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Windbreak Practices

Windbreaks and shelterbelts are barriers used to reduce wind speed. Usually consisting of trees and shrubs, they also may be perennial or annual crops, grasses, wooden fences, or other materials. They are used to protect crops and livestock, control erosion and blowing snow, define boundaries, provide habitat for wildlife, provide tree products, and improve landscape aesthetics.

The systematic use of windbreaks in agriculture is not a new concept. At least as early as the mid-1400s the Scottish Parliament urged the planting of tree belts to protect agricultural production (Droze, 1977). From these beginnings, shelterbelts have been used extensively throughout the world to provide protection from the wind (Caborn, 1971). As settlement in North America moved west into the grasslands, homesteaders planted trees to protect their homes, farms, and ranches. In response to the 1930s Dust Bowl conditions, the U.S. Congress authorized the Prairie States Forestry Project. This conservation effort led to the establishment of 29,927 km (over 96,000 ha) of shelterbelts in the Great Plains (Droze, 1977). In northern China, extensive planting of shelterbelts and forest blocks was initiated in the 1950s. Today the area is extensively protected and studies have documented a modification in the regional climate (Zhao et al., 1995). Windbreak programs also have been established in Australia (Miller et al., 1995; Cleugh et al., 2002), New Zealand (Sturrock, 1984), Russia (Mattis, 1988), and Argentina (Peri and Bloomberg, 2002). Although the value of protection is widely recognized, the inclusion of windbreaks as an integral component of sustainable agriculture in the United States remains limited.

The goal of this chapter is to provide practical information for landowners, producers, conservation professionals, and students. It is our hope that this information will help others understand the value of windbreaks and encourage their inclusion as components of sustainable agricultural production systems. The chapter is divided into four main sections: (i) how windbreaks work; (ii) how organisms respond to wind protection; (iii) the design, management, and benefits of windbreaks; and (iv) the overall role of windbreaks in the sustainable agricultural landscape. The emphasis is on temperate regions and, in most cases, on mechanized agriculture. This chapter will present only a summary of the wealth of information available on windbreaks. For more detail on any of the subjects covered here, the reader is referred to reviews by Brandle et al. (1988), Miller et al. (1995) and Cleugh et al. (2002).

North American Agroforestry: An Integrated Science and Practice, 2nd edition, H.E. Garrett (ed.)

How Windbreaks Work

Wind Flow in the Environment

Wind is defined as air in motion. It is caused by the differential heating of the earth's surface, resulting in differences in pressure; wind is also influenced by Coriolis forces created by the earth's rotation. On a global scale, atmospheric circulation drives our daily weather patterns. On a microscale, there is a very thin layer of air (several millimeters or less) next to any surface within which transfer processes are controlled by the process of diffusion across the boundary layer. Between these two scales are the surface winds. They move in both vertical and horizontal directions and are affected by the conditions of the surfaces they encounter. Surface winds extend above the earth's surface 50 to 100 m and are dominated by strong mixing or turbulence (Rosenberg et al., 1983). These surface winds influence wind erosion, crop growth and development, animal health, and the general farm or ranch environment. They are also the winds that are affected by shelterbelts.

Although surface winds can be quite variable and the flows highly turbulent, the main component of the wind moves parallel to the ground. Wind speed at the soil surface approaches zero because of the frictional drag of the surface. The amount of drag is a function of surface roughness. In the case of vegetation, the height, uniformity, and flexibility of that vegetation determines the surface roughness and the amount of drag (Lowry, 1967). A rough surface such as wheat stubble has greater frictional drag, slower wind speeds, and greater turbulence near the surface than a relatively smooth surface, such as mown grass. A windbreak increases surface roughness and, when properly designed, reduces wind speed over large areas to the benefit of agriculture. Discussions of wind, wind profiles, turbulent transfer, and exchange coefficients can be found in McNaughton (1988) and Cleugh (2002). For our purposes, turbulent transfer rates are defined as the rates of exchange between the crop and the atmosphere for heat, water vapor, and CO_2 caused by the vertical mixing of air.

Wind Flow across a Barrier

A windbreak is a barrier on the land surface that obstructs the wind flow and alters flow patterns both upwind of the barrier (windward) and downwind of the barrier (leeward). As wind approaches a windbreak, some of the air passes through the barrier while the rest flows around the ends of the barrier or is forced up and over the barrier. These flow patterns are illustrated in Fig. 5–1.

Shelterbelts can be considered as a collection of porous obstacles that create a series of pressure fields in the presence of wind in the atmospheric surface layer (Takle et al., 1997). As air flow approaches the barrier, surface static pressure increases and reaches a maximum at the windward edge of the barrier. This pressure drops as the wind passes through the barrier, reaching a minimum just to the lee of the barrier then gradually increasing with increasing distance from the barrier (Fig. 5–2). The magnitude of the pressure difference between the windward and leeward sides of the windbreak is one factor determining the flow modification caused by the barrier and is a function of windbreak structure (Schmidt et al., 1995; Takle et al., 1997).

As the air moves around or over the barrier, the streamlines of air are compressed (van Eimern et al., 1964). This upward alteration of

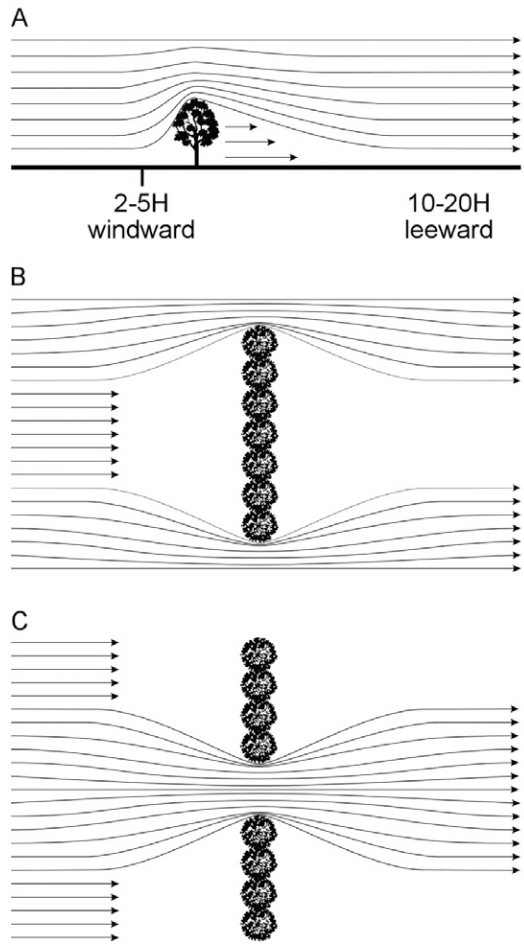

Fig. 5–1. Windflow patterns (A) over, (B) around, and (C) through a field windbreak. Areas of increased windflow are indicated by the close spacing of the lines.

flow begins at some distance windward of the windbreak and creates a protected zone on the windward side of the windbreak where wind speed is reduced. This protected zone extends windward for a distance of 2 to 5*H*, where *H* is the height of the barrier. A much larger region of reduced wind speed is created in the lee of the windbreak (Caborn, 1957; van Eimern et al., 1964). This zone typically extends for a distance of 10 to 30*H* (Heisler and DeWalle, 1988; Brandle, 1990; Wang and Takle, 1995b).

The magnitude of wind speed reduction at various locations within the protected zones is a function of windbreak structure (Heisler and DeWalle, 1988; Brandle, 1990; Wang and Takle, 1995a; 1996; Cornelis and Gabriels, 2005; Bird et al., 2007). By adjusting windbreak structure or density, different windflow patterns and zones of protection are created. The best structure for a given windbreak depends on the objective of the windbreak. In general, the denser a windbreak the more wind speed is reduced. This general concept is illustrated in Fig. 5–3 while specific design criteria are discussed later.

Windbreak Structure

The ability of a windbreak to reduce wind speed is a function of its *external structural features*—height, orientation, length, width, continuity or uniformity, and cross-sectional shape, and its *internal structural features*—the amount and arrangement of the solid and open portions and the surface area of the barrier components (Zhou et al., 2002, 2005, 2008). The overall size of the protected zones, the extent of the wind speed reductions within the zones, and the resulting microclimate depend on these structural features (Wang and Takle, 1996, 1997; Zhou et al., 2005, 2008). By manipulating windbreak structure through various management practices, a range of conditions within the protected zone may be created that can be used to meet various design objectives (Brandle, 1990).

External Structure

Windbreak height is the most important factor determining the extent of the protected zone; *H* combined with the windbreak length determines the total area protected. Windbreaks are most effective when they are oriented perpendicular to the wind. As winds become more oblique to the windbreak, the extent of the protected zone is reduced. The length of a windbreak should be at least ten times its height to minimize the effect of wind flow around the ends of the windbreak. Windbreak width influences windbreak effectiveness through its influence on density (Heisler

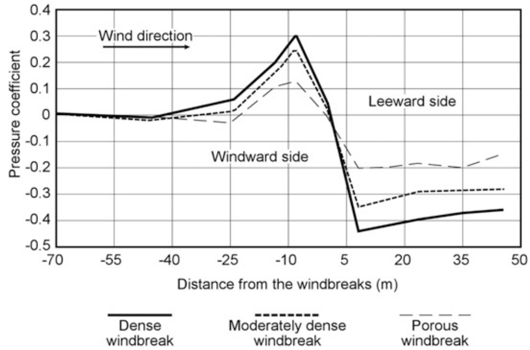

Fig. 5–2. Changes in the pressure coefficient at ground level windward and leeward of three, two-row field windbreaks with different optical densities. The pressure gradient increases with increasing windbreak density, leading to more turbulence in the lee of the windbreak.

Deciduous 25-35% Density
Open Wind Speed 10 m s^{-1}

H distance from windbreak	5H	10H	15H	20H	30H
m s^{-1}	5	6.5	8	8.5	10
% of open wind speed	50%	65%	80%	85%	100%

Conifer 40-60% Density
Open Wind Speed 10 m s^{-1}

H distance from windbreak	5H	10H	15H	20H	30H
m s^{-1}	3	5	6	7.5	9.5
% of open wind speed	30%	50%	60%	75%	95%

Multi-Row 60-80% Density
Open Wind Speed 10 m s^{-1}

H distance from windbreak	5H	10H	15H	20H	30H
m s^{-1}	2.5	3.5	6.5	8.5	9.5
% of open wind speed	25%	35%	65%	85%	95%

Solid Fence 100% Density
Open Wind Speed 10 m s^{-1}

H distance from windbreak	5H	10H	15H	20H	30H
m s^{-1}	2.5	7	9	9.5	10
% of open wind speed	25%	70%	90%	95%	100%

Fig. 5–3. Wind speed reductions at different distances to the lee of windbreaks with different densities, where *H* is the height of the windbreak.

and DeWalle, 1988). Windbreak continuity is also important. A gap or opening concentrates wind flow through the opening, creating a zone of increased wind speed to the lee. In both cases, increased flow around the ends or through a gap directly reduces the extent of the protected zone (Caborn, 1957; Jacobs, 1984) and reduces windbreak effectiveness in the area adjacent to the gap or end of the barrier (Fig. 5–1C).

Internal Structure

Historically, windbreak structure was defined in terms of density or porosity and these terms are still used in many situations. Windbreak density is the ratio of the solid portion of the windbreak to the total volume of the windbreak, while porosity is the ratio of the open portion of the windbreak to the total volume. The two terms are complementary in that their sum equals 1 or 100%. Wind flows through the open portions of a windbreak, thus as density increases, less wind passes through the barrier and wind speed reductions are greater.

