ie. the energy equivalent of the evaporation rate
$Q_{E\mathrm{eq}}$	equilibrium evaporation rate (see text for definition of equilibrium)
r_s	stomatal resistance
r_{scrit}	critical stomatal resistance when _QE/_U is zero
σ_u^2	variance of horizontal windspeed
C	scalar (e.g. humidity, CO_2, air temperature etc.) concentration
u_0*	the upwind shear stress – a measure of the airflow's turbulence and the surface roughness upwind
h_c	canopy height

Notes

1. ε is the dimensionless slope of the saturation specific humidity (q_s)-temperature curve = $(L_v/c_p)\mathrm{d}q_s/\mathrm{d}T$.
2. The saturation vapour pressure is the amount of water vapour in air, over a plane liquid surface, that can be maintained as vapour. It is strongly dependent on temperature – exponentially increasing with increasing temperature. The saturation specific humidity, mentioned with reference to equation 1, is the same as the saturation vapour pressure but rather than expressing the water vapour content as a partial pressure, it is expressed as the mass of water vapour per mass of air.
3. The 'strength' of the decoupling depends on the canopy or windbreak density – here we are considering closely-spaced windbreaks (around 10–20*H*) or dense tree canopies. This discussion also ignores any changes to the regional climate that may arise from this decoupling.

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