2000

Windbreak Practices

James R. Brandle
University of Nebraska - Lincoln, jbrandle1@unl.edu

4 Windbreak Practices

James R. Brandle and Laurie Hodges

University of Nebraska
Lincoln, Nebraska

Bruce Wight

USDA-NRCS
Lincoln, Nebraska

Windbreaks or 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. Throughout history they have been used to protect crops and livestock, control erosion and blowing snow, and provide habitat for wildlife. Some authors distinguish between windbreaks and shelterbelts based on their use or objective. The distinction appears to be based primarily on local usage and is not consistent among areas. Rather than try to resolve these differences, we have chosen to make no distinction between the terms and use them interchangeably throughout this chapter.

Windbreaks or shelterbelts are not a new concept, having their origins in the mid-1400s when 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 (Timofeev, 1951; Caborn, 1971) to provide protection from the wind. As settlement in the USA moved west into the grasslands, homesteaders planted trees to protect their homes, farms, and ranches. In the 1930s, in response to the Dust Bowl conditions, the U.S. Congress authorized the Prairie States Forestry Project. This conservation effort led to the establishment of 29 927 km (more than 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), New Zealand (Sturrock, 1984), and Russia (Konstantinov & Struzer, 1965; Mattis, 1988). Although the value of protection is widely recognized, the inclusion of windbreaks as an integral component of sustainable agriculture in the USA 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 and other agroforestry practices 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 extensive reviews by Caborn (1957, 1965); van Eimern et al. (1964); Grace (1977); Rosenberg (1975); Rosenberg et al. (1983); Sturrock (1984); and more recently Brandle et al. (1988) and Miller et al. (1995).

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 and is influenced by Coriolis forces due to 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 50 to 100 m above the earth's surface 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 also are 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 is zero due to the frictional drag of the surface. The amount of drag is a function of the type of surface. In the case of vegetation, the height, uniformity, and flexibility of that vegetation determines the amount of frictional drag exerted on wind flow (Lowry, 1967). A rough surface [e.g., wheat stubble (*Tritcum aestivum* L.)] has greater frictional drag, slower wind speeds, and greater turbulence near the surface than a relatively smooth surface (e.g., mown grass). A windbreak increases surface roughness and, when properly designed, provides large areas of reduced wind speed useful for agriculture. A good discussion of wind, wind profiles, turbulent transfer, and exchange coefficients may be found in Rosenberg et al. (1983). 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.

Wind Flow Across a Barrier

A windbreak is a barrier placed on the land surface that obstructs the wind flow and alters flow patterns both up-wind of the barrier (windward) and down-wind of the barrier (leeward). As wind approaches a windbreak, a portion of the air passes

through the barrier. The remaining air flows around the ends of the barrier, or is forced up and over the barrier. As the air moves around or over the barrier, the streamlines of air are compressed (van Eimern et al., 1964). This upward alteration of flow begins at some distance windward of the windbreak and creates a region of reduced wind speed on the windward side of the barrier. This protected area 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 barrier (Caborn, 1957; van Eimern et al., 1964). This region typically extends for a distance of 10 to 30 *H* (Heisler & DeWalle, 1988; Brandle, 1990; Wang & Takle, 1995b). These flow patterns are illustrated in Fig. 4–1. Some reports indicate that wind speed reductions extend as far as 60 *H* to the lee (Caborn, 1957, 1971), but it is unlikely that these reductions have significant microclimatic or biological impacts.

Pressure on the ground is increased as the wind approaches the barrier and reaches a maximum at the windward edge of the barrier. Pressure drops as the wind passes through the barrier, reaching a minimum just to the lee of the barrier. Pressure gradually increases to the lee, returning to the original pressure condition at or beyond 10 *H* (see Fig. 4–2). The magnitude of the pressure difference between the windward and leeward sides of the windbreak is one factor determining the flow modification of the barrier and is a function of windbreak structure (Schmidt et al., 1995b; Takle et al., 1997).

Windbreak Structure

Seven features determine windbreak effectiveness: height, density, orientation, length, width, continuity or uniformity, and cross-sectional shape. The over-

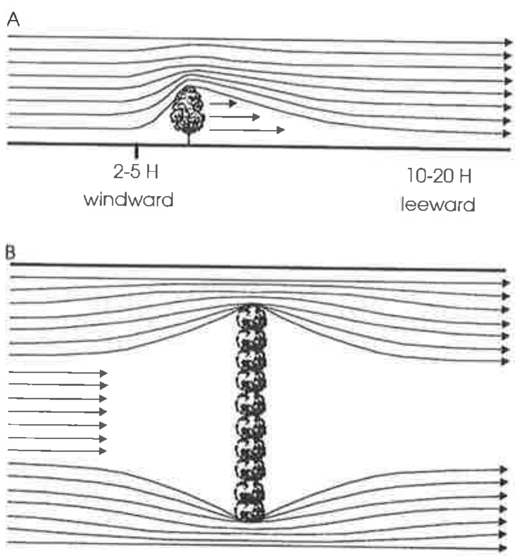

Fig. 4–1. Windflow patterns over (A) and around (B) a field shelterbelt. Note areas of increased windflow above (A) and at the ends (B) of the shelterbelt.

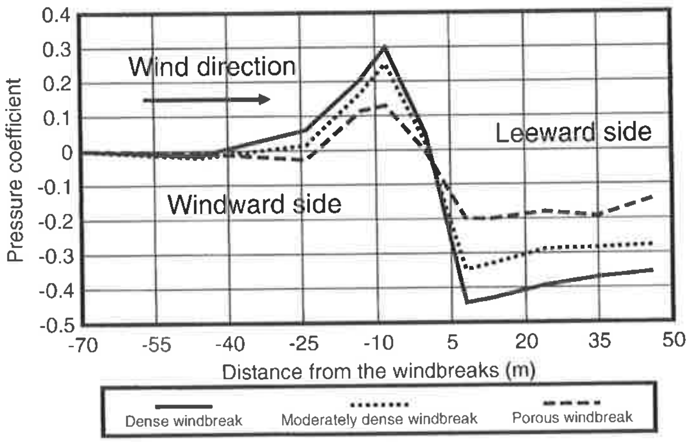

Fig. 4–2. Changes in the pressure coefficient at ground level windward and leeward of a two-row field windbreak with approximately 60% density. Distances from the leeward edge of the windbreak are given as positive distances (leeward) and negative distances (windward).

all size of the protected zones, the extent of the wind speed reductions within the zones, and the resulting microclimate depend on these structural features (Wilson, 1985; Heisler & DeWalle, 1988; Wang & Takle, 1994, 1996b, 1997). 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).

Height

Windbreak height (*H*) is the most important factor determining the extent of the down-wind zone protected by a windbreak. This value varies from windbreak to windbreak and increases as the windbreak matures. In multiple-row windbreaks, the average height of the tallest tree-row determines the value of *H*. In order to facilitate comparisons among windbreaks, distance from the windbreak is usually expressed in terms of the height of the windbreak and designated by *H*. If the windbreak is 3 m tall, 4 *H* would be 12 m; if the windbreak is 15 m tall, 4 *H* is 60 m. Distance is usually measured from the most leeward row of trees within a windbreak.

Density

Windbreak density is the ratio of the solid portion of the windbreak to the total volume of the windbreak. The term porosity also is used and 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%. We will use density in this discussion.

Wind flows through the open portions of a windbreak. Thus the more solid a windbreak, the less wind passes through and the greater the wind speed reduction. In most cases, a windbreak with a density of 40 to 60% provides the greatest reduction in wind speed across the greatest distance. As density increases, less wind passes through the barrier and wind speed reductions are greater, but the extent of

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

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

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

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

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

H distance from windbreak	5H	10H	15H	20H	30H
m sec^{-1}	2.5	3.5	6.5	8.5	9.5
% of open wind speed	30%	50%	60%	75%	95%

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

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

Fig. 4–3. Wind speed reductions at different distances to the lee of windbreaks with different densities, where *H* is the height of the windbreak (after Brandle & Finch, 1991).

the protected area decreases and more turbulence is generated. In contrast, as density decreases, more wind passes through the barrier, wind speed reductions are less, but the extent of the protected area increases slightly, and less turbulence is generated (Heisler & DeWalle, 1988; Brandle, 1990; Wang & Takle, 1995a, 1996b). By adjusting windbreak density, different wind flow patterns and zones of protection are established. This concept is generalized in Fig. 4–3.

Precise determination of windbreak density is 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. Unlike the slat fence, the shape and size of plant elements (stems, branches, and leaves) are not uniform. Similarly, the size and shape of the open spaces varies with time and movement. In addition, the arrangement of these components (plant elements and open spaces) is not uniform and in some cases changes as wind speed changes. Furthermore, vegetative barriers have a significant width such that for any given transect through the barrier there may be many solid elements. This makes estimation of the amount of solid material difficult because some elements may be hidden from view. 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 as increasing the barrier width, which increases density and alters the effect of the windbreak on windflow.