Precise determination of windbreak density remains one of the problems facing researchers in windbreak technology. A solid barrier, such as a wall, will have a density of 100%. In the case of a slat fence or screen, the uniform size and distribution of the solid material and the relative "thinness" of the barrier make density both easy to determine and to manipulate.

For vegetative barriers, density is considerably more difficult to determine. There are a number of problems. First, it is impossible to have a vegetative barrier with 100% density. There will always be spaces between the various plant elements. Unlike a slat fence, the size, shape, and arrangement of plant elements (stems, branches, and leaves) are not uniform. Similarly, the size and shape of the open spaces varies with time and branch or leaf movement. Furthermore, vegetative barriers have a significant width such that for any given transect through the barrier there is a unique arrangement of solid elements. Finally, as the angle of the approaching wind becomes more oblique to the barrier (less perpendicular), the length of the path of the wind through the barrier increases. This is the same result as increasing the barrier width, which increases density and alters the effect of the windbreak on wind flow.

In the past, estimates of density or porosity were based on the relative abundance of solid or open areas as seen by an experienced observer—how easy it was to see through the windbreak. We now refer to this as the optical density or porosity. With the advent of digital image processing techniques, the speed and accuracy of these estimations have improved significantly (Kenny, 1987; Loeffler et al., 1992; Zhang et al., 1995). However, the issues related to the distribution of plant elements within the windbreak have not been resolved. While optical density is often used in applied situations, it is important to note that the path of the wind through the windbreak is not a straight line and that the wind flows over and around the various elements within the windbreak. To describe this flow, the three dimensional or aerodynamic structure of the windbreak must be defined.

Heisler and DeWalle (1988) and others (Caborn, 1957; Jensen, 1961; Read, 1964; van Eimern et al., 1964; Brandle, 1990; Cornelis and Gabriels, 2005; Bird et al., 2007) suggest that the vertical distribution of density within the windbreak influences wind flow response and windbreak effectiveness. Experience tells us that windbreaks with greater porosity in the lower levels will funnel wind through these areas, increasing wind speed in the lee of the windbreak and decreasing the level of leeward protection (Read, 1964).

Wang and Takle (1994; 1996; 1997) have developed numerical simulation models of the influence of shelterbelts on wind flow. Their results indicate that variation in the distribution of the surface area across the width of the windbreak may have minimal influence on shelter efficiency. Wang et al. (2001) attribute this to the fact that it is the overall structure of the barrier that creates the pressure fields driving the force equations in the model. However, field observations of the location of snow drifts around windbreaks show that a dense windward tree row (i.e., conifer or shrub component) gives a different snow drift than a dense leeward tree row.

As these contradictions point out, the relationship between the internal structure of a windbreak and the resulting wind flow patterns will remain an active area of research, particularly with regard to field verification of numerical simulations of shelter effects. Discussions have led us to believe that the discrepancies between simulation results and field experience may be best resolved with better three-dimensional descriptions of windbreak structure. To facilitate this effort, Zhou et al. (2002, 2005, 2008) and Wang and Takle (1996) have developed two structural descriptors: *vegetative surface area density* (vegetative surface area per unit canopy volume) and *cubic density* (vegetative volume per unit of canopy volume) for testing in numerical simulations of shelter effects. The first field tests of these descriptors indicated an improved ability to estimate the drag force term in the equations of motion used to predict boundary-layer flows near windbreaks (Zhou et al., 2003; Brandle et al., 2003). Additional field verification of the rigor of these descriptors remains a research goal.

Microclimate Changes

While research on the aerodynamic structure continues, it is clear that dense windbreaks result in greater wind speed reductions, that the vertical distribution of structural components influences wind flow patterns, and that structure influences the amount of turbulence generated. All of these factors influence the microclimate changes that occur in the sheltered zones.

As a result of wind speed reduction and changes in turbulent transfer rates, the microclimate (temperature, precipitation, relative humidity, and CO_2) in the sheltered zone is altered (McNaughton, 1988, 1989). The magnitude of microclimate change for a given windbreak varies within the protected zone depending on existing atmospheric conditions, windbreak density and orientation, distance from the windbreak, time of day, and height above the ground.

McNaughton (1988), following the terminology of Raine and Stevenson (1977), defined two zones in the lee of the windbreak: The *quiet zone* extends from the top of the windbreak down to a point in the field located approximately 8*H* leeward where both wind speed and turbulence are reduced, and the *wake zone* lies leeward of the *quiet zone* and extends approximately 20 to 25*H* from the barrier where wind speed is reduced but turbulence is increased relative to open field conditions. The boundary between these two zones is a function of windbreak structure and atmospheric stability and lies between 6 and 10*H* to the lee of the windbreak.

One useful concept explaining exchange rates between various surfaces and the atmosphere is the concept of coupling (Grace et al., 1981). Monteith (1981) defines coupling as the capacity of exchanging energy, momentum, or mass between two systems. Exchange processes between single leaves and the atmosphere or between plant canopies and the atmosphere are controlled by the gradients of temperature, humidity, and CO_2 that exist in the immediate environment above the surface. When these gradients are modified by shelter, microclimate within the sheltered zone will be modified (Grace, 1981, 1988; Monteith, 1981; McNaughton, 1988).

In the quiet zone, the transfer coefficients are less and thus turbulent exchange is reduced. In the wake zone, transfer coefficients are greater and the rates of turbulent exchange are increased. As a result, the transport of heat, water vapor, and carbon dioxide within these two zones is different.

Radiation

Solar radiation provides essentially all of the energy received at the earth's surface and influences most of the environmental conditions in which plants and animals live. On a regional scale, shelterbelts have minimal influence on the direct distribution of incoming radiation; however, they do influence radiant flux density (the amount of energy per unit surface area per unit time) primarily by shading and reflection in the area immediately adjacent to the windbreak.

Solar radiant flux density within and immediately adjacent to the windbreak is influenced by sun angle (a function of location, season, and time of day) and by windbreak height, density, and orientation. Likewise, at any given location, the extent of the shaded zone is dependent on latitude, time of the day, season of the year, and height of the windbreak. North–south oriented windbreaks produce morning shade on the western side and afternoon shade on the eastern side. In the northern hemisphere, windbreaks oriented in an east–west direction produce a shaded area on the north side of the windbreak throughout the day while radiation is reflected off the south-facing surfaces increasing radiant flux density adjacent to the windbreak. The amount of reflected radiant flux is dependent on time of day, season of the year, and the reflectivity of the windbreak's vertical surface.

Air Temperature

In general, daytime temperatures within 8*H* of a medium-dense barrier can be several degrees warmer than temperatures in the open because of the reduction in turbulent mixing. This effect appears to be greater early in the growing season. Between 8 and 24*H*, daytime turbulence increases and air temperatures tend to be several degrees cooler than for unsheltered areas (McNaughton, 1988; Cleugh, 2002). Nighttime temperatures within 1 m of the ground are generally 1 to 2°C warmer in the protected zone (up to 30*H*) than in the exposed areas (Read, 1964; Zhang et al., 1999; Hodges et al., 2004). In contrast, temperatures 2 m above the surface tend to be slightly cooler. On very calm nights, temperature inversions may occur and protected areas may be several degrees cooler at the surface than exposed areas because of the absence of even slight air movement (McNaughton, 1988; Argete and Wilson, 1989).

In warmer regions of the temperate zone, for example, southern Texas or Florida, temperature increases in shelter may exceed optimal temperatures for some crops or livestock. In these cases, the increase in sheltered temperature may increase plant or animal stress and decrease productivity. In more northern latitudes, temperature increases in the sheltered zones are generally beneficial to crop growth.

Soil Temperature

Average soil temperatures in shelter are slightly warmer than in unprotected areas (McNaughton, 1988; Hodges et al., 2004; Zhang et al., 1999). In most cases, this is due to the reduction in heat transfer away from the surface. In areas within the shadow of a windbreak, soil temperatures are lower because of shading of the surface. The magnitude of this effect is dependent on the height and orientation of the barrier and the angle of the sun (the size and duration of the shaded area). Conversely, soil temperatures may be slightly higher in areas receiving additional radiation reflected off the surface of the windbreak. These differences are greatest early in the season before the crop canopy closes (Caborn, 1957). Soil texture and moisture strongly affect soil heat retention and release and will influence the duration and magnitude of soil temperature differences between sheltered and unsheltered zones.

Frost

On clear, calm nights, infrared radiation emitted from soil and vegetative surfaces is unimpeded. Under these conditions, surfaces may cool rapidly, resulting in decreased air temperature next to the surface. When this temperature reaches the dew point, condensation forms on surfaces. If temperatures fall below freezing, this condensation freezes, resulting in a radiation frost. In sheltered areas where wind speed is reduced, radiation frosts may occur more frequently than in exposed areas, especially in sandy soils with low capacity to retain daytime solar gain. In contrast, advection frosts are generally associated with large-scale cold air masses. Strong winds are typically associated with the passage of the front and, while the radiative process contributes to heat loss, temperature inversions do not occur. Shelterbelts may offer some protection against advection frosts when episodes are of short duration and when windward temperatures are just below 0°C. In sheltered areas, reductions in turbulent mixing (less mixing of the warm air near the surface with the colder air of the front) may reduce heat loss from the sheltered area and provide some degree of protection. The process may be influenced by evaporation from the soil surface and subsequent condensation of vapor on the leaves. If soil moisture is higher in shelter, then not only might there be less mixing and loss of water vapor, but sensible heat from the soil may be held in the crop canopy by the reduction in turbulent mixing, thus reducing the potential of frost. It is also possible that the increase in water vapor in the sheltered area will reduce the rate of radiative cooling (Rosenberg et al., 1983). At our research site in Nebraska, we have recorded frost occurring in sheltered areas where none has occurred in exposed areas and in exposed areas where none has occurred in the sheltered areas (Brandle and Hodges, unpublished data, 1996). It should be noted that in all of these cases, temperatures were very close to freezing and may or may not have resulted in frost, depending on interacting microclimate conditions. A better understanding of the conditions leading to frost leeward of shelterbelts is needed if practical management recommendations are to be made for temperature-sensitive crops.

Precipitation

Rainfall over most of the sheltered zone is generally unaffected except in the area immediately adjacent to the windbreak. These areas may receive slightly more or less than the open field depending on wind direction and intensity of rainfall. On the leeward side there may be a small rain shadow where the amount of precipitation reaching the surface is slightly reduced. The converse is true on the windward side, as the windbreak may function as a barrier and lead to slightly higher levels of measured precipitation at or near the base of the trees because of increased stemflow or drip from the branches.

In contrast, the distribution of snow is greatly influenced by the presence of a windbreak and can be manipulated by managing windbreak density (Shaw, 1988; Scholten, 1988). A dense windbreak (>60% optical density) will lead to relatively short, deep snow drifts on both the windward and leeward sides, while a more porous barrier (∼35% optical density) will provide a long, relatively shallow drift primarily to the leeward side. In both cases, the distribution of snow and the resulting soil moisture will affect the microclimate of the site. In the case of field windbreaks, a more uniform distribution of snow may provide moisture for significant increases in crop yield. This is especially true in areas where snowfall makes up a significant portion of the annual precipitation. In addition, fall-planted crops insulated by a blanket of snow are protected against desiccation by cold, dry winter winds (Brandle et al., 1984). The effect of windbreak density on snow distribution is illustrated in Fig. 5–4.

Humidity

Humidity, the water vapor content of the air, is a major factor in the regulation of crop microclimate. Again, this is related to its role in the energy balance of the system (Rosenberg et al., 1983). Decreases in turbulent mixing reduce the amount of water vapor transported away from surfaces in the sheltered area. As a result, humidity and vapor pressure gradients are generally greater in shelter both during the day and at night (McNaughton, 1988). As water vapor is a strong absorber of infrared radiation, higher humidity levels in shelter tend to protect the crop from radiative heat losses, reducing the potential for frost.