In the past, estimates of density were based primarily on the relative abundance of solid elements and open spaces as seen by an experienced observer. The relatively recent introduction of digital image processing techniques has greatly improved the speed and accuracy of optical density estimation (Kenny, 1987; Loeffler et al., 1992; Zhang et al., 1995). It has not, however, resolved the issues related to the distribution of plant elements within the windbreak.

Heisler and DeWalle (1988) and others (Caborn, 1957; Jensen, 1961; Read, 1964; van Eimern et al., 1964; Brandle, 1990) suggest that the vertical distribution of density within the windbreak also may influence wind flow response. In contrast, recent numerical simulations by Wang and Takle (1994, 1996b, 1997) indicate that variation in the distribution of the surface area within the width of the windbreak may have minimal influence on shelter effects. The relationship between the internal structure of a windbreak and the resulting wind flow patterns remains an active area of research, particularly with regard to field verification of numerical simulations of shelter effects.

Orientation

Maximum effectiveness is obtained when the windbreak is oriented perpendicular to the problem wind. If the winds are primarily from the north or south, windbreaks should be planted along an east–west transect. In most areas, wind direction varies through the year. As the wind direction becomes more oblique to the windbreak, the extent of the protected zone decreases. As winds become parallel to the windbreak, wind speeds may increase under some conditions because of the channeling effects of the windbreak (Schmidt et al. 1995a; Wang & Takle, 1995b, 1996a). In these situations, patterns or networks of windbreaks will provide greater protection and should be incorporated into windbreak design.

Length

Wind speeds at the ends of the windbreak are greater than open wind speed. This is caused by the flow of the wind around the end of the barrier as it seeks the path of least resistance (see Fig. 4–1B). In order to minimize this effect, a windbreak should be at least 10 times as long as it is tall.

Width

The major influence of windbreak width is on the density of the windbreak (Caborn, 1957; Heisler & DeWalle, 1988). As windbreaks become wider, usually by adding rows, the density increases. Additional width has minimal influence on shelter response until the width exceeds 5 *H* (Read, 1964). Wang and Takle (1996b), using numerical simulation methods, have suggested that the complex interaction between width and internal shelterbelt structure may be more important than previously believed. They concluded that as width of the windbreak increases the location of maximum wind speed reduction moves closer to the belt. They also confirmed the results of Read (1964) that additional width has minimal influence on shelter response until the width exceeds 5 *H*, but cautioned that field studies are required to verify this relationship.

Continuity

The continuity of a windbreak influences its efficiency. Gaps in a windbreak concentrate wind flow, creating a zone on the leeward side of the gap in which wind speeds exceed open field wind velocities (Fig. 4–4). Fortunately, there is little lateral extension of this zone of increased wind speed into areas adjacent to the gap (Caborn, 1957). Within the zone, however, protective benefits are lost, reducing windbreak efficiency. In most cases, lanes or other openings through a windbreak should be avoided.

Cross-Sectional Shape

Early work (Caborn, 1957; Read, 1964; van Eimern et al., 1964) indicated that cross-sectional shape influences the magnitude and extent of wind speed reductions in the sheltered zone. It appears that wind speed reductions for windbreaks with vertical sides are greater due to more flow being forced through the barrier. In wind tunnel studies, Woodruff and Zingg (1953; cited in Heisler & DeWalle, 1988) reported that within 10 *H* of the windbreak, the effect of cross-sectional shape may be minimal. Unfortunately, Woodruff and Zingg (1953) did not consider tall, narrow windbreaks with vertical sides. Wang and Takle (1996b) investigated the horizontal distribution of vegetative surface area within a shelterbelt and found little influence of the distribution, provided the total density was unchanged. They also considered different cross-sectional shapes (Wang & Takle, 1997) and concluded that shape has more influence than horizontal distribution on sheltering effect. This too, remains an active area of research, and the new generation of numerical models, when fully tested, should lead to a better understanding of the

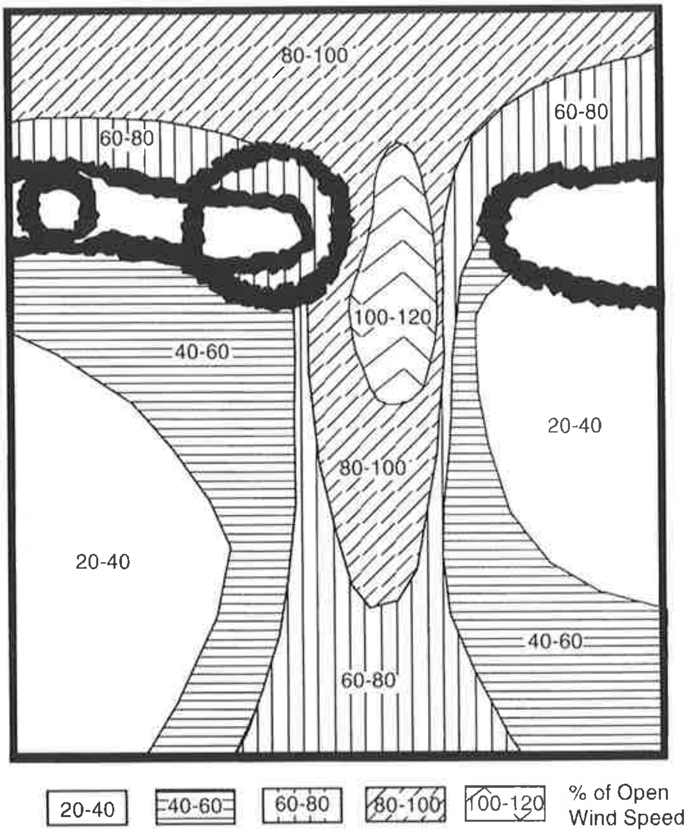

Fig. 4–4. Wind speed increases through gaps in a windbreak, decreasing the effectiveness of the windbreak. Numerical values represent the percentage of open field wind speed (after Caborn, 1957).

relationships between wind speed reduction, windbreak width, plant element distribution, and cross-sectional shape.

Microclimate Changes

Windbreaks reduce wind speed in the sheltered zone. As a result of wind speed reduction and changes in turbulent transfer rates, the microclimate (radiation, temperature, moisture relations, and CO_2) in the sheltered zone is altered (McNaughton, 1988, 1989). The magnitude of microclimate changes for a given windbreak varies within the protected zone. It depends on the existing atmospheric conditions and on the windbreak's density, orientation, time of day, and the height above the ground at which measurements are made.

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) in the area immediately adjacent to the windbreak.

Solar radiant flux density 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 time of the day, season of the year, and height of the windbreak. Windbreaks oriented in a north–south direction produce shaded areas on the west side in the morning hours and on the east side in the afternoon hours. 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. The extent of the shaded zone depends on latitude and season of the year. On the south side of an east–west windbreak, radiation is reflected off the south-facing surfaces of the windbreak and increases radiant flux density immediately adjacent to the windbreak. The amount of reflected radiant flux is dependent on time of day, season of the year, and to a lesser extent the reflectivity of the windbreak's vertical surface.

Air Temperature

In general, daytime temperatures within 8 *H* of a medium-dense barrier tend to be several degrees warmer than temperatures in the open due to 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). Nighttime temperatures near the ground (within 1 m) are generally 1 to 2°C warmer in the protected zone (up to 30 *H*) than in the exposed areas (Read, 1964). 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 (van Eimern et al., 1964; McNaughton, 1988; Argete & Wilson, 1989; Brandle, 1990).

There are exceptions to these general conditions which complicate the temperature regimes in sheltered areas, especially at the beginning and end of the growing season. Heat stored in the soil may act as a heat source under some conditions. As air temperature decreases, a layer of air above the soil may be warmed by the release of heat from the soil. In conjunction with evaporation and dew formation, soil moisture and the energy required to change water from the liquid to vapor state may have an effect on temperature patterns in the sheltered zone.

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 lead to an increase in plant or animal stress and decreased productivity.

Growing Degree Days

Most crops are rated according to the number of days to maturity. But a day in Texas is not like a day in North Dakota. This has led to the use of heat units (or growing degree days) to assess when a cultivar will reach maturity at any location.

While some crops, for example soybean [*Glycine max* (L.) Merr.], are day length dependent, the rate of development is still related to temperature and thus may be assessed in terms of heat units. Although there are several ways to calculate heat units, the simplest and most common is based on the difference between the base temperature for a given crop and the daily average temperature (Perry et al., 1986). These units are totaled over the growing season to get the total number of heat units or growing degree days.

The number of heat units accumulated in the sheltered zone is greater than in the unsheltered zone due to the higher temperatures in the protected area. This provides several benefits to the producer. Crops grown in sheltered areas mature more quickly than unsheltered crops. For vegetable crops, this may provide a marketing advantage and may result in a premium price for the product. For grain crops, the increase in the rate of growth and development may mean that critical stages of development occur earlier in the season when periods of water stress may be less likely. The increased number of heat units at the beginning and end of the season may extend the growing season, allowing greater flexibility in selecting crops or cultivars.

Soil Temperature

Average soil temperatures in shelter are slightly warmer than in unprotected areas (McNaughton, 1988; van Eimern et al., 1964). In most cases this is due to the reduction in heat transfer away from the surface. In areas immediately to the north of an east–west windbreak, soil temperatures are lower due to shading of the surface. The magnitude of this effect is dependent on the height of the barrier and the angle of the sun (the size and duration of the shaded area). In areas immediately to the south of an east–west barrier, soil temperatures are higher due to the radiation reflected off the surface of the windbreak. Again, it appears that these differences are greatest early in the season (Caborn, 1957).

Frost

On clear, calm nights, infrared radiation emission by soil and vegetation 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 are below freezing, this condensation freezes resulting in a radiation frost (Rosenberg et al., 1983). Radiation frosts are most likely under very calm conditions when strong temperature inversions may occur. In contrast, advection frosts, sometimes called a *hard freeze*, 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 advective frosts when episodes are of short duration and when windward temperatures are just below 0°C. In sheltered areas, wind speed is reduced resulting in reduced turbulent transfer coefficients (less mixing of the warm air near the surface with the colder air of the front) and reduced heat loss from the sheltered area.

On calm nights early in the spring or late in the fall, shelterbelts may reduce wind speed such that radiation frost may occur in sheltered areas but not in exposed areas. In these cases, terrestrial radiation loss leads to surface cooling and, as a result, heavy, chilled air accumulates near the surface, giving rise to temperature inversions and possibly frost. The process is enhanced by very low wind speeds or calm conditions where turbulent mixing is minimal. The process also 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 also may be held in the crop canopy by the reduction in turbulent mixing reducing the potential of frost. It also is possible that the increase in water vapor in the sheltered area reduces the rate of radiative cooling (Rosenberg et al., 1983). It should be noted that in all of these cases, temperatures are very close to freezing and may or may not result in frost, depending on interacting microclimate conditions.

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 may be 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 due to increased stemflow or dripping from the canopy.

In contrast, the distribution of snow is greatly influenced by the presence of a windbreak and can be manipulated by managing windbreak density (Read, 1964; Shaw, 1988; Scholten, 1988). A dense windbreak (>60% density) will lead to relatively short, deep snow drifts on the leeward side, while a more porous barrier (~35% density) will provide a long, relatively shallow drift to the lee. 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 some northern 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. The effect of density on snow distribution is illustrated in Fig. 4–5.

Humidity

Humidity, or 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 in shelter are generally greater both during the day and at night (Caborn, 1957; van Eimern et al., 1964; Rosenberg et

al., 1983; McNaughton, 1988). And, because 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.

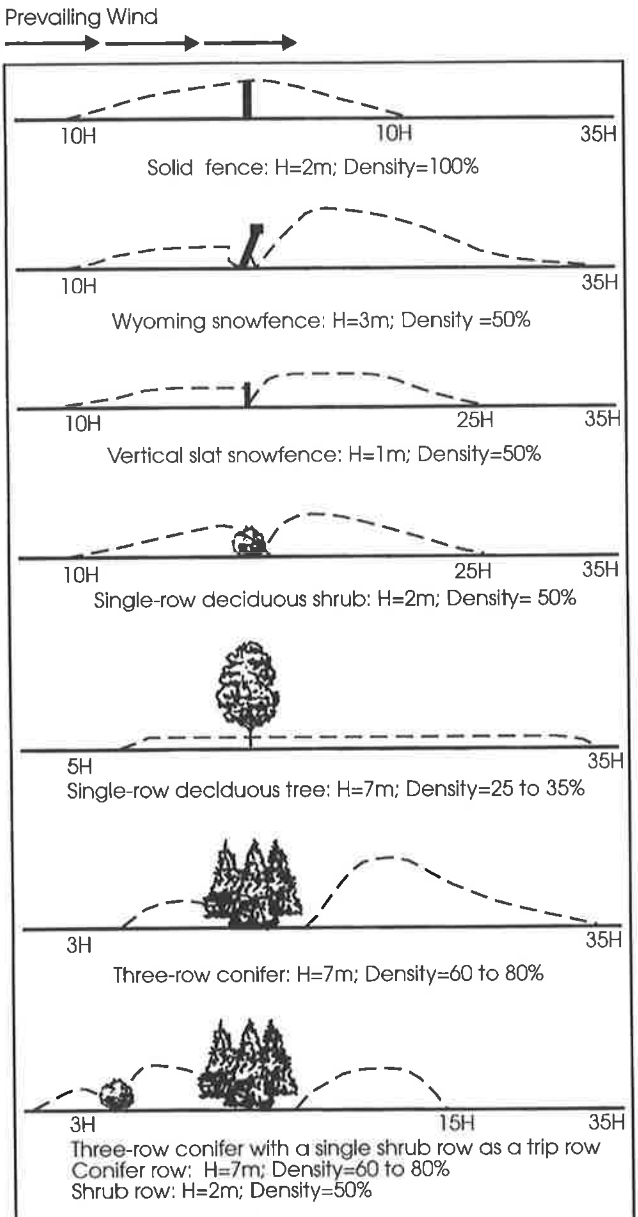

Fig. 4–5. The amount of snow storage windward and leeward of a snow fence or windbreak is determined by the height and density of the barrier (after Brandle & Nickerson, 1996).

Evaporation

Evaporation of water is the physical process by which liquid water changes to the vapor form. It is a major mechanism for the redistribution of energy within the ecosystem (Rosenberg et al., 1983). It is driven by the amount of available energy and influenced by wind, turbulent mixing, air temperature, and vapor pressure.

Evaporation from bare soil is reduced in shelter 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 plant growth. This is especially true for seed germination. Under some situations, slower soil drying may restrict field access and may be a concern in areas with short growing seasons. In the case of forage production, slower drying rates increase the length of time needed for proper curing and expose the producer to greater risk from rainfall during the drying process.

Evaporation from leaf surfaces also is reduced in shelter. In most cases windbreak design is such that increased humidity and reduced evaporation do not contribute to a higher incidence of disease. Situations do occur, however, where 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, in order to increase the incidence of white mold disease in dry edible bean cultivar tests designed to 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. During the past 20 yr of shelter research in eastern Nebraska, we have observed this phenomenon only twice, once in winter wheat (Brandle et al., 1984) and once in soybean (unpublished data, Nieto & Brandle, 1996).

Carbon Dioxide

It has been suggested (Lemon, 1970) that under low wind speed conditions, CO_2 concentration within the canopy may decrease. Given the reductions in turbulent mixing in sheltered areas, one might expect significant reductions of CO_2 levels in these areas. Brown and Rosenberg (1972) reported that CO_2 concentration in a sheltered sugar beet crop decreased by 1 $\mu L\ L^{-1}$ (ppm) during the day and increased by 3.5 $\mu L\ L^{-1}$ at night when compared with open fields. According to Heisler and DeWalle (1988), the differences that occur in sheltered areas are quite variable and are of the magnitude of plus or minus 10 to 20 $\mu L\ L^{-1}$. It is unlikely that differences of this magnitude will contribute to any significant physiological changes in the crop.

Quiet and Wake Zones

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* lee-

ward. Both wind speed and turbulence in this region are reduced. The *wake zone* lies leeward of the *quiet zone* and extends to a distance approximately 20 to 25 *H* from the barrier. In this region wind speed is reduced but turbulence is increased. The boundary between these two zones is a function of windbreak density and atmospheric stability and lies between 6 and 10 *H* to the lee of the windbreak. As a result of differences in turbulence in these two regions, the transport of heat, water vapor, and CO_2 within these two zones is different. 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. These differences contribute to the different microclimate conditions created in these two zones.

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. In the case of agriculture, two types of windbreaks have direct application to the production system, 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 will 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 in range and feedlot situations from the adverse effects of wind.

Field Windbreaks

Agricultural producers frequently recognize the value of field windbreaks as a way to reduce wind erosion (Tibke, 1988; Ticknor, 1988). In northern areas, the value of field windbreaks to harvest snow for crop production is widely recognized (Scholten, 1988). Field windbreaks are regularly 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, 1981, 1988; Coutts & Grace, 1995; Miller et al., 1995). Both photosynthesis and transpiration are driven in part by environmental conditions, particularly those within the leaf and canopy boundary layers of the plant. As shelter modifies micro-environment, it impacts plant productivity.

One useful concept explaining how plants respond to shelter is that of coupling (Grace, 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 leaf or canopy. When these gradients are modified by shelter, plant processes within the sheltered zone may become uncoupled from these environmental gradients (Grace, 1981, 1988; Monteith, 1981; McNaughton, 1988).

In the quiet zone where turbulence is reduced, we expect conditions to be uncoupled as the canopy is isolated from the atmospheric conditions above the sheltered area. In contrast, conditions in the wake zone become more strongly coupled as turbulence increases the concentration gradients. In either case we can expect to see the exchange rates for heat, water vapor, and CO_2 altered by the effect of shelter.

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 by decreased vertical temperature gradients 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 cell division and expansion (Grace, 1988; van Gardingen & Grace, 1991). Lower night temperatures in shelter may reduce the rate of respiration that may result 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 & 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 both the temperature 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. 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. Sheltered plants tend to be taller, however, 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). 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.