Evaporation

Evaporation from bare soil in shelter is reduced due to wind speed reductions and the reduction in transfer of water vapor away from the surface. In most cases this is an advantage, conserving soil moisture for early season plant growth. Evaporation from leaf surfaces is also reduced in shelter. However, as plants get larger, with greater leaf areas, sheltered crops may use more water than unsheltered crops (Rosenberg 1966). In contrast, Sudmeyer et al. (2002b) reported that a high leaf area did not increase soil water use. Under very limited moisture conditions it is possible that insufficient soil moisture may limit full development of crop yield potential in larger plants found in sheltered areas. This remains a fertile area for research of water use under sheltered conditions.

In most cases, increased humidity and reduced evaporation do not contribute to a higher incidence of disease. However, situations may occur in which windbreak design, high humidity, rainfall, or irrigation contribute to abnormally high humidity levels in sheltered areas. Combined with lower nighttime temperatures in shelter, high humidity levels may cause more dew formation. In these cases, the added humidity and reduced evaporation in shelter may increase the possibility of disease. For example, to increase the incidence of white mold, *Sclerotinia sclerotiorum* (Lib.) de Bary, on dry edible bean (*Phaseolus vulgaris* L.) and identify resistant cultivars, Deshpande et al. (1995) used closely spaced windbreaks to increase humidity levels and dew formation in sheltered areas. In contrast, when windbreak systems are designed for optimal crop production, disease incidence is normally not a problem. Over the past 30 yr of shelter research in eastern Nebraska, we have observed this phenomenon only twice, once in winter wheat, *Triticum aestivum* L., (Brandle et al., 1984) and once in soybean, *Glycine max* (L.) Merr. (Nieto and Brandle, 1996, unpublished data).

Windbreaks in Agricultural Production Systems

The goal of any system of windbreaks is to provide microclimate conditions that can be used for the benefit of the landowner. Two types of windbreaks have direct application to agricultural

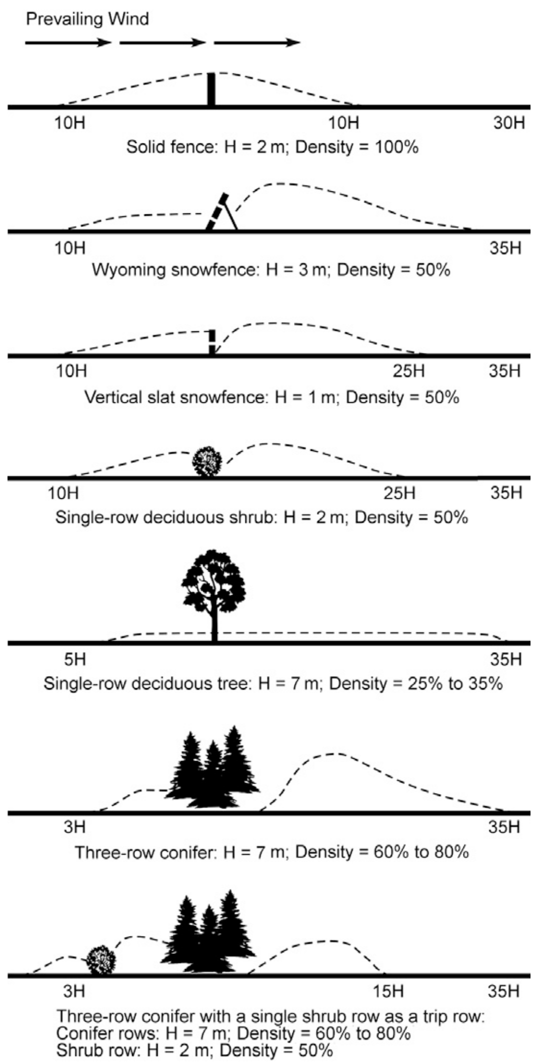

Fig. 5–4. The amount of snow storage windward and leeward of a snow fence or windbreak is determined by the height and density of the barrier.

production systems: field windbreaks and livestock windbreaks. Two other types, farmstead windbreaks and living snowfences, provide indirect support to the agricultural operation and are significant components of any sustainable agricultural ecosystem. In this section we consider the effect of wind protection on individual plant growth and development, the effect of field windbreaks on crop production, and the benefits of protecting livestock under range and feedlot conditions from the adverse effects of wind.

Field Windbreaks

Agricultural producers frequently recognize the value of field windbreaks to reduce wind erosion (Tibke, 1988; Ticknor, 1988). In northern areas, the value of field windbreaks to harvest snow for crop production is also widely recognized (Scholten, 1988). Field windbreaks are often used to protect wind-sensitive crops such as fruits and vegetables (Baldwin, 1988; Norton, 1988). Unfortunately, their role in the protection of grain crops is less widely recognized (Brandle, 1990). In this review, the effect of wind on individual plant growth and development is considered first and then the overall benefits of field windbreaks at the farm scale are reviewed.

Physiological Response of Plants to Shelter

The effect of wind on plants is well studied and has been reviewed extensively (Grace, 1977; Coutts and Grace, 1995; Miller et al., 1995; Cleugh, 1998). Both photosynthesis and transpiration are driven in part by environmental conditions, particularly those within the leaf and canopy boundary layers. As shelter modifies the microenvironment, it affects plant productivity.

Plant temperature differences between sheltered and exposed sites are relatively small, on the order of 1 to 3°C. In the quiet zone, where the rate of heat transfer from a plant is reduced, a slight increase in temperature can be an advantage, especially in cooler regions, where even a small increase in plant temperature may have substantial positive effects on the rate of cellular processes and cell physiology (Grace, 1988; van Gardingen and Grace, 1991). Lower nighttime temperatures in shelter may reduce the rate of respiration, resulting in higher rates of net photosynthesis and more growth. Indeed, there are many examples of sheltered plants being taller and having more extensive leaf areas (Rosenberg, 1966; Frank et al., 1974; Grace, 1977; Ogbuehi and Brandle, 1981; 1982). Higher soil temperatures in the sheltered zone may result in more rapid crop emergence and establishment, especially for crops with a high heat unit accumulation requirement for germination and establishment (Drew, 1982). In contrast, under hot conditions, temperatures above the optimum for plant development may lead to periods of water stress if the plant is unable to adjust to the higher demands for moisture.

The overall influence of shelter on plant–water relations is extremely complex and linked to the temperature, soil moisture, and wind speed conditions found in shelter. Until recently, the major effect of shelter and its influence on crop growth and yield was assumed to be due primarily to soil moisture conservation and a reduction in water stress of sheltered plants (Caborn, 1957; van Eimern et al., 1964; Grace, 1988). There is little question that evaporation rates are reduced in shelter (McNaughton, 1983; 1988; Grace, 1988); however, the effect on plant water status is less clear. Understanding how plant water status affects the physiological and morphological aspects of crop response to wind and wind protection in production fields remains a fertile area for potential research.

According to Grace (1988), transpiration rates may increase, decrease, or remain unaffected by shelter depending on wind speed, atmospheric resistance, and saturation vapor pressure deficit. Davis and Norman (1988) reviewed the concept of water-use efficiency in shelter and concluded that under some conditions, sheltered plants make more efficient use of available water. Monteith (1993) suggested that water-use efficiency in shelter was unlikely to increase except when there was a significant decrease in saturation vapor pressure deficit. And indeed, the increase in humidity in shelter would contribute to a decrease in saturation vapor pressure deficit and thus an increase in water-use efficiency. However, sheltered plants tend to be taller and have larger leaf areas. Given an increase in biomass, sheltered plants have a greater demand for water and under conditions of limited soil moisture or high temperature may actually suffer greater water stress than exposed plants (Rosenberg, 1966; Grace, 1988; Nuberg and Mylius, 2002). Cleugh (2002) simulated crop microclimate and found that shelter was more effective in reducing direct water loss from the soil than reducing transpiration. A negative consequence of increased temperatures in shelter can be increased vapor pressure deficit at the end of the growing season in semiarid environments (Sudmeyer et al., 2002b). Overall, shelter improves water conservation and allows the crop to make better use of available moisture over the course of a growing season. The magnitude of this response depends on the crop, stage of development, and environmental conditions. Additionally, species and ecotypes can vary in sensitivity to wind and response to wind protection (van Gaal and Erwin, 2005; Emery et al., 1994).

Growth and Development Response of Plants to Shelter

As a result of favorable microclimate and the resulting physiological changes, the rate of growth and development of sheltered plants may increase. The increase in the rate of accumulation of heat units in shelter contributes to early maturity of many crops. For example, Ogbuehi and Brandle (1982) reported that flowering of soybean occurred 4 to 10 d earlier in sheltered fields than in unsheltered fields. Similar results have been reported with corn, *Zea mays* L. (Zohar and Brandle, 1978); cotton, *Gossypium hirsutum* L. (Barker et al., 1989); and many vegetables (Baldwin, 1988; Hodges and Brandle, 1996). In recent research conducted at the University of Nebraska (Zhang et al., 1999), earlier anthesis in muskmelon (*Cucumis melo* L.) contributed to earlier harvest of sheltered plants (Fig. 5–5). In snap beans (*Phaseolus vulgaris* L.), an increase in soil temperature early in the season resulted in earlier maturity (Hodges et al., 2004). Similarly, in cultivar trials of cabbage, *Brassica oleracea* (L.) var. *capitata*, and pepper, *Capsicum annum* L., most cultivars reached harvest maturity 3 to 10 d earlier in the sheltered fields (Hodges and Brandle, unpublished data, 1996). The ability to reach the early market with many of these perishable crops can mean sizable economic returns to producers (Sturrock, 1984; Baldwin, 1988; Norton, 1988; Brandle et al., 1995; Hodges et al., 2004).

Vegetative growth or biomass is generally increased in sheltered environments (Bates, 1911; Caborn, 1957; Stoeckeler, 1962; van Eimern et al., 1964; Skidmore et al., 1974; Sturrock, 1984; Baldwin, 1988; Kort, 1988) but not universally so. Nebraska research has demonstrated biomass and leaf area increases in sheltered soybean (Ogbuehi and Brandle, 1981; 1982), snap bean (Hodges et al., 2004), and muskmelon (Zhang et al., 1999) but not in corn (Zhang and Brandle, 1997) or alfalfa, *Medicago sativa* L. (Hans, 1987).

In many fruit and vegetable crops, reproductive growth is dependent on pollination by insects. In addition to the physical movement of the insect to the flower, the process has a number of critical aspects: attraction of the appropriate insect, receptivity of the stigmatic surface, pollen viability, rate of growth of the pollen tube, and fertilization of the ovule. All of these processes are partially dependent on the microclimate of the flower. In particular, they benefit from warm, moist, calm conditions similar to those found in sheltered areas during the spring (Norton, 1988). As a result, sheltered orchard and vineyard crops show significantly increased levels of fertilization and fruit formation that can be attributed to the improved microclimate in sheltered areas (Waister, 1972b; Norton, 1988).