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 & Brandle, 1978), cotton (*Gossypium hirsutum* L., Barker et al., 1989), and many vegetables (Baldwin, 1988; Hodges & Brandle, 1996). In recent research conducted at the University of Nebraska, earlier flower formation in cantaloupe (*Cucumis melo* L., Zhang, 1994) contributed to earlier harvest of sheltered plants (see Fig. 4–6). In snap beans (*Phaseolus vulgaris* L.), an increase in air temperature early in the season re-

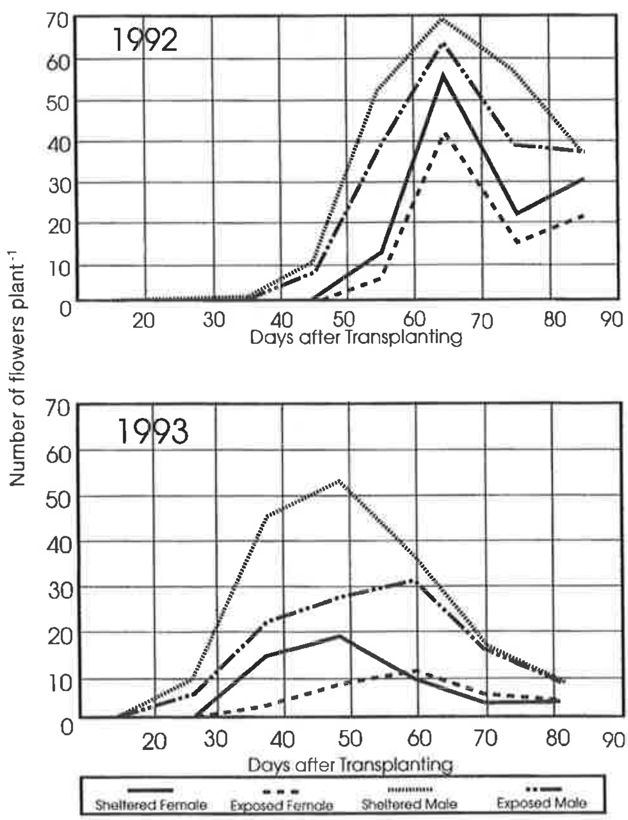

Fig. 4–6. Number and time of occurrence of male and female flowers of cantaloupe grown in sheltered or exposed conditions in 1992 and 1993.

sulted in earlier maturity (Suratman, 1996). 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 & Brandle, 1996, unpublished data). 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).

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 & Brandle, 1981, 1982), but not in corn (Zhang & Brandle, 1997) or alfalfa (*Medicago sativa* L., Hans, 1987).

In many fruit and vegetable crops, reproductive growth is dependent on pollination by insects. 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 (Caborn, 1957; van Eimern et al., 1964; Waister, 1972b; Norton, 1988), which can be attributed to the improved microclimate in sheltered areas.

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 size (Jaffe, 1976; Grace, 1988; Nobel, 1981), and affect cellular composition (Armbrust, 1982). On the whole-plant level, the interaction of ethylene and auxin (Erner & Jaffe, 1982; Biro & Jaffe, 1984; Biddington, 1986) 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 ms^{-1} for <1 min. 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 sheltered and nonsheltered conditions (Biddington, 1985; van Gardingen & 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 et al., 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 larger, 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

Table 4–1. Estimated crop tolerances to damage by wind blown soil (Finch, 1988).

Tolerant crops: Estimated crop tolerance >5.4 Mt ha^{-1} yr^{-1}	
Wheat	*Triticum aestivum* L.
Oat	*Avena sativia* L.
Barley	*Hordeum vulgare* L.
Flax	*Linum usitatissimum* L.
Moderately tolerant crops: Estimated 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 tolerance crops: Estimated crop tolerance <2.7 Mt ha^{-1} yr^{-1}	
Alfalfa seedlings	*Medicago sativa* L.
Beans	*Phaseolus* sp.
Cotton	*Gossypium hirsutum* L.
Flowers	All species
Leafy vegetables	All species
Peas	*Pisum sativum* L.
Peppers	*Capsicum annuum* L.
Soybean	*Glycine max* (L.) Merr.
Tobacco	*Nicotiana tobacum* L.
Young orchards	*Citrus* sp., *Malus* sp., *Persica* sp., *Prunus* sp., *Pyrus* sp.

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 (see Table 4–1). 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 the 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 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* where 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 & Ferguson, 1999). It is interesting to note that we found areas of *brittle-snap* in several of our unsheltered corn fields but none in our sheltered fields. Meteorological measurements indicated that in the exposed areas wind speeds exceeded 18 m s^{-1} while in sheltered fields wind speeds were generally <9 m s^{-1} (Brandle, 1993, unpublished data). The effect appeared to be related to stem characteristics of certain corn cultivars since not all cultivars exhibited damage.

Table 4–2. 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
Other hay	14	20

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 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% (see Table 4–2).

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 are unlimited, and the probability of a single combination and the corresponding crop response occurring on an annual basis is relatively small. 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 mesoclimate, windbreak efficiency, and growth and development of the protected crop.

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

In this review we define horticultural crops primarily as fruits and vegetables. There are few articles on the production of cut flowers in shelter, but one would suspect that they would be extremely responsive to the microclimate of shelter due to their sensitivity to desiccation. In addition, high quality factors, 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. Other important works include those of van Eimern et al. (1964), Waister (1972b), Shah (1970), and Sturrock (1984). The responsiveness of many vegetable crops to the physical movement induced by wind or mechanical methods is covered by Latimer (1991).

In horticultural crops, marketable yields, quality of the product, and earliness to market maturity are of primary importance (Baldwin, 1988; Hodges & Brandle, 1996). 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 & 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 beets (*Beta vulgaris* L., Bender, 1955), tobacco (*Nicotiana tobacum* L.), and French beans (*Phaseolus vulgaris* L., Kreutz, 1952a,b), strawberries (*Fragaria* sp., Shah, 1970; Waister, 1972a,b), potatoes (*Solanum tuberosum* L.), and lettuce (*Lactuca sativa* L.; Strupl, 1953), plum (*Prunus* sp., Preez, 1986), kiwifruit (*Actinidia chinensis* L., McAneney & Judd, 1987), oranges [*Citrus sinensis* (L.) Osbeck, Rodriquez et al., 1986; Pohlan et al., 1986], carrots (*Daucus carota* L., Taksdal, 1992), and others (for more details, see reviews by van Eimern et al., 1964; Grace, 1977; Baldwin, 1988; Norton, 1988; 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 & 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 wind abrasion and abrasion by wind-blown soil may result in damage to or loss of buds and flowers (Bubenzer & Weis, 1974). Vegetable producers need to be especially aware of the problems associated with wind erosion because the soil characteristics that favor vegetable production are typical of erosive soils.

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) as well as damage plant tissues, providing 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, infested river sand increased from 3 to 5 min (Claflin et al., 1973). Similarly, bell peppers (Pohronezhy et al., 1992) and prunes (Michailides & Morgan, 1993) showed increased disease incidence when wind exposure increased. Windbreaks can reduce the distribution and rate of spread of aphids, vectors for various plant 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 & 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. There are general principles, however, 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 in order 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 noncrop 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 form. Individual species should be cold hardy and drought tolerant, with good insect and disease resistance. Native species are usually a good choice. The overall windbreak should have a 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).

Zone of Competition

One of the most common negative comments concerning the benefits of field windbreaks is related to the impact of competition between the windbreak and the adjacent crop. There is no question that under conditions of limited moisture, competition between the windbreak and the crop has significant, negative impacts on yield. Crop yields within the zone of competition may be reduced due to allelopathy, nutrient deficiency, shading, temperature, or soil moisture deficiency (Kort, 1988). The degree of competition varies with crop, geographic location (Stoeckeler, 1962; Lyles et al., 1984), windbreak species (Greb & Black, 1961; Lyles et al., 1984; Brandle & Kort, 1991), and annual weather conditions.

Some types of competition may be reduced by root pruning, the cutting of lateral tree roots extending into the crop field. The effectiveness of the practice depends on the rooting patterns of the windbreak species, the depth of root pruning, and soil moisture levels (Stoeckeler, 1962; Kort, 1988; Rasmussen & Shapiro, 1990). Under limited moisture conditions, root pruning significantly increases crop yields within the zone of competition. During wet years the benefits are less obvious (Stoeckler, 1962). 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 & Capel, 1982; Lyles et al., 1984). Although Lyles et al. (1984) estimated an average economic return from root pruning a field windbreak protecting winter wheat in Kansas at $164 per 800 m. There are no long-term evaluations of the economics of root pruning.

Windbreak Economics

Field windbreaks occupy land and thus remove this land from crop production. From an economic perspective, the amount of land occupied by the windbreak should be minimized in order to maximize the number of crop acres available. 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) have 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 cropland due to areas 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 from the area occupied by the windbreak and increased yields in the protected areas. For example, a 64-ha field, protected by four, single row, pine-cedar field

windbreaks approximately 150 m apart, with a crop rotation of corn and soybean, will provide more than $35,000 of additional income to the producer during the life of the windbreak. A lifespan of 60 yr and a discount rate of 5% were assumed in the analysis.

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. If 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 are an additional economic benefit flowing from the windbreak investment (Brandle et al., 1992a). Off-site costs, which are more difficult to quantify, also are incurred by both the private and public sectors (Huszar & Piper, 1986) and include damage to water storage facilities, irrigation systems, road ditches, and other facilities (Ribaudo, 1986). Reducing off-site costs provides an additional economic benefit from the windbreak investment.

Wind erosion is a natural process and its total control is neither practical nor desirable. The primary 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, generally <50 μm, but as large as 100 μm, 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 <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 both 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 rough-

ness, 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 we can do very little 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 contribute to wind erosion control 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 depends in part on the shape, width, height, and density of the windbreak. Windbreaks designed to control wind erosion must have a density of at least 40% during the period when the soil is exposed to the erosive forces of the wind. Most often this is 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. 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 & Siddoway, 1974). 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, (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 & 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 wind desiccation.

Field windbreaks designed exclusively for the uniform distribution of snow across the field should have a density of no more than 40%. Planting a single row of a tall deciduous tree species on a wide spacing (5 to 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 air-stream on the relatively still, leeward side of the windbreak. Wind passing through the relatively 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.

Areas or fields susceptible to wind erosion during winter present additional challenges because field windbreaks with densities <40%, which are ideal for snow distribution, offer little 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. The effects of density on snow distribution are illustrated in Fig. 4–5.

Integrated Pest Management and Windbreaks

Both crop pests and their natural enemies are influenced by the presence of windbreaks (Lewis, 1965, 1970; van Emden, 1965; Bowden & Dean, 1977; Solomon, 1981; Shi & Gao, 1986; Marshall, 1988; Dix et al., 1995, 1997; Burel, 1996). This influence is reflected in the distribution of insects as a result of wind speed reductions in the sheltered zone (Lewis & Dibley, 1970; Heisler & Dix, 1988; Pasek, 1988) or as a function of the numerous micro-habitats, including the diversity of the associated plant species, that are created both within the windbreak and in the sheltered zones (Southwood & Way, 1970; Slosser & Boring, 1980; Forman, 1995; Corbett & Plant, 1993). Windbreaks influence the distribution of both predator and prey. In narrow vegetative windbreaks or artificial windbreaks, insect distribution appears to be primarily a function of wind conditions. As windbreak structure becomes more complex, a variety of micro-habitats are created and as a result insect populations increase in both number and diversity (Pasek, 1988). Greater vegetative diversity of the edges provides numerous micro-habitats for life-cycle activities and a variety of hosts, prey, pollen, and nectar sources.

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. Bee flight is inhibited at wind speeds greater than 6 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 & Smith, 1969; Norton, 1988). 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 where habitat structure, microclimate, and potential prey are maintained without annual disturbance could benefit from spiders as biological control agents.

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 of 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 *Juniperus* 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. The key to a successful wood product agroforestry practice 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* sp.), oak (*Quercus* sp.), and ash (*Fraxinus* sp.) offer the best opportunities. Some windbreaks may include fruit and nut producing species. Raspberries (*Rubus* sp.) or blackberries (*Rubus* sp.) may be included to increase density of the understory and may provide fruit for home use or local fresh markets. In some cases, Christmas trees and/or 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, but in each case they may add considerable income to the overall economic return of a windbreak investment (Quam et al., 1991).

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, survival, and milk production when livestock are protected from winter storms (Stoeckeler & Williams, 1949). Livestock vary in their need for wind protection. Beef cattle (*Bos taurus*) are very hardy and require protection primarily during calving or during severe winter storms (Webster, 1970a,b). Milk production is increased with protection of dairy cattle during cold windy conditions (Johnson, 1965), and mortality is significantly decreased with protection of newborn lambs (Holmes & Sykes, 1984). Unfortunately, the literature on the effects of shelter on livestock production is not nearly as extensive as that pertaining to crop production. There does appear, however, to be a consensus, especially among producers, that reducing wind speed in winter lowers animal stress, improves animal health, increases feed efficiency, and provides positive economic returns (Atchison & Strine, 1984; Quam et al., 1994). This section describes the re-

sponses 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 & Morgan, 1986). For example, when air temperature is –18°C (~0°F) and the wind speed is 12 m s^{-1} (~25 mph), the wind chill factor is –44°C (~ –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 (~ –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.

Primault (1979) defines 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 ranges. Within the thermoneutral zone, 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 use, 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 & 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.

Fortunately, many types of livestock have excellent abilities to adapt to a wide range of low environmental temperatures (see Table 4–3) and maintain a constant body temperature (Primault, 1979). This ability is influenced by the age, health, and diet of the animal (Johnson & Beck, 1988). Newborns are particularly sensitive to cold temperatures while older animals tend to perform better at lower temperatures.

The ability of the animal to generate body heat is much greater than its ability to dissipate excess heat (Primault, 1979; Rosenberg et al., 1983). As air temperatures increase, the animal must release heat, usually through the process of evaporation either from the surface of the body or through the respiratory process. Unfortunately, both of these processes have limited capacity to relieve high tem-

Table 4–3. Optimum temperature ranges for livestock (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
Dairy cows	0–15
Suckling pigs (newborn animals)	33→22†
Swine	22→15†
Lambs	12–16
Sheep for slaughter or wool	5–15
Horses	8–15
Chicks	34→21†
Egg-laying hens	15–22

† The optimum temperature decreases as the animal ages or gains weight.

perature stress, and thus high temperatures are of far greater concern to producers than cold temperatures.

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.

Animal behavior is influenced by cold, windy temperatures. As minimum daily temperatures decrease, cattle on rangeland spend less time grazing, reducing forage intake and weight gain (Malechek & 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; Jordon et al., 1997), average winter temperatures (1994–1995 and 1995–1996) were moderate and animals behaved similarly on both open and sheltered fields. On days with low temperatures (less than –20°C) and strong winds (>10 m s^{-1}), however, 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. Using slat-fence windbreaks, protection was provided for a portion of one-half of the feedlot pens. All feeding areas were located in exposed areas such that the animals would need to move out of shelter to feed. 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 snow storms. 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 & Johnson, 1971; Jairell & Schmidt, 1986; 1992). Protecting confinement systems with multirow 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 can intercept dust, screen unsightly areas from the road or living area, and reduce the perception of odors. High density or irregular structure in the upper canopy of a windbreak increases turbulence and air mixing. There is speculation that by creating additional turbulence in the wind flow, it would be possible to foster dilution of undesirable odors. Unfortunately, no real evidence of this dilution is available. Finally, livestock windbreaks can provide significant wildlife habitat and aesthetic value to the area.

Windbreak Design for Livestock Systems

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

Livestock protection requires that the windbreak system have sufficient 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 southern Canada, 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). There should be at least 25 m between the leeward row and the feeding area to prevent air stagnation and heat build-up during the summer months. In most cases, protection from two or three

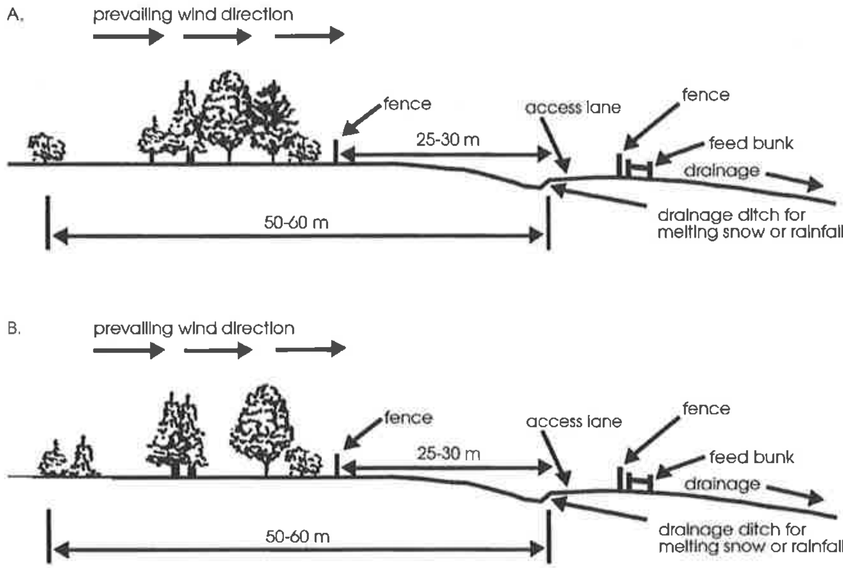

Fig. 4–7. Cross-section of a feedlot windbreak designed for wind and snow protection. (A) Traditional multirow windbreak with a trip-row of shrubs on the windward side. (B) Modified twin-row, high-density windbreak including a double row of shrubs on the windward side to trip snow.

directions is best. For example, most areas in North Dakota should have protection on both the north and west exposures and, in some cases, on the east as well. Drainage must be provided for the melting snow and for the runoff from the feeding area. All livestock windbreaks should be fenced to prevent damage by grazing livestock. Typical livestock windbreak systems are illustrated in Fig. 4–7.