Wind also influences plant growth directly by the mechanical manipulation of plant parts (Miller et al., 1995). This movement may increase the radial enlargement of the stem, increase leaf thickness, reduce stem elongation and leaf area (Jaffe, 1976; Grace, 1988; Nobel, 1981), and affect cellular composition (Armbrust, 1982). On the whole-plant level, the interaction of ethylene and auxin (Erner and Jaffe, 1982; Biro and Jaffe, 1984; Biddington, 1986; Jaffe and Forbes, 1993) as well as possible inhibition of auxin transport (Mitchell, 1977) appear to be involved. The threshold wind speed and duration for these types of direct responses appears to be very low, perhaps as low as 1 m s^{-1} for less than 1 min (van Gaal and Erwin, 2005; Garner and Bjorkman, 1996). As a result, these types of responses may be more indicative of a no-wind situation rather than an indicator of various wind speed differences as found in

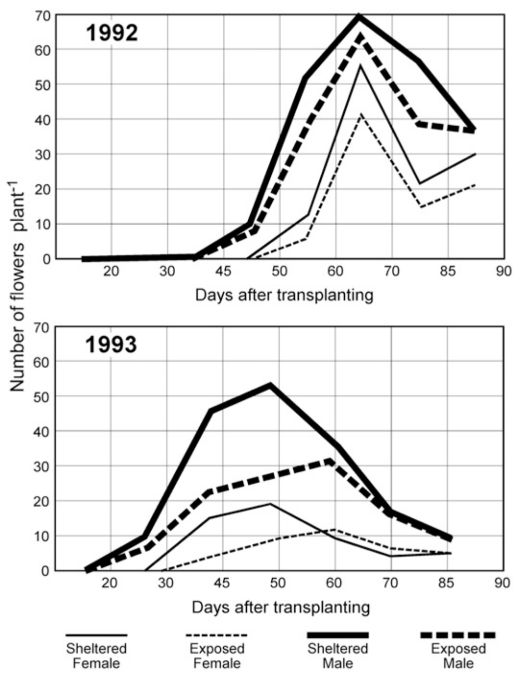

Fig. 5–5. Number and time of occurrence of male and female flowers of cantaloupe grown in sheltered or exposed conditions in 1992 and 1993.

sheltered and nonsheltered conditions (Biddington, 1985; van Gardingen and Grace, 1991; Miller et al., 1995).

Wind can cause direct physical damage to plants through abrasion and leaf tearing (Miller et al., 1995). Abrasion is caused when plant parts (leaves, stems, branches, or fruits) rub against each other. As tissue surfaces rub, the epicuticular waxes on the surfaces are abraded, increasing cuticular conductance and water loss (Pitcairn et al., 1986; van Gardingen and Grace, 1991). The magnitude of the impact on transpiration is determined by the degree of abrasion and the relative importance of the epicuticular wax in controlling the total resistance of the cuticle to the diffusion of water vapor.

Tearing is common on leaves that are large, damaged by insects, or subjected to high wind speeds. Wind contributes to the abrasion of plant surfaces by wind blown particulates (usually soil), often referred to as sandblasting. The extent of injury depends on wind speed and degree of turbulence, amount and type of abrasive material in the air stream, duration of exposure, plant species and its stage of development, and microclimatic conditions (Skidmore, 1966). Finch (1988) summarized the sensitivity of many crops to wind-blown soil based on estimates of crop tolerance to blowing soil (Table 5–1). All three of these—abrasion, leaf tearing, and sandblasting—damage plant surfaces and can lead to uncontrolled water loss from the plant (Grace, 1977, 1981; Miller et al., 1995).

Plant lodging is another direct mechanical injury caused by wind. It takes two forms: stem lodging, where a lower internode permanently bends or breaks; and root lodging, where the soil or roots supporting the stem fail. Stem lodging is most common as crops approach maturity, while root lodging is more common on wet soils and during grain filling periods (Pinthus, 1973; Easson et al., 1993; Miller et al., 1995). In both cases, heavy rainfall tends to increase the potential for lodging (Marshall, 1967).

Sheltered plants tend to be taller with heavier heads and reduced culm stiffness, characteristics that tend to contribute to lodging (Grace, 1977). Medium-dense shelterbelts tend to reduce crop

Table 5–1. Estimated crop tolerances to damage by wind blown soil (Finch, 1988).

Crops grouped by tolerance	Species
Tolerant crops: Est. crop tolerance >5.4Mt ha^{-1} yr^{-1}	
Barley	*Hordeum vulgare* L.
Buckwheat	*Fagopyrum* spp.
Flax	*Linum usitatissimum* L.
Millet	*Panicum miliaceum* L.
Oat	*Avena sativa* L.
Rye	*Secale cereale* L.
Wheat	*Triticum aestivum* L.
Moderately tolerant crops: Est. crop tolerance between 2.7 and 5.4 Mt ha^{-1} yr^{-1}	
Corn	*Zea mays* L.
Grain sorghum	*Sorghum bicolor* (L.) Moench
Sunflower	*Helianthus annuus* L.
Very low tolerant crops: Est. crop tolerance <2.7 Mt ha^{-1} yr^{-1}	
Alfalfa seedlings	*Medicago sativa* L.
Cabbage and broccoli	*Brassica oleracea* L.
Cotton seedlings†	*Gossypium hirsutum* L.
Cucumbers	*Cucumis sativus* L.
Flowers†	Most species
Green, snap, or Lima beans	*Phaseolus* spp. (all varieties)
Leafy vegetables†	All species
Muskmelon	*Cucumis melo* L.
Onions†	*Allium cepa* L.
Peas	*Pisum sativum* L. (all varieties)
Table and sugar beets Sugar beet seedlings†	*Beta vulgaris* L.
Soybean	*Glycine max* (L.) Merr.
Watermelon	*Citrullus lanatus* (Thumb) Matsum. ex Nakai
Young orchards	Most species

† Tolerances <0.5 Mt ha^{-1} event^{-1}.

lodging within the sheltered zone because of reduced wind speeds (Bates, 1944; Sturrock, 1981). As windbreak density increases, turbulence increases and the likelihood of lodging is greater (Kort, 1988).

Under extremely windy conditions, some plants may experience a phenomenon called *wind-snap*, *green-snap*, or *brittle-snap*, in which the force of the wind breaks the stem. In 1993, eastern and central Nebraska experienced a severe wind storm in mid-July and a number of corn fields exhibited areas of *brittle-snap* (Elmore and Ferguson, 1996). It is interesting to note that we found areas of *brittle-snap* in several of our unsheltered cornfields, yet none in our sheltered fields. Meteorological measurements at 2 m above the surface indicated that in the exposed areas, wind speeds exceeded 18 m s^{-1} while in sheltered fields wind speeds were generally less than 9 m s^{-1} (unpublished data, Brandle, 1993). The effect appeared to be related to stem characteristics of certain corn cultivars because not all cultivars exhibited damage.

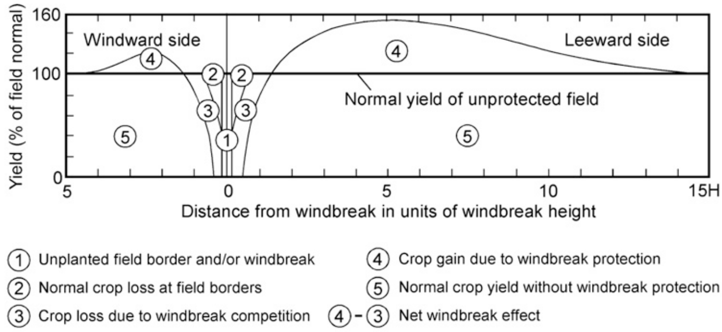

Fig. 5–6. The generalized case for crop yield responses for a field windbreak in the Great Plains. Adapted from Read (1964).

Crop Yield Response to Shelter

While the influences of wind and shelter on individual plant processes are only partially understood, the net effect of shelter on crop yield is positive (see Fig. 5–6 and reviews by Grace, 1977; Baldwin, 1988; Kort, 1988; Norton, 1988). The reasons vary with crop, windbreak design, geographic location, moisture condition, and cultural practice. In this section we will focus on the benefits of shelter on the crop as a whole, field windbreak design, and economics.

One of the most extensive studies on the effects of windbreaks on field crops in the northern Great Plains was conducted by J.H. Stoeckeler (1962). His survey of 184 corn fields and 94 fields of small grain indicated significant yield benefits in the sheltered zones of both east–west and north–south oriented field windbreaks. More recently, Kort (1988) summarized yield responses for a number of field crops from temperate areas around the world. Average yield increases varied from 6 to 44% (Table 5–2).

A close reading of the individual studies behind these averages indicates great variability in yield results. In most cases, the data indicate a strong positive response to shelter, while in others, the response is either neutral or negative. This is understandable because final crop yield is the culmination of a series of interacting factors present throughout the growth and development of the crop. The possible combinations of growth response and microclimate conditions are unlimited, and the probability that a single combination and the corresponding crop response occurring on an annual basis is relatively small. It is likely that this variability in growing conditions and the stage of development at which a particular condition is present accounts for many of the contradictory responses reported in the literature. As Sturrock (1984) explained, the relationship between shelter and crop response is complex and dynamic, subject to continual change as a result of changes in microclimate, windbreak efficiency, and growth and development of the protected crop.

Australian windbreak research demonstrates the complex interactions of climatic and edaphic influences where growing conditions are characterized by soils with low water holding capacity, terminal drought, and often dry conditions at the end of the growing season. While microclimate changes in the sheltered zone often increase crop yields, particularly leguminous crops, (Bicknell,

Table 5–2. Crop response to shelter (Kort, 1988; Baldwin, 1988; Brandle et al.,1992a).

Crop	Number of field years	Weighted mean yield increase
		%
Spring wheat	190	8
Winter wheat	131	23
Barley	30	25
Oat	48	6
Rye	39	19
Millet	18	44
Corn	209	12
Soybean	17	15
Grass hay	14	20

1991; Nuberg et al., 2002; Sudmeyer et al., 2002a; Oliver et al., 2005), these increases are often offset by yield declines in the zone of competition where windbreak trees and crops compete for water (Nuberg et al., 2002; Sudmeyer et al., 2002a; Unkovich et al., 2003; Oliver et al., 2005). In the Australian example, the greatest benefits of windbreaks are seen in dry, windy years when wind erosion and sandblast damage to establishing crops can cause significant losses to unprotected crops (Sudmeyer et al., 2002a; Bennell et al., 2007). An economic evaluation of crops growing in windbreak systems in southwestern Australia found that the protection benefits they provided would offset all of the costs associated with establishment and competition if unprotected crops were damaged three to four times over the 30-yr life of the windbreak (Jones and Sudmeyer, 2002).

Another factor that may influence crop response to shelter is that of crop cultivar. Almost without exception, crops have been bred and selected under exposed conditions. As a result, most common cultivars represent those selections best able to perform under exposed conditions. To take full advantage of the microclimate conditions created by windbreaks, a producer should select crop cultivars best suited to sheltered conditions. For example, using shorter, thicker-stemmed wheat cultivars will reduce the potential for lodging while taking advantage of the favorable growing conditions found in sheltered fields (Brandle et al., 1984).

In this review we define horticultural crops primarily as fruits and vegetables. There are few papers on the production of floral crops in shelter, but we suspect that they would be extremely responsive to the microclimate of shelter because of their sensitivity to desiccation. In addition, high-quality characteristics, such as uniformity of size and shape, and the absence of physical defects, such as abrasion, are required for market acceptance.