WINDBREAK TECHNOLOGY AT THE FARM AND LANDSCAPE LEVELS

Windbreak Uses

Sustainable agriculture is a system of whole-farm resource use balanced with whole-farm productivity (Quam et al., 1991). 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. In the strictest sense of the definition, agroforestry must produce a marketable product. In that sense, other types of windbreaks do not meet this criteria. If agroforestry is to be true to its basic ecological principles, however, it must recognize the use of other types of windbreaks to support the whole-farm system and the agricultural landscape. 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) and the excellent text on landscape ecology by Forman (1995).

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 USA and Canada by 10 to 30% (DeWalle & 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 & 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 farm working areas and driveways. Locating the family garden within the sheltered zone improves yield and quality, and incorporating fruit and nut production into the windbreak will add additional benefits. Multirow farmstead windbreaks provide significant wildlife habitat in the form of nesting, feeding, singing, and breeding sites and enrich the comfort and enjoyment of outdoor activities. Adding particular 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 discussed briefly the use of field windbreaks to control snow on crop fields and have identified that both livestock windbreaks and farmstead windbreaks provide for 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,b,c) and others (see Johnson & Beck, 1988, for an extensive review) have documented the critical nature of these habitats for various wildlife species. More recently, Johnson et al. (1993) reemphasized the potential role of these types of habitats in the control of crop pests in agricul-

tural 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 micro-habitats are added (Forman & 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.

Windbreaks and Climate Change

Brandle et al. (1992b) recently reviewed the use of windbreaks as a means to reduce atmospheric CO_2 concentration. They identified not only the direct sequestration of C in the growing trees but also quantified the indirect benefits to agricultural production systems due to crop and livestock protection and energy savings. They estimated that a minimum windbreak planting program of 1.96 million ha would result in the storage of 22.2 million tons of C. In addition, indirect benefits in the agricultural sector would reduce diesel fuel consumption by 328 millions gallons, and save >5.4 billion m^3 of natural gas. These reductions in fossil fuel use could reduce CO_2 emissions by as much as 291 million tons during the 50-yr life of the windbreak plantings.

Windbreaks also could 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 production 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 the change in climate, indicating the potential value of shelter under these conditions.

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, and contribute to the economic return of producers. Designed for snow management, they can capture snow for crop or livestock production.

As part of the overall agricultural enterprise, they reduce energy consumption by the farm or ranch home 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 larger, regional scale. Reductions in erosion not only benefit the landowner but reduce the 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.

REFERENCES

Aase, J.K., and F.H. Siddoway. 1974. Tall wheatgrass barriers and winter wheat response. Agric. Meteorol. 13:321–338.

Aase, J.K., and F.H. Siddoway. 1976. Influence of tall wheatgrass wind barriers on soil drying. Agron. J. 68:627–631.

Adams, D.C., T.C. Nelsen, W.L. Reynolds, and B.W. Knapp. 1986. Winter grazing activity and forage intake of range cows in the northern Great Plains. J. Anim. Sci. 62:1240–1246.

Anderson, V.L., and J. Bird. 1993. Effect of shelterbelt protection on performance of feedlot steers during a North Dakota winter. 1993 Beef Production Field Day, Carrington Res. Ext. Ctr., Livestock Unit. Vol. 16:19–21. North Dakota State Univ., Fargo.

Argete, J.C., and J.D. Wilson. 1989. The microclimate in the center of small square sheltered plots. Agric. For. Meteorol. 48:185–199.

Armbrust, D.V. 1982. Physiological responses to wind and sandblast damage by grain sorghum plants. Agron J. 74:133–135.

Atchison, F.D. 1976. Windbreaks for livestock protection in the central Great Plains. p. 101–102. *In* Windbreaks: What are they worth? Proc. 34th Annual Meeting of the Forestry Committee, Dodge City, KS. 22–24 June 1982. Great Plains Agric. Council, Dodge City, KS.

Atchison, F.D., and J.H. Strine. 1984. Windbreak protection for beef cattle. Kansas State Univ. Coop. Ext. Serv. Publ. L-708. Kansas State Univ., Manhattan.

Bagley, W.T. 1988. Agroforestry and windbreaks. Agric. Ecosyst. Environ. 22/23:583–591.

Baldwin, C.S. 1988. The influence of field windbreaks on vegetable and specialty crops. Agric. Ecosyst. Environ. 22/23:159–163.

Barker, G.L., J.L. Hatfield, and D.F. Wanjura. 1989. Influence of wind on cotton growth and yield. Trans. ASAE 32:97–104.

Bates, C.G. 1911. Windbreaks: Their influence and value. USDA For. Serv. Bull. 86. U.S. For. Serv., Washington, DC.

Bates, C.G. 1944. The windbreak as a farm asset. USDA Farmers Bull. 1405. U.S. For. Serv., Washington, DC.

Bender, M. 1955. Influence of shelterbelts on the yield of crops. Mitteil. Deutsch. Landw. Gesellschaft, 70, no. 29. and AID, Reihe Landwirtschaft-Angewandthe Wissenschaft, no. 37. Landw. Verlag Hiltrup/Westfalen, p. 75–102. (cited in van Eimern et al., 1964).

Biddington, N.L. 1985. A review of mechanically induced stress in plants. Sci. Hortic. 36:12–20.

Biddington, N.L. 1986. The effects of mechanically-induced stress in plants: A review. Plant Growth Regul. 4:103–123.

Biro, R.I., and J.J. Jaffe. 1984. Thigmomorphogenesis: Ethylene evolution and its role in the changes observed in mechanically perturbed bean plants. Physiol. Plant. 62:289–296.

Bond, T.E., and D.B. Laster. 1974. Influence of windbreaks on feedlot cattle in the Midwest. Trans. ASAE 17:505–507, 512.

Bowden, J., and G.J.W. Dean. 1977. The distribution of flying insects in and near a tall hedgerow. J. Appl. Ecol. 14:343–354.

Brandle, J.R. 1990. Management of microclimate with windbreaks. p. 61–69. *In* Proc. of the 17th Annual Meeting. Plant Growth Regulator Society of America, St. Paul, MN. 5–9 Aug 1990. Plant Growth Regulator Soc. of Am, Ithaca, NY.

Brandle, J.R., and S. Finch. 1991. How windbreaks work. University of Nebraska Ext. EC 91-1763-B. Univ. of Nebraska, Lincoln.

Brandle, J.R., D.L. Hintz, and J.W. Sturrock. 1988. Windbreak technology. Elsevier Science Publ., Amsterdam.

Brandle, J.R., L. Hodges, and J. Stuthman. 1995. Windbreaks and specialty crops for greater profits. p. 81–91. *In* W.J. Rietveld (ed.). Proc. of the Symp. Agroforestry and sustainable systems, Ft. Collins, CO. 7–10 Aug. 1994. U.S. For. Serv. Gen. Tech. Rep. RM-GTR-261. U.S. For Serv., Rocky Mountain For. and Range Exp. Stn., Ft. Collins, CO.

Brandle, J.R., B.B. Johnson, and T. Akeson. 1992a. Field windbreaks: Are they economical? J. Prod. Agric. 5:393–398.

Brandle, J.R., B.B. Johnson, and D.D. Dearmont. 1984. Windbreak economics: The case of winter wheat production in eastern Nebraska. J. Soil Water Conserv. 39:339–343.

Brandle, J.R., and J. Kort, 1991. WBECON: A windbreak evaluation model: 1. Comparison of windbreak characteristics. p. 129–131. *In* S. Finch and C.S. Baldwin (ed.) Proc. of the 3rd Int. Symp. on Windbreaks and Agroforestry, Ridgetown College, Ridgetown, Ontario, Canada. June 1991. Ridgetown College, Ridgetown, ON.

Brandle, J.R., and H.D. Nickerson. 1996. Windbreaks for snow management. Univ. of Nebraska Coop. Ext. EC 96-1770-X. Univ. of Nebraska, Lincoln.

Brandle, J.R., T.D. Wardle, and G.F. Bratton, 1992b. Opportunities to increase tree planting in shelterbelts and the potential impacts on carbon storage and conservation. p. 157–176. *In* N.R. Sampson and D. Hair (ed.) Forests and global change. Vol.1. Opportunities for increasing forest cover. American Forests, Washington, DC.

Brown, K.W., and N.J. Rosenberg, 1972. Shelter effects on microclimate, growth, and water use by irrigated sugar beets in the Great Plains. Agric. Meteorol. 9:241–263.

Bubenzer, G.D., and G.G. Weis, 1974. Effect of wind erosion on production of snap beans and peas. J. Am. Soc. Hortic. Sci. 99:527–529.

Burel, F. 1996. Hedgerows and their roles in agricultural landscapes. Crit. Rev. Plant Sci. 15(2):169–190.

Cable, T.T., and P.S. Cook. 1990. The use of windbreaks by hunters in Kansas. J. Soil Water Conserv. 45:575–577.

Caborn, J.M. 1957. Shelterbelts and microclimate. Forestry Commission Bull. no. 29. Edinburgh Univ., Edinburgh.

Caborn, J.M. 1965. Shelterbelts and windbreaks. Faber & Faber, London.

Caborn, J.M. 1971. The agronomic and biological significance of hedgerows. Outlook Agric. 6:279–284.