Baldwin (1988) and Norton (1988) provide the most recent comprehensive reviews of horticultural crops and shelter. In horticultural crops, marketable yields, quality of the product, and earliness to market maturity are of primary importance (Baldwin, 1988; Hodges and Brandle, 1996; Hodges et al., 2004; 2006). Earliness is primarily a function of temperature and was discussed in the microclimate section. Physiological and anatomical responses of snap bean to wind were found to interact with temperature, with plants being less responsive to wind when grown under cooler temperatures (Hunt and Jaffe, 1980). For horticultural crops grown in sheltered conditions, the moderation of temperature extremes, warmer soil and air temperatures, and improved plant water status contributed to yield increases in total marketable yield and individual fruit weight. The moderated microclimate in shelter contributes to longer flowering periods and increased bee activity, and can result in improved fruit set and earlier maturity (Norton, 1988). Quality improvements have been reported for many crops, including: sugar beet, *Beta vulgaris* L. (Bender, 1955); tobacco, *Nicotiana tabacum* L., and French bean, *Phaseolus vulgaris* L. (Kreutz, 1952a; 1952b); strawberries, *Fragaria* spp. (Shah, 1970; Waister, 1972a, 1972b); lettuce, *Lactuca* spp. (Strupl, 1953); plum, *Prunus* spp. (de Preez, 1986); kiwifruit, *Actinidia chinensis* L. (McAneney and Judd, 1987); orange, *Citrus sinensis* (L.) Osbeck, (Rodriquez et al., 1986; Pohlan et al., 1986); carrot, *Daucus carota* L. (Taksdal, 1992); potato, *Solanum tuberosum* L. (Sun and Dickinson, 1994); and others (for more details, see reviews by van Eimern et al., 1964; Grace, 1977; Baldwin, 1988; Norton, 1988; and Miller et al., 1995).

Wind-induced sandblasting and abrasion compound the direct effects of wind on the yield and quality of vegetable and specialty crops. As the amount of wind-blown soil, wind speed, or exposure time increases, crop survival, growth, yield, and quality decrease (Fryrear and Downes, 1975). Young plants tend to be more sensitive to damage (Liptay, 1987). Concern for damage by wind-blown soil is greatest during the early spring when stand establishment coincides with seasonally high winds and large areas of exposed soil during field preparation. Another critical time is during the flowering stage when rubbing and abrasion by wind-blown soil may result in damage to or loss of buds and flowers (Bubenzer and Weis, 1974). Vegetable producers need to be especially aware of the problems associated with wind erosion because the light-textured soils that favor vegetable production are most easily eroded.

Wind-blown soil and rain can carry inoculum for bacterial and fungal diseases (Claflin et al., 1973; Kahn et al., 1986; Pohronezhy et al., 1992) and wind-damaged plant tissues are potential entry points for pathogens, especially bacteria. For example, common blight of bean, *Xanthomonas phaseoli* (E.F. Sm) Dows, increased 120% when the duration of exposure to wind-blown, infected river sand increased from 3 to 5 min (Claflin et al., 1973). Similarly, bell peppers (Pohronezhy et al., 1992) and prunes, *Prunus domestica* L. 'French' (Michailides and Morgan, 1993), showed increased disease incidence when wind exposure increased. Windbreaks can also reduce the distribution and rate of spread of wind-blown, aphid-transmitted viruses (Simons, 1957). If windbreaks are too dense, higher humidity levels and slower drying can create conditions favorable for disease development. In some cases, windbreak vegetation or litter may serve as alternative hosts or overwintering sites for various diseases and insect vectors of plant pathogens (Slosser and Boring, 1980). Insect populations may increase or decrease in the lee of windbreaks with variable effects on the protected crops. A more complete discussion of insect distribution and movement in windbreak protected crops is included in a later section.

Field Windbreak Design

In designing any windbreak system it is critical to have a good understanding of the objective of the planting. Windbreaks designed for snow management are different from those designed for wind erosion control or protection of summer crops. Field windbreaks should be designed to accommodate the cultural practices, equipment, and land situation of the individual farm operation. However, there are general principles that apply to the majority of situations (Finch, 1988). This section considers the general principles of field windbreak design, looking first at individual windbreaks and then at windbreak systems. Later sections will deal with the individual needs of wind erosion control (Tibke, 1988; Ticknor, 1988) and snow management (Shaw, 1988; Scholten, 1988).

Field windbreaks should be oriented perpendicular to the prevailing or problem winds to maximize the protected zone. If only a single windbreak is planted, it is usually located at the field edge such that the leeward zone extends into the crop field. This is not the most efficient location because all of the windward protection falls on non-crop ground. Locating the windbreak within the field at a distance of 2 to 5*H* from the field edge increases the amount of land protected by the windbreak and increases economic return. In most cases, a single windbreak will not protect the entire field and additional windbreaks, parallel to the first, will need to be established at intervals across the field. Typically the distance between windbreaks should range from 10 to 20*H*, depending on the degree of protection desired and the size of farm equipment. In many areas, problem winds will come from several directions. In these cases, additional windbreaks with different orientations may be required to achieve the desired level of protection (Finch, 1988).

The ideal field windbreak designed for maximum crop production should be one or two rows and composed of several tall, long-lived species with good rates of growth and similar growth forms. Individual species should tolerate local stress conditions, and have good insect and disease resistance. Native species are usually a good choice. The overall windbreak should have an optical density during the growing season of approximately 40 to 60% with a tall, narrow crown and a deep root system that minimizes the degree of competition with the adjacent crop (Cunningham, 1988).

The Zone of Competition

One of the most commonly expressed concerns about field windbreaks is the impact of competition between the windbreak and adjacent crops. Reduced crop yields have been associated with less water in the soil exploited by tree roots, shading close to trees, phytotoxins in the soil (allelopathy), rainfall interception, and competition for soil nutrients (Kort, 1988; Ong and Huxley, 1996). Competition is usually confined to the area occupied by tree roots (Greb and Black 1961; Sudmeyer et al., 2004). North American studies indicate that competition commonly extends between 0.5 and 2*H* (Kort, 1988), but can extend further on occasion (Greb and Black, 1961; Chaput and Tuskan, 1990). The degree of competition varies with crop type, geographic location (Stoeckeler, 1962; Lyles et al., 1984), tree species (Greb and Black, 1961; Lyles et al., 1984; Brandle and Kort, 1991), and soil or climate conditions (Sudmeyer et al., 2002a).

Because of the complex interactions of wind shelter and above- and belowground competition, it is often difficult to demonstrate the underlying mechanisms of tree–crop competition in the field. However, nutrient competition and shading probably play a relatively minor role compared to competition for water in most North American agroforestry systems (Hou et al., 2003: Jose et al., 2004; Reynolds et al., 2007). There is no question that where crop growth is moisture limited, competition between the windbreak and crops has significant, negative impacts on yield (Kowalchuk and de Jong, 1995; Jose et al., 2000; Sudmeyer et al., 2002c; Jose et al., 2004; Reynolds et al., 2007). These conditions are often met in semiarid areas, on soils with low plant-available water capacity, such as sands or shallow soils, or in exceptionally dry years in more temperate climates.

Belowground competition can be minimized by using windbreak trees that are deep rooted and have limited lateral extent (Greb and Black, 1961). Where water is limiting and the lateral tree roots extending into the crop field are confined close to the soil surface, cutting the lateral tree roots (root pruning) can significantly improve crop yields (Rasmussen and Shapiro, 1990; Chaput and Tuskan, 1990; Jose et al., 2000; Hou et al., 2003; Sudmeyer et al., 2004; Sudmeyer and Flugge, 2005).

The effectiveness of root pruning depends on the rooting patterns of the windbreak trees and the depth of root pruning (Stoeckeler, 1962; Kort, 1988; Rasmussen and Shapiro, 1990). Where lateral roots are left uncut below the rip line, they will continue to grow and ramify back through the soil over time, making subsequent ripping less effective (Sudmeyer et al., 2004). Root pruning must be repeated every 1 to 5 yr depending on tree species and local weather conditions (Stoeckeler, 1962; George, 1971; Umland, 1979; Naughton and Capels, 1982; Lyles et al., 1984; Sudmeyer and Flugge, 2005). North American studies have found root pruning can improve crop yield in the competition zone by 10 to 44% (Chaput and Tuskan, 1990; Rasmussen and Shapiro, 1990; Hou et al., 2003).

The annual economic returns from root pruning depend on the magnitude and extent of competition losses, the ability to sever all or most tree lateral roots, the cost of ripping, the inherent productivity of the site, the costs associated with the root-pruning operation and how often roots must be pruned. In Western Australia, the increase in annual returns from crops by root-pruning windbreaks ranged between A$−14 and A$309 km^{-1} (Sudmeyer and Flugge, 2005). Lyles et al. (1984) estimated an average economic return from root pruning a field windbreak protecting winter wheat in Kansas at $205 km^{-1}.

Windbreak Economics

Field windbreaks have costs associated with establishment, maintenance, and removal. They occupy cropland, reducing the number of crop hectares, and compete with crops immediately adjacent to the windbreak (see above). From an economic perspective, the amount of land occupied by the windbreak and the degree of competition should be minimized to maximize the number of crop hectares available and the yield increases resulting from wind protection. Ideally, the windbreak should take advantage of both the windward and leeward protection zones. For a windbreak system to be profitable, the long-term average yield increase from the protected zones must be large enough to compensate for the land occupied by the windbreak, for the crop losses within the zone of competition, and for the costs associated with planting and maintaining the windbreak.

Using the general yield responses as described by Kort (1988), field windbreak systems that occupy between 5 and 6% of the crop field provide positive economic returns to producers based entirely on the increased yields found in sheltered areas (Brandle et al., 1984; 1992a). Other benefits, such as wind erosion control, snow management, and wildlife habitat, provide additional returns to the landowner.

Using a net present value approach, Brandle and Kort (1991; also Kort and Brandle, 1991) developed an interactive computer model to evaluate the economic returns to grain producers when crops are protected by windbreaks. The analysis includes the costs of windbreak establishment and maintenance, the loss of crop yield due to hectares planted to trees, the loss of productivity associated with the zone of competition, the length of time required to grow the windbreak, and the cost of removal at some point in the future. These costs are offset by reduced input costs on those hectares removed from production and increased yields in the protected areas.

More recently Grala and Colletti (2003) and Helmers and Brandle (2005) completed economic analyses indicating positive economic benefits from field windbreaks. Grala and Colletti (2003) indicated that the magnitude of the economic response was dependent on the rate of growth of the windbreak and the total lifespan. Windbreaks that grew rapidly and lived longer were more economically beneficial. They emphasized the long-term nature of an investment in a windbreak system. Helmers and Brandle (2005) used integer programming techniques to determine the optimal spacing of field windbreaks for corn and soybean production. An optimal spacing of 13*H* increased net returns by 7.6% for corn and 9.2% for soybean on the windbreak investment over the net return for unprotected corn and soybean.

Wind Erosion Control

Of all the benefits of field windbreaks, wind erosion control is the most widely recognized and accepted. The link between wind speed and wind erosion is well established: when wind speed is reduced, the potential for wind erosion is reduced. This has direct impact on both crop productivity and off-site costs.

As a soil erodes, its productivity is decreased due to the loss of fine soil particles containing organic matter and nutrients (Williams et al., 1981; Pimentel et al., 1995). In many cases, compensation for these losses is made by the addition of fertilizer, which increases crop production costs. In other cases, yields are reduced, resulting in lower economic returns. By controlling wind erosion, windbreaks limit long-term losses in soil productivity, reducing the need for added inputs. The reduction of these losses from wind erosion is an additional economic benefit flowing from the windbreak investment (Brandle et al., 1992a).

Off-site costs, which are more difficult to quantify, are also incurred by both the private and public sectors (Huszar and Piper, 1986; Piper, 1989) and include damage to water storage facilities, irrigation systems, road ditches (Ribaudo, 1986) and increased health care costs associated with blowing dust and asthma (Rutherford et al., 1999). In South Australia, Williams and Young (1999) estimated that the annual health care costs associated with wind erosion and asthma exceed A$20 million. In extreme cases, wind-blown dust has contributed to highway accidents, resulting in traffic fatalities. Reducing off-site impacts and the associated costs are additional economic benefits from the windbreak investment and further justify public funding for wind erosion control.

Wind erosion is a natural process and its total control is neither practical nor desirable. What is of concern is *accelerated erosion*, or erosion at rates in excess of the natural ability of the soil to replenish itself. Accelerated erosion occurs primarily on large, open fields under dry conditions. It is enhanced when soil is loose, dry, and finely granulated and when the soil lacks vegetative cover (Lyles, 1988).

For those soils most prone to erosion, wind speeds in excess of 3 to 5 m s^{-1} will cause the soil to move (Woodruff et al., 1972; Zachar, 1982; Tibke, 1988). It moves in three general ways (Lyles, 1988). The largest particles (500 to 1000 µm) are generally too large to be lifted above the surface by ordinary erosive winds and are either pushed, rolled, or driven along the surface in a process called *surface creep*. The smallest particles are generally less than 50 µm, but may be as large as 100 µm. These are lifted into the air stream and may be carried for great distances. Certainly the most dramatic of the three types of soil movement, *suspension* generally accounts for less than 25% of wind erosion. Movement of soil particles in the range of 100 to 500 µm comprises the third and largest portion of soil erosion. In this process, called *saltation*, the individual particles are lifted from the soil surface to a height of 30 to 45 cm and then fall to the surface. As these particles strike the surface, they may break into smaller particles, dislodge other particles from the surface, or break down other surface particles reducing them in size. Combined with the force of the wind, this process, known as *soil avalanching*, tends to increase the level of soil movement (Tibke, 1988). Because saltation initiates and sustains suspension and soil creep, control measures should focus on reducing the amount of saltation (Lyles, 1988).

Rates of wind erosion are determined by a number of factors: (i) the inherent erodibility of the soil; (ii) the climatic conditions of the location; (iii) ridge roughness, or height and orientation of the crop rows; (iv) the amount and type of vegetative or residue cover; and (v) the width of the field along the prevailing wind direction. From a management perspective, little can be done about either the soil properties or the climate of the area. In contrast, ridge roughness and vegetative cover can be manipulated by various cultural practices, and field windbreaks can be used to reduce the width of the field. Windbreaks mitigate wind erosion by reducing wind speed in the sheltered zone below the threshold for soil movement. By dividing the field into smaller units, windbreaks reduce field width and interrupt soil avalanching.

The effectiveness of any barrier for wind protection depends in part on its shape, width, height, and density. Windbreaks designed to control wind erosion must have an optical density of at least 40% during the period when the soil is exposed to the erosive forces of the wind (Ticknor, 1988). Cornelis and Gabriels (2005) were more specific, recommending a uniform optical density of 65 to 80% but they caution that optimal design depends on the protection goals for the windbreak. Most often, protection is needed at the time of planting, when most deciduous trees are leafless. Typically, this means that the windbreak must contain either coniferous species or a dense shrub understory. Spacing between field windbreaks designed for erosion control should be in the range of 10 to 20*H*. At spacings of 10*H* or less, risk of wind erosion is negligible but economic returns are reduced. As windbreak spacings are increased to 15*H*, economic returns from crop protection increase while the risk of erosion, though increasing, remains low. As spacings approach 20*H*, the risk of erosion increases and economic returns from crop production decrease (Brandle et al., 1992a and 1992b). The proper spacing for field windbreaks designed for wind erosion control depends on climatic conditions, soil properties, residue management practices, and the producer's willingness to accept the risk of erosion.

Snow Management

In many northern, semiarid areas, snow is a critical source of soil moisture for crop and forage production during the next growing season. Greb (1980) estimated that over one-third of the snowfall in these northern areas is blown off the field. Much of this wind-blown snow is deposited in road ditches, gullies, or behind fence rows or other obstructions (Aase and Siddoway, 1976). Even more may simply evaporate (Schmidt, 1972; Tabler, 1975). Many factors influence snow distribution, including: (i) the amount and specific gravity of the snow; (ii) the topography and surface conditions, particularly the amount and type of vegetative cover or crop residue; (iii) wind velocity and direction; and (iv) the presence and characteristics of barriers to wind flow (Scholten, 1988).

Field windbreaks can help capture the moisture available in snow by slowing the wind and distributing the snow across the field. As a result, wheat yields on croplands protected by field windbreaks are increased 15 to 20% (Lehane and Nielsen, 1961; Brandle et al., 1984; Kort, 1988). These increases are a result of increased moisture due to snow capture and the protection of the wheat crop from desiccation.

Field windbreaks designed exclusively for the uniform distribution of snow across the field should have an optical density of no more than 40%. Planting a single row of a tall deciduous tree species on a wide spacing (5–7 m between trees), perpendicular to the prevailing winter wind direction will provide good snow distribution across a field for a distance of 10 to 15*H*. Snow blowing over the tops of the trees falls out of the airstream on the relatively still, leeward side of the windbreak. Wind passing through the porous windbreak provides the mechanism to distribute the snow uniformly across the field. Field windbreaks that are too dense will cause snow to collect in narrow, deep drifts near the tree row (Fig. 5–4).

Areas or fields susceptible to wind erosion during winter present additional challenges because field windbreaks with densities less than 40%, which are ideal for uniform snow distribution, offer minimal wind erosion control. If the field is covered with snow, the soil is protected; however, many areas where snow is an important source of water do not have continuous winter snow cover. Increasing windbreak density will increase the size of the drift, and in more northern areas, may delay snow melt and spring tillage operations due to wet conditions.

Integrated Pest Management and Windbreaks

Both crop pests and their natural enemies are influenced by the presence of windbreaks (Solomon, 1981; Shi and Gao, 1986; Marshall, 1988; Dix et al., 1995; Dix et al., 1997; Burel, 1996; Tremblay et al., 2001; Pierce et al., 2001; Beecher et al., 2002; Perkins et al., 2003; Puckett, 2006). This influence is reflected in the distribution of insects as a result of wind speed reductions in the sheltered zone (Lewis and Dibley, 1970; Heisler and Dix, 1988; Pasek, 1988), and as a function of additional foraging sites that are created both within the windbreak and in the sheltered zones (Southwood and Way, 1970; Slosser and Boring, 1980; Forman, 1995; Corbett and Plant, 1993).

In narrow vegetative or artificial windbreaks, insect distribution appears to be primarily a function of wind conditions (Pasek, 1988). As windbreak structure becomes more complex, a variety of microhabitats are created and insect and avian populations increase in both number and diversity. Greater vegetative diversity of the edges provides numerous microhabitats for life-cycle activities and a variety of hosts, prey, pollen, and nectar sources (Andow, 1991; Flint and Dreistadt, 1998). The addition of woody plants, particularly several rows of tall trees, increases the suitable habitat for numerous avian species (Jobin et al., 2001; Pierce et al., 2001; Tremblay et al., 2001).

The impacts of the various insect distribution patterns are less clear (for more detail see Pasek, 1988; Dix et al., 1995). Both positive and negative aspects are reported in the literature. For example, Slosser and Boring (1980) reported that in northern Texas the success of cotton boll weevils (*Anthonomus grandis* Boheman) overwintering in the litter of deciduous windbreaks was considerably greater than those overwintering in coniferous windbreaks. Danielson et al. (2000) reported mixed results for the presence of bean leaf beetle (*Cerotoma trifucata* Foster) in sheltered and unsheltered soybean fields in eastern Nebraska. In 70% of the cases, there were no differences in bean leaf beetle populations. Sheltered fields had significantly higher populations 20% of the time and unsheltered fields had higher populations only 10% of the time. Corbett and Rosenheim (1996) found that French prune trees planted along the edges of vineyards in California provided significant overwintering habitat for *Anagrus*, an egg parasitoid of the grape leafhopper, *Erythroneura elegantula* (Kido et al., 1984).

Riechert and Lockley (1984) reviewed the role of spiders as biological control agents and concluded that agricultural systems with some type of perennial component in which habitat structure, microclimate, and potential prey are maintained without annual disturbance, could benefit from spiders as biological control agents.

Pollinating insects are typically three times more abundant in sheltered fields than in exposed areas (Williams and Wilson, 1970), contribute to increased levels of pollination, and are dependent on the availability of noncrop habitat (Kremen et al., 2002). Bee flight is inhibited at wind speeds greater than 6.5 to 9 m s^{-1} and the increased levels of pollination that occur in sheltered areas have been attributed to the calmer, warmer conditions found in protected zones (Lewis and Smith, 1969; Norton, 1988).

Crops within the Windbreak

We have discussed the use of windbreaks to protect crops. Within the agroforestry concept, we should recognize the plant materials within the windbreak itself as potential products and as contributors to the total economic return from the agricultural system.

The management of existing multiple-row windbreaks (10 rows or more) for timber or fuelwood is similar to small woodlot management. Larger trees can provide lumber for crates and pallets. Various species of cedar, *Juniperus* spp., and Osage-orange, *Maclura pomifera* (Raf.) Schneid., are resistant to decay and can be used for posts or poles. Cedar may be chipped or shaved for animal bedding and brings a premium when packaged for the small animal or pet market. Other types of wood chips may be used for livestock bedding, landscape and garden mulches, and fuel. In areas near large urban markets, firewood can provide additional income. In recent years, the production and marketing of alternative products from agroforestry has increased dramatically (Josiah et al., 2004; Gold et al., 2004). These include small, nontraditional fruits, hazelnuts, and woody florals. Incorporating these and other understory species into windbreaks provides additional density to the lower portions of the windbreak. The key to a successful agroforestry enterprise is the ability to recognize local market conditions and to supply products to that market (Brandle et al., 1995).

For those with a long-term outlook, new windbreaks can be designed to produce timber crops (Bagley, 1988; Sturrock, 1988). High quality hardwoods, such as walnut (*Juglans*), oak (*Quercus*), and ash (*Fraxinus*) offer the best opportunities. In some cases, Christmas trees and nursery stock may be incorporated into a windbreak design. These types of crops require a little imagination, extensive management, a good understanding of windbreak ecology, and, in some cases, specialized equipment. Some are very labor intensive, and all require extensive business skills and a good understanding of marketing, yet in each case they may add considerable income to the overall economic return of a windbreak investment (Josiah et al., 2004; Gold et al., 2004).

Livestock Windbreaks

Windbreaks play an important role in the protection of livestock, particularly young animals. In the northern Great Plains and the Canadian Prairie region, livestock protection is a vital part of successful operations. Producers in North and South Dakota report significant savings in feed costs, improved survival, and greater milk production when livestock are protected from winter storms (Stoeckeler and Williams, 1949). Livestock vary in their need for wind protection. Beef cattle are very hardy and require protection primarily during calving or during severe winter storms (Webster, 1970a; 1970b). Milk production is increased when dairy cattle are protected from cold, windy conditions (Johnson, 1965), and mortality is significantly decreased with protection of newborn lambs (Holmes and Sykes, 1984). Unfortunately, the literature on the effects of shelter on livestock production is not nearly as extensive as that pertaining to crop production. However, there does appear to be a consensus, especially among producers, that reducing wind speed in winter reduces animal stress, improves animal health, increases feed efficiency, and provides positive economic returns (Atchison and Strine, 1984; Quam et al., 1994). This section describes the responses of livestock to environmental conditions influenced by shelter, how shelter fits into livestock management systems, and the design and management of windbreaks for livestock protection.

Windchill Temperatures

The combined effect of low temperatures and high wind speeds is known as the windchill equivalent temperature and is commonly referred to as the windchill factor. It reflects the rate of sensible heat loss from the body. As wind speeds increase, the thickness of the boundary layer next to the body decreases and the rate of heat loss increases (Moran and Morgan, 1986). For example, when air temperature is −18°C (−0°F) and the wind speed is 12 m s^{-1} (approx. 27 mph), the windchill factor is −44°C (approx. −47°F). At this equivalent temperature, danger to animals increases, including freezing of exposed flesh. A windbreak would reduce wind speed by 50 to 60% and raise the equivalent temperature to −30°C (approx. −22°F), still stressful to young animals but of little consequence to healthy, mature animals.