Claflin, L.E., D.L. Stuteville, and D.V. Armbrust. 1973. Wind-blown soil in the epidemiology of bacterial leaf spot of alfalfa and common blight of bean. Phytopathology 63:1417–1419.

Cook, D.I., and D.F. van Haverbeke. 1971. Trees and shrubs for noise abatement. Nebraska Agric. Exp. Stn. Res. Bull. no.246. Univ. of Nebraska, Lincoln.

Corbett, A., and R.E. Plant. 1993. Role of movement in the response of natural enemies to agroecosystem diversification: A theoretical evaluation. Environ. Entomol. 22(3): 519–531.

Corbett, A., and J.A. Rosenheim. 1996. Impact of a natural enemy overwintering refuge and its interaction with the surrounding landscape. Ecol. Entomol. 21:155–164.

Coutts, M.P., and J. Grace. 1995. Wind and trees. Cambridge Univ. Press, Cambridge.

Cunningham, R.A. 1988. Genetic improvement of trees and shrubs used in windbreaks. Agric. Ecosyst. Environ. 22/23:483–498.

Davis, J.E., and J.M. Norman. 1988. Effects of shelter on plant water use. Agric. Ecosyst. Environ. 22/23:393–402.

Deshpande, R.Y., K.G. Hubbard, D.P. Coyne, J.R. Steadman, and A.M. Parkhurst. 1995. Estimating leaf wetness in dry bean canopies as a prerequisite to evaluating white mold disease. Agron. J. 87:613–619.

DeWalle, D.R., and G.M. Heisler 1988. Use of windbreaks for home energy conservation. Agric. Ecosyst. Environ. 22/23:243–260.

Dix, M.E., L. Hodges, J.R. Brandle, R.J. Wright, and M.O. Harrell. 1997. Effects of shelterbelts on the aerial distribution of insect pests in muskmelon. J. Sustain. Agric. 9(2/3):5–24.

Dix, M.E., R.J. Johnson, M.O. Harrel, R.M. Case, R.J. Wright, L. Hodges, J.R. Brandle, M.M. Schoenberger, N.J. Sunderman, R.L. Fitzmaurice, L.J.Young, and K.G. Hubbard. 1995. Influence of trees on abundance of natural enemies of insect pests: A review. Agrofor. Syst. 29:303–311.

Drew, R.L.K. 1982. The effects of irrigation and of shelter from wind on emergence of carrot and cabbage seedlings. J. Hortic. Sci. 57:215–219.

Dronen, S.I. 1988. Layout and design criteria for livestock windbreaks. Agric. Ecosyst. Environ. 22/23:231–240.

Droze, W.H. 1977. Trees, prairies, and people: a history of tree planting in the plains states. USDA For. Serv. and Texas Woman's Univ. Press, Denton, TX.

Easson, D.L., E.M. White, and S.J. Pickles. 1993. The effects of weather, seed rate, and cultivar on lodging and yield in winter wheat. J. Agric. Sci. 121:145–156.

Easterling, W.E., C.J. Hays, M.M. Easterling, and J.R. Brandle. 1997. Modeling the effect of shelterbelts on maize productivity under climate change: An application of the EPIC model. Agric. Ecosyst. Environ. 61:163–176.

Elmore, R.W., and R.B. Ferguson. 1999. Mid-season stalk breakage in corn: Hybrid and environmental factors. J. Prod. Agric. 12:293–299.

Erner, Y., and M.J. Jaffe. 1982. Thigmomorphogenesis: the involvement of auxin and abscisic acid in growth retardation due to mechanical perturbation. Plant Cell Physiol. 23:935–941.

Ferber, A.E. 1969. Windbreaks for conservation. USDA-SCS Agric. Inf. Bull. 339. USDA-SCS, Washington, DC.

Finch, S.J. 1988. Field windbreaks: Design criteria. Agric. Ecosyst. Environ. 22/23:215–228.

Forman, R.T.T. 1995. Land mosaics: The ecology of landscapes and regions. Cambridge Univ. Press, Cambridge.

Forman, R.T.T., and J. Baudry. 1984. Hedgerows and hedgerow networks in landscape ecology. Environ. Manage. 8(6):495–510.

Frank, A.B., D.G. Harris, and W.O. Willis. 1974. Windbreak influence on water relations, growth, and yield of soybeans. Crop Sci.14:761–765.

Fryrear, D.W., and J.D. Downes. 1975. Consider the plant in planning wind erosion control systems. Trans. ASAE 18:1070–1072.

George, E.J. 1971. Effect of tree windbreaks and slat barriers on wind velocity and crop yields. USDA-ARS Prod. Res. Rep. no. 121. USDA, Washington, DC.

Grace, J. 1977. Plant response to wind. Academic Press, London.

Grace, J. 1981. Some effects of wind on plants. p. 31–56. *In* J. Grace et al. (ed.). Plants and their atmospheric environment. Blackwell Scientific Publ., Oxford.

Grace, J. 1988. Plant response to wind. Agric. Ecosyst. Environ. 22/23:71–88.

Graham, N.M., F.W. Wainman, K.L. Blaxter, and D.G. Armstrong. 1959. Environmental temperature, energy metabolism, and heat regulation in sheep: 1. Energy metabolism in closely clipped sheep. J. Agric. Sci. 52:13–24.

Greb, B.W. 1980. Snowfall and its potential management in the semiarid central Great Plains. USDA. Res. Sci. Ed. Admin., Western Series no. 18. USDA-ARS, Oakland, CA.

Greb, B.W., and A.L. Black. 1961. Effects of windbreak plantings on adjacent crops. J. Soil Water Conserv. 16(5):223–227.

Hans, T.G. 1987. Effect of shelterbelts on growth, yield, and quality of alfalfa (*Medicago sativa* L.). M.S. thesis. Univ. of Nebraska, Lincoln.

Heisler, G.M., and D.R. DeWalle. 1988. Effects of windbreak structure on wind flow. Agric. Ecosyst. Environ. 22/23:41–69.

Heisler, G.M., and M.E. Dix. 1988. Effects of windbreaks on local distribution of airborne insects. p. 5–12. *In* M.E. Dix and M Harrell (ed.) Proc. of the Insects of Windbreaks and Related Plantings: Distribution, Importance, and Management Conf., Louisville, KY. 6 Dec. 1988. U.S. For. Serv. Gen. Tech. Rep. RM-204. U.S. For. Serv., Rocky Mountain For. and Range Exp. Stn., Ft. Collins, CO.

Hodges, L., and J.R. Brandle. 1996. Windbreaks: An important component in a plasticulture system. HortTechnology 6(3):177–181.

Holmes, C.W., and A.R. Sykes. 1984. Shelter and climatic effects on livestock. p. 19–35. *In* J.W. Sturrock (ed.) Shelter research needs in relation to primary production. The report of the National Shelter Working Party, Wellington, New Zealand. Water Soil Misc. Publ. no. 59. Ministry of Works and Dev., Soil and Water Div. for the Natl. Water and Soil Conserv. Organ.., Wellington, New Zealand.

Hunt, E.R., and M.J. Jaffe. 1980. Thigmomorphogenesis: The interaction of wind and temperature in the field on the growth of *Phaseolus vulgaris*. L. Ann. Bot. (London) 45:665–672.

Huszar, P.C., and S.L. Piper. 1986. Estimating the off-site costs of wind erosion in New Mexico. J. Soil Water Conserv. 41(6):414–416.

Jaffe, M.J. 1976. Thigmomorphogenesis: A detailed characterization of the response of beans *(Phaseolus vulgaris* L.) to mechanical stimulation. Z. Pflanzenphysiol. 77:437–453.

Jairell, R.L., and R.A. Schmidt. 1986. Scale model tests help optimize wind protection and water improvements for livestock. p. 159–161. *In* D.L. Hintz and J.R. Brandle (ed.) Proc. Int. Symp. on Windbreak Technology, 23–27 June 1986. Great Plains Agricultural Council-Forestry Committee. Publ. no. 117. Great Plains Agric. Council, For. Comm., Lincoln, NE.

Jairell, R.L., and R.A. Schmidt. 1992. Harvesting snow when water levels are low. p. 121–124. *In* B. Shafer (ed.) Proc. 60th Western Snow Conf., Jackson, WY. 14–16 Apr. 1992. Colorado State Univ., Ft. Collins, CO.

Jensen, M. 1961. Shelter effect: Investigation into the aerodynamics of shelter and its effects on climate and crops. Danish Technical Press, Copenhagen.

Johnson, H.D. 1965. Environmental temperature and lactation (with special reference to cattle). Int. J. Biometeorol. 9(2):103–116.

Johnson, R.J., and M.M. Beck. 1988. Influences of shelterbelts on wildlife management and biology. Agric. Ecosyst. Environ. 22/23:301–335.

Johnson, R.J., M.M. Beck, and J.R. Brandle. 1991. Windbreaks and wildlife. Univ. of Nebraska Ext. EC 91-1771-B. Univ. of Nebraska, Lincoln.

Johnson, R.J., M.M. Beck, and J.R. Brandle. 1994. Windbreaks for people: The wildlife connection. J. Soil Water Conserv. 49(6):546–550.

Johnson, R.J., J.R. Brandle, R.L. Fitzmaurice, and K.L. Poague. 1993. Vertebrates for biological control of insects in agroforestry systems. p. 77–84. *In* Proc. of the 44th Annual Meeting on Biological Control of Forest Pests in the Great Plains: Status and Needs, Bismark, ND. 13–16 July 1992. GPAC Publ. no. 145. Great Plains Agric. Council, For. Comm., Frago, ND.

Jones, D.D., W.H. Friday, and S.S. DeForest. 1983. Wind and snow control around the farm. North Central Regional Ext. Publ. no.191. North Central Regional Ext., West Lafayette, IN.

Jordan, D.J., T. Klopfenstein, J. Brandle, and M. Klemesrud. 1997. Cornstalk grazing in protected and unprotected fields. p. 24. *In* 1997 Nebraska Beef Report. Univ. of Nebraska MP 67. Univ. of Nebraska, Lincoln.

Kahn, B.A., K.E. Conway, and C.G. Fisher. 1986. Effects of wirestem, wind injury, and iprodione on yields of six broccoli cultivars. HortScience 21:1136–1139.

Kartchner, R.J. 1980. Effects of protein and energy supplementation of cows grazing native winter range forage on intake and digestibility. J. Anim. Sci. 51:432–438.

Kenny, W.A. 1987. A method for estimating windbreak porosity using digitized photographic silhouettes. Agric. Forest Meteorol. 39:91–94.

Kido, H., D.L. Flaherty, D.F. Bosch, and K.A. Valero. 1984. French prune trees as overwintering sites for the grape leafhopper egg parasite. Am. J. Enol. Viticul. 35:156–160.

Konstantinov, A.R., and L.R. Struzer. 1965. Shelterbelts and crop yields. Translated from Russian by Israel Program for Scientific Translations. U.S. Dep. of Commerce. Clearinghouse for Federal Scientific Technical Information, Springfield, VA.

Kort, J. 1988. Benefits of windbreaks to field and forage crops. Agric. Ecosyst. Environ. 22/23:165–190.

Kort, J., and J.R. Brandle. 1991. WBECON: A windbreak evaluation model: 2. Economic returns from a windbreak investment in the Great Plains. p. 131–134. *In* S. Finch and C.S. Baldwin (ed.) Proc. of the 3rd Int. Symp. on Windbreaks and Agroforestry, Ridgetown College, Ridgetown, Ontario, Canada. June 1991, Ridgetown College, Ridgetown.

Kreutz, W. 1952a. Der Windschutz. Windschutztechnik, klima und bodenertrag (The windshelter. Techniques, climate and yield of crops). Ardey-Verlag, Dortmund (cited in van Eimern et al., 1964).

Kreutz, W. 1952b. Die bedeutung des windschutzes fur den Tabakanbau. (The importance of windbreaks for tobacco growing.) Der Deutsche Tabakbau 32:(11)93–95.

Lehane, J.J., and K.F. Nielson. 1961. The influence of field shelterbelts on climatic factors, soil drifting, snow accumulation, soil moisture and grain yields. Mimeo. Report of the Canada Dep. of Agric. Exp. Farm, Swift Current, Saskatchewan.

Lemon, E. 1970. Gaseous exchange in crop stands. p. 117–137. *In* J.D. Eastin et al. (ed.) Physiological aspects of crop yield. ASA and CSSA, Madison, WI.

Lewis, T. 1965. The effects of an artificial windbreak on the aerial distribution of flying insects. Annu. Appl. Biol. 55:503–512.

Lewis, T. 1970. Patterns of distribution of insects near a windbreak of tall trees. Annu. Appl. Biol. 65:213–220.

Lewis, T., and G.C. Dibley. 1970. Air movement near windbreaks and a hypothesis of the mechanism of the accumulation of airborne insects. Annu. Appl. Biol. 66:477–484.

Lewis, T., and B.D. Smith. 1969. The insect faunas of pear and apple orchards and the effect of windbreaks on their distribution. Annu. Appl. Biol. 64:11–20.

Liptay, A. 1987. Field survival and establishment of tomato transplants of various age and size. Acta Hortic. 220:203–209.

Loeffler, A.E., A.M. Gordon, and T.J. Gillespie. 1992. Optical porosity and windspeed reduction by coniferous windbreaks in Southern Ontario. Agrofor. Syst. 17:119–133.

Lowry, W.P. 1967. Weather and life: An introduction to biometeorology. Academic Press, New York.

Lyles, L. 1988. Basic wind erosion processes. Agric. Ecosyst. Environ. 22/23:91–102.

Lyles, L., J. Tatarko, and J.D. Dickerson. 1984. Windbreak effects on soil water and wheat yield. Trans. ASAE 20:69–72.

Malechek, J.C., and B.M. Smith. 1976. Behavior of range cows in response to winter weather. J. Range Manage. 29:9–12.

Marshall, E.J.P. 1967. The effect of shelter on the productivity of grasslands and field crops. Field Crop Abstracts 20:1–14.

Marshall, E.J.P. 1988. The ecology and management of field margin floras in England. Outlook Agric. 17(4):178–182.

Mattis, G.Y. 1988. Scientific achievements in agricultural afforestation in the USSR. p. 98–104. *In* Proc. of the Great Plains Agricultural Council Forestry Committee, Regina, Saskatchewan. 27–30 June 1988. GPAC Publ. no. 126. Great Plains Agric. Council For. Comm., Indian Head, SK.

McAneney, K.J., and M.J. Judd. 1987. Comparative shelter strategies for kiwi fruit: A mechanistic interpretation of wind damage measurements. Agric. Forest Meteorol. 39:240–255.

McNaughton, K.G. 1983. The direct effect of shelter on evaporation rates: Theory and an experimental test. Agric. Forest Meteorol. 29:125–136.

McNaughton, K.G. 1988. Effects of windbreaks on turbulent transport and microclimate. Agric. Ecosyst. Environ. 22/23:17–40.

McNaughton, K.G. 1989. Micrometeorology of shelterbelts and forest edges. Phil. Trans. R. Soc. London B 324:351–368.

Michailides, T.J., and D.P. Morgan. 1993. Wind scab of French prune: Symptomology and predisposition to preharvest and postharvest fungal decay. Plant Dis. 77:90–93.

Miller, J.M., M. Bohm, and H.A. Cleugh. 1995. Direct mechanical effects of wind on selected crops: A review. Ctr. for Environ. Mechanics ACT. Tech. Rep. no. 67. Ctr. for Environ. Mechanics, Canberra, Australia.

Mitchell, C.A. 1977. Influence of mechanical stress on auxin stimulated growth of excised pea stem sections. Physiol. Plant. 41:129–134.

Monteith, J.L.. 1981. Coupling of plants to the atmosphere. p. 1–29. *In* J. Grace et al. (ed.) Plants and their atmospheric environment. Blackwell Scientific Publ., Oxford.

Monteith, J.L., 1993. The exchange of water and carbon by crops in a Mediterranean climate. Irrig. Sci. 14:85–91.

Moran, J.M., and M.D. Morgan. 1986. Meteorology: The atmosphere and the science of weather. Burgess Publ., Edina, MN.

Morris, C., T. Klopfenstein, J. Brandle, R. Stock, D. Shain, and M. Klemesrud. 1996. Winter calf grazing and field windbreaks. 1996 Nebraska Beef Rep. Univ. of Nebraska MP 66-A:44. Univ. of Nebraska, Lincoln.

Naughton, G.C., and S.W. Capels. 1982. Root-pruning Osage-orange windbreaks. Cont. no. 82-419-A. Kansas. Agric. Exp. Stn., Manhattan, KS.

Nobel, P.S. 1981. Wind as an ecological factor. p. 475–500. *In* O.L. Langeet al. (ed.). Physiological plant ecology I: Responses to the physical environment. Encyclopedia of Plant Physiology New Series Vol. 12A. Springer-Verlag, Berlin.

Norton, R.L. 1988. Windbreaks: Benefits to orchard and vineyard crops. Agric. Ecosyst. Environ. 22/23:205–213.

Ogbuehi, S.N., and J.R. Brandle. 1981. Influence of windbreak shelter on light interception, stomatal conductance, and carbon dioxide exchange rate of soybean, *Glycine max* (L.) Merrill. Trans. Nebraska Acad. Sci. 9:49–54.

Ogbeuhi, S.N., and J.R. Brandle 1982. Influence of windbreak-shelter on soybean growth, canopy structure, and light relations. Crop Sci. 22:269–273.

Pasek, J.E. 1988. Influence of wind and windbreaks on local dispersal of insects. Agric. Ecosyst. Environ. 22/23:539–554.

Perry, K.B., T.C. Wehner, and G.L. Johnson. 1986. Comparison of 14 methods to determine heat unit requirements for cucumber harvest. HortScience 21(3):419–423.

Pitcairn, C.E.R., C.E. Jeffree, and J. Grace. 1986. Influence of polishing and abrasion on the diffusive conductance of leaf surfaces of *Festuca arundinacea* Schreb. Plant Cell Environ. 9:191–196.

Pimental, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science (Washington, DC) 267:1117–1123.

Pinthus, M.J. 1973. Lodging in wheat, barley, and