Animal Response to Shelter

Livestock, like all warm-blooded animals, must maintain their body temperature within a very narrow range if they are to survive. Body temperatures outside this range induce either cold or heat stress and can cause death in a relatively short period of time. This temperature varies with species, breed, age, general health, animal weight, and season of the year. Fortunately, many types of livestock have excellent abilities to adapt to a wide range of low environmental temperatures (see Table 5–3) and maintain a constant body temperature (Primault, 1979).

Primault (1979) defined five thermal zones centered around a zone of thermal indifference. These zones vary with species and age of the animal. Young animals tend to have high, narrow zones while older animals have lower and broader zones. Within the zone of thermal indifference, normal metabolism supplies the necessary energy to maintain body temperature. As air temperatures decrease, the animal must generate additional heat to maintain its critical body temperature and to survive. This requires the use of stored fat reserves or the ingestion of additional feed (Graham et al., 1959; Winchester, 1964; Young, 1983). In addition, long-term exposure to cold temperatures reduces the efficiency of feed utilization, meaning that not only must the animal eat more as it gets colder, but also that the energy gained per unit of feed may decrease with continued exposure (Webster, 1970a,b; Young and Christopherson, 1974). As air temperatures continue to decline, the ability to maintain body temperature is no longer sufficient to meet the animal's need and body temperature begins to fall, resulting in death.

Table 5–3. Optimum temperature conditions for efficient livestock production systems (Primault, 1979).†

Age or type of livestock	Temperature range
	°C
Calves for breeding	5–20
Calves while fattening	18–12‡
Young breeding cattle	5–20
Young cattle while fattening	10–20
Milk cows	0–15
Suckling pigs (newborn animals)	33–22‡
Young pigs and pigs for slaughter	22–15‡
Pregnant and lactating sows	5–15
Lambs	12–16
Sheep for slaughter or wool	5–15
Horses	8–15
Newborn chicks	34–21‡
Egg-laying hens	15–22

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‡ Optimal temperature gradually decreases as animals age or gain weight.

Windbreaks for Livestock Operations

There are many benefits of windbreaks to the successful livestock operation. As in the case of crops, the goal is to use the microclimate conditions created by shelter to benefit the animal production system.

Cold, windy conditions influence animal behavior. As minimum daily temperatures decrease, cattle on rangeland spend less time grazing, reducing forage intake and weight gain (Malechek and Smith, 1976; Kartchner, 1980; Adams et al., 1986). In a pair of recent studies of winter stalk grazing in east-central Nebraska (Morris et al., 1996; Jordan et al., 1997), average winter temperatures were moderate and animals behaved similarly on both open and sheltered fields. However, on days with low temperatures (less than −20°C) and strong winds (>10 m s^{-1}), cattle sought any available shelter. In particular, it was noted that cattle on the sheltered fields were grazing in the sheltered zones, while cattle on the exposed fields were lying down in low areas to reduce stress associated with the cold, windy conditions. Even so, they concluded that shelter had little effect on weight gain from winter stalk grazing during mild winters in east-central Nebraska.

Bond and Laster (1974) investigated the impacts of providing shelter to livestock in confinement. Their results indicated that when given a choice of remaining in shelter or feeding in exposed areas, cattle spent more time in the sheltered zone than feeding. They concluded that shelter was not economical in feedlot situations in south-central Nebraska because animals spent less time feeding and gained less weight. In contrast, Anderson and Bird (1993) reported significant increases in average daily gain and daily feed intake in a North Dakota feeding study. Similarly, livestock feeders in South Dakota, Nebraska, and Kansas report significant feed savings and increased weight gains (Atchison, 1976; Robbins, 1976). These differences emphasize the need to have properly designed windbreaks with feeding areas well within the sheltered zone if the benefits of protection are to be realized. They also emphasize the need for long-term studies under various climatic conditions.

Properly designed livestock windbreaks provide additional benefits to the livestock producer. On rangeland, windbreaks located across the landscape will increase the amount of forage production on the sheltered areas (Kort, 1988) and provide protection for calving against early spring snowstorms. In a Kansas study, average calving success increased 2% when cows were protected by a windbreak (Quam et al., 1994). Windbreaks can be designed to harvest snow and provide water to supplement stock ponds located in remote areas (Tabler and Johnson, 1971; Jairell and Schmidt, 1986; 1992).

Protecting confinement systems with multi-row windbreaks can control snow drifting, enabling access to feedlots and other facilities such as grain and hay storage, and reducing costs associated with snow removal. Wind protection provides a more moderate working environment for feedlot workers, reducing their exposure to cold winds and increasing their efficiency. Windbreaks intercept dust, screen unsightly areas from the road or living area, and assist in control of odors.

Windbreak Design for Livestock Systems

As with other types of windbreaks, livestock windbreaks need to be designed for each specific operation. Some general principles are defined here; a more complete discussion of design criteria can be found in Dronen (1988).

Livestock protection requires that the windbreak system have sufficient optical density (at least 60%) during the winter months. To meet this need, livestock windbreaks should have from three to five rows of trees or shrubs, including at least one or two rows of dense conifers. Rows should extend at least 30 m past the area needing protection to prevent snow from drifting around the ends and into the livestock area. In areas with extreme winter conditions, such as the northern Great Plains and the Canadian Prairies, a minimum of five to seven rows are required for adequate protection.

Placement of the windbreak is critical. It should be located to provide protection against the prevailing winter winds and drifting snow. There should be sufficient distance (at least 50 m) between the windward row and the feeding or calving area to allow for snow deposition. A shrub row located 10 to 15 m windward of the main windbreak will reduce snow deposition leeward of the main windbreak, and allow greater flexibility in the livestock operation (Dronen, 1988). Loafing sheds should be located leeward of the drift zone (Jones et al., 1983). In areas with hot summers, particular attention must be paid to the distance between the leeward edge of the windbreak and feeding areas. Feed bunks should be located at least 25 m (typically 2 to 3*H*) leeward to prevent air stagnation, heat buildup in the feeding area, and animal stress.

In most cases, protection from two or three directions is best. For example, livestock facilities in most areas of the northern Great Plains should have protection on both the north and west exposures and, in some cases, on the east as well. Drainage for melting snow must be provided so that water does not flow through the feeding area. Similarly, runoff from the feeding area should not drain through the windbreak as high nitrate levels can damage many tree species. All livestock windbreaks should be fenced to prevent damage by grazing livestock. Typical livestock windbreak systems are illustrated in Fig. 5–7.

Windbreaks for Odor Mitigation

The strategic use of shelterbelts for odor mitigation has been drawing a lot of attention in livestock producing states. Research suggests that shelterbelts located near and within livestock

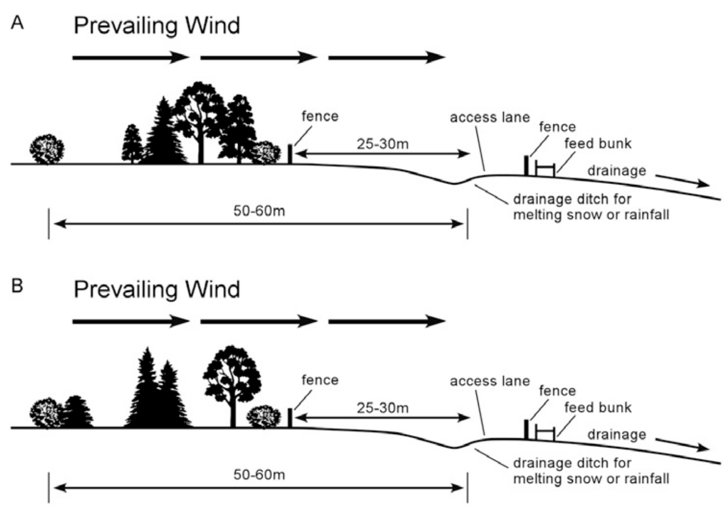

Fig. 5–7. Cross-section of a feedlot windbreak designed for wind and snow protection. (A) Traditional multi-row windbreak with a row of shrubs on the windward side. (B) Modified twin-row, high-density windbreak, including a double row of shrubs on the windward side to catch snow.

facilities can play an important role in biophysically and sociopsychologically mitigating odor in an economically feasible way (Tyndall and Colletti, 2007). Trees and shrubs alter air movement helping to intercept, disperse, and dilute odors before they can accumulate and become a nuisance to downwind areas.

Because the livestock odor source is near the ground and the tendency of the odor is to travel along the ground, shelterbelts of modest heights (6–12 m) are ideal for plume interception, disruption, and dilution (Tyndall and Colletti, 2007; Lin et al., 2006; Bottcher, 2001; Takle, 1983). The majority of odorous chemicals and compounds are absorbed onto, concentrated by, and carried on particulates generated in animal facilities (e.g., animal houses and manure storage) or from land application (Bottcher, 2001). If particulate movement can be controlled, odor movement will be partially controlled (Hammond and Smith, 1981). Shelterbelts have been shown to mitigate odors through a complex of physical and social dynamics (Tyndall and Colletti, 2007; Malone et al., 2006).

The most important odor mitigation dynamic provided by shelterbelts is vertical mixing through turbulence, leading to enhanced dilution and dispersion of odor. Modeling the movement of odor up and over a shelterbelt, Lammers et al. (2001) observed that odor emissions from a livestock building would experience a significantly elevated airstream that is distributed by turbulent eddies diluting the downwind stream of odor (Lammers, Univ. Bonn, personal communication, 2002).

It is generally accepted that trees and other woody vegetation are among the most efficient natural filtering structures in a landscape in part because of the very large total surface area of leafy plants (Bolund and Hunhammer, 1999). Field studies in Delaware (Malone et al., 2006) have quantified a reduction of 49% (±27%; $p < 0.01$) in particulate emissions from a working pullet facility with a 9.2-m wide, three-row shelterbelt consisting of bald cypress, *Taxodium distichum* (L.) Rich; Leyland cypress, × *Cupressocyparis leylandii* (A.B. Jacks. and Dallim.); and eastern red cedar, *Juniperus virginiana* L.

Laird (1997) and Thernelius (1997) modeled the potential of windbreaks to cause airstream fallout of odorous particulates by reducing wind speeds. Using an open-circuit wind tunnel, a small-scale model of an open-air ventilated hog confinement building, and a three-row simulated shelterbelt, mass transport of particulates was reduced by 35 to 56% (depending on wind angle and speed), primarily because of reduced wind speeds (Laird, 1997).

Professionals involved with livestock agriculture generally accept that a well-landscaped operation, which is visually pleasing or screened, is more acceptable to the public than one that is not (Lorimor, 1998; NPPC, 1995; Melvin, 1996). Focus groups in Iowa suggested that the general public is "highly appreciative" of more trees in agricultural landscapes and showed a "high level of agreement" that shelterbelts improve the site aesthetics of confinement livestock production. They also indicated a more positive view of the effectiveness of odor control practices when the sources of odor were hidden from view (Tyndall, 2006a). A general windbreak design for livestock odor control is illustrated in Fig. 5–8.

The few studies that have attempted field quantification of reduced downwind odor concentration and movement have recorded reductions ranging from a low of 6% (Malone et al., 2006) to a high of 33% (Lin et al., 2006; Vezina, 2005). Financial analysis of shelterbelts used for odor mitigation across a series of hog production sites of varying scale and production types showed a range of costs from $0.03 to $0.33 per pig produced (Tyndall, 2006b), all well below producer-revealed expenses for odor management (Tyndall, 2006b). Shelterbelts are not a substitute for comprehensive odor management strategies. Rather, their use should be thought of as a complimentary technology used within a "suite" of odor management strategies (Tyndall and Colletti, 2007).

Windbreak Technology at the Farm and Landscape Levels

Sustainable agriculture is a system of whole-farm resource use balanced with whole-farm productivity (Jackson and Jackson, 2002; Lefroy et al., 1999). Agroforestry is one component of a successful sustainable agriculture system, and the use of field and livestock windbreaks within that system are specific management options. The past several years have seen the initial development of a new field shelterbelt modeling system (Mize et al., 2008). When completed, the model will use windbreak characteristics to calculate changes in wind speed and microclimate in shelter and use this climate data to grow a crop of corn or soybean using standard crop growth models. This model will calculate an economic analysis of the yield benefits; the value of other benefits, including erosion control, carbon sequestration, and wildlife habitation can be added to the final analysis.

According to some definitions, agroforestry must produce marketable products. In that sense, other types of windbreaks—such as farmstead windbreaks or living snow fences—are not agroforestry. However, if agroforestry is true to the basic ecological principles of sustainability, it must recognize the use of other types of windbreaks to support the whole-farm system and the agricultural ecosystem. To that end, in this section we identify other windbreak uses and their benefits and discuss very briefly the ecological implications of windbreak technology to support the farm operation. Those seeking a more detailed discussion of these concepts are referred to the Proceedings of the First International Symposium on Windbreak Technology (Brandle et al., 1988); the excellent text on landscape ecology by Forman (1995); the Proceedings from the Workshop on Agriculture as a Mimic of Natural Ecosystems (Lefroy et al., 1999) and finally, a recent text by Batish et al. (2008) on the ecological basis of agroforestry.

Farmstead Windbreaks

The basic goal of a farmstead windbreak is to provide protection to the living and working area of a farm or ranch and thus to contribute to the overall well-being of the farm operation (Wight, 1988; Wight et al., 1991). The greatest economic benefit is derived from reducing the amount of energy needed to heat and cool the home. The amount of savings varies with climatic conditions (particularly wind and temperature), local site conditions, home construction, and the design and condition of the windbreak. Well-designed farmstead windbreaks can cut the average energy use of a typical farm or ranch home in the northern portions of the United States and Canada by 10 to 30% (DeWalle and Heisler, 1988; Brandle et al., 1992b).

Farmstead windbreaks improve living and working conditions by screening undesirable sights, sounds, smells, and dust from nearby agricultural activities or roads (Ferber, 1969; Cook and van Haverbeke, 1971; Wight, 1988). They reduce the effects of windchill and make outdoor activities less stressful. Properly located farmstead windbreaks can help in snow management, reducing the time and energy involved in snow removal from working areas and driveways. Locating the family garden within the sheltered zone improves yield and quality, and incorporating fruit and nut trees in the windbreak will give additional benefits. Multirow farmstead windbreaks provide significant wildlife habitat in the form of nesting, feeding, singing, and breeding sites for many bird species and enrich the comfort and enjoyment of outdoor activities. Adding particular tree and shrub species to the windbreak can enhance the wildlife component and attract desirable species to the area (Johnson et al., 1991).

Windbreaks for Snow Control

There are basically three objectives for snow management: (i) to spread snow across a crop field to protect the crop or to provide soil moisture for the next season, (ii) to harvest snow for use in stock ponds, and (iii) to prevent snow accumulation in undesirable locations, such as roadways or work areas (Scholten, 1988; Shaw, 1991). Each objective has specific design requirements. We have

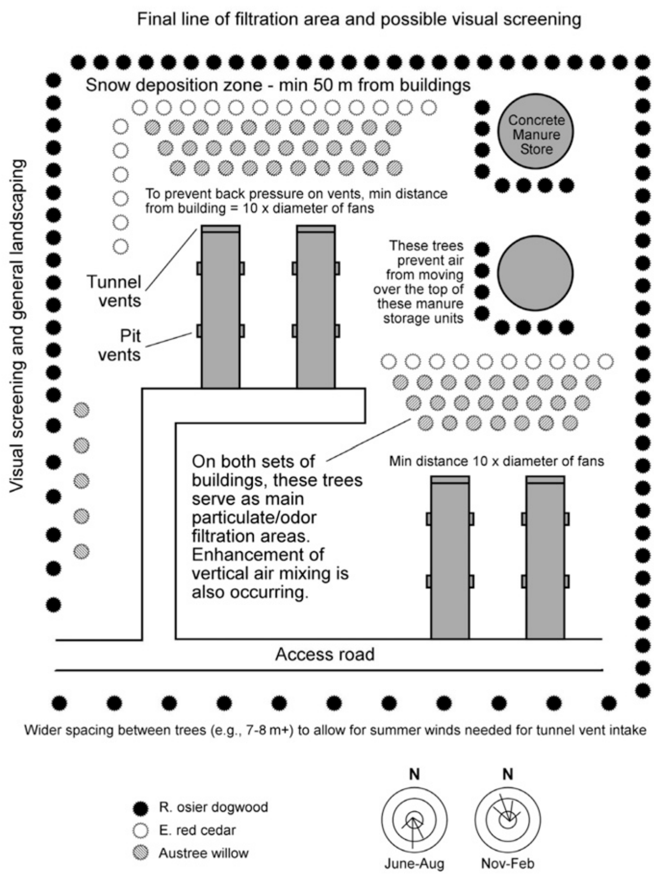

Fig. 5–8. Generalized windbreak design for odor mitigation in central Iowa.

discussed briefly the use of field windbreaks to control snow on crop fields and have discussed the use of livestock windbreaks and farmstead windbreaks to provide snow control. In general, porous windbreaks spread snow across a large area, while dense windbreaks cause snow to accumulate in deep drifts near the windbreak.

Wildlife Windbreaks

In many agricultural areas, windbreak and riparian systems offer the only woody habitat for wildlife (Johnson et al., 1994). In Nebraska, foresters identify wildlife as a primary reason given by landowners for the establishment of windbreaks on agricultural land. Yahner (1982a; 1982b; 1982c) and others (see Johnson and Beck, 1988 for an extensive review) have documented the critical nature of these habitats for various wildlife species. More recently, Johnson et al. (1993) re-emphasized the potential role of these types of habitats in the control of crop pests in agricultural regions. Because of their linear nature, windbreaks are dominated by edge species (both plants and animals). As the width of a windbreak increases, species diversity increases as additional microhabitats are added (Forman and Baudry, 1984; Forman, 1995). In a Kansas study of habitat use within agricultural settings, these linear forests were favored by hunters because many game species are attracted to the cover provided by the woody vegetation. Cable and Cook (1990) estimated that annual economic returns associated with hunting linear forests in Kansas were in the range of $30 to $35 million.

More recently, interest has turned to the overall role of woody habitat in agricultural ecosystems. (See earlier discussion on integrated pest management.) Holland and Fahrig (2000) found that insect diversity in and adjacent to alfalfa fields was enhanced by adjacent woody borders. Perkins et al. (2003) indicate management of the agricultural landscape for a diverse avifauna requires consideration of the amount and distribution of woody cover in the surrounding landscape. Similarly, the amount and distribution of grassland areas is critical to the success of grassland birds associated with agricultural landscapes (Hanson, 2007).

Windbreaks and Climate Change

Brandle et al. (1992b) reviewed the use of windbreaks as a means to reduce atmospheric CO_2 concentration. They identified not only the direct sequestration of carbon in the growing trees but also quantified the agricultural production systems' indirect benefits due to crop and livestock protection and energy savings. They estimated that a minimum windbreak planting program of 1.96 million hectares would result in the storage of 22.2 million metric tons of carbon. In addition, indirect benefits from windbreaks in the agricultural sector from the reduction in hectares farmed would reduce diesel fuel consumption by 1240 million liters. Additional fuel savings from the protection of farmsteads and reduction in fertilizer use would save over 5.4 billion cubic meters of natural gas. These reductions in fossil fuel use could reduce CO_2 emissions by as much as 291 million metric tons over the 50-yr life of the windbreak plantings.

Kort and Turnock (1999) conducted a study of the amount of carbon stored in shelterbelts of the Canadian prairie. They surveyed 11 sites and 12 major shelterbelt species. Based on their results, they estimated that a shelterbelt planting program of six million trees and shrubs in the Prairie Provinces could potentially sequester 0.4 million metric tons of carbon yearly.

More recently Montagnini and Nair (2004) summarized the environmental benefits of agroforestry systems to the overall carbon sequestration issue. They estimated total annual potential carbon storage of over 90 trillion metric tons from five agroforestry practices, with windbreaks contributing to that total by 4 million metric tons of carbon yearly.

Windbreaks could also play a significant role in adaptation strategies as agricultural producers strive to adapt to changing climates. Easterling et al. (1997) reported that windbreaks could help maintain corn yields in eastern Nebraska under several climate scenarios. Using a crop modeling approach, they considered temperature increases up to 5°C, precipitation levels of 70 to 130% of normal, and wind speed changes of plus or minus 30%. In all cases, sheltered crops continued to perform better than nonsheltered crops. In all but the most extreme cases, windbreaks more than compensated for yield losses due to possible climate change, indicating the value of shelterbelts to ameliorate potential climate changes to the agricultural community.

Summary

In the context of agroforestry practices in temperate regions, windbreaks or shelterbelts are a major component of successful agricultural systems. By increasing crop production while reducing the level of inputs, they reduce the environmental costs associated with agriculture. They help control erosion, particularly wind erosion, and contribute to the long-term health of our agricultural systems. When various species are included in the design, they can contribute directly to the production of nuts, fruits, timber, and other wood products. When used in livestock production systems, they improve animal health, improve feed efficiency, mitigate odors, and contribute to the economic return for producers. Designed for snow management, they can capture snow for crop or livestock production.

As part of the overall agricultural enterprise, they reduce home energy consumption and improve working conditions within the farm area. When designed for snow control, they can reduce the costs of snow removal and improve access to livestock feeding areas. Windbreaks provide habitat for wildlife and a number of benefits to landowners and producers alike. The interspersion of woody wildlife habitat in agricultural areas contributes to a healthy and diverse wildlife population to the benefit of both hunters and nonhunters.

On a larger scale, windbreaks provide societal benefits both locally and on a regional scale. Reductions in erosion benefit landowners and reduce off-site costs of erosion as well. Windbreaks have potential to assist with adapting to future changes in climate and may, in some cases, ease the economic burdens associated with change.

The integration of windbreaks and other agroforestry practices into sustainable agricultural systems can provide many rewards. It requires, however, careful consideration of all aspects of the agricultural system, an understanding of basic ecological principles, and a working knowledge of local conditions and markets.

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Study Questions

1. Explain the relationship between windbreak structure and the reduction of wind speed in the lee of a windbreak.

2. Discuss how windbreak structure influences turbulence in the lee of a windbreak. Why is the amount of turbulence important? How does it affect plant processes?

3. Different windbreak structures are used to accomplish different landowner goals. Describe typical windbreaks (species and spacings) for crop protection, wind erosion control, snow management, and protection of livestock or buildings.

4. Changes in wind speed in the lee of windbreaks result in microclimate changes in the sheltered zones. Describe these microclimate changes and explain how these changes influence crop growth and development.

5. Discuss the pros and cons of root pruning as a management option for field windbreaks.

6. Economic analysis of windbreaks indicates positive returns from a windbreak investment. Identify and discuss the costs and benefits associated with field windbreaks and farmstead windbreaks to landowners and society.

7. Discuss the role of noncrop areas such as windbreaks and riparian systems in the biological control of crop pests.

8. Identify and discuss the potential role of windbreaks as a means of ameliorating climate change. What are the direct and indirect benefits of windbreaks in carbon balance issues?

9. Discuss the production of timber or other forest-related products from windbreaks. How does including these products in your windbreak affect design considerations? What else do you need to consider if you were to include these practices in your windbreak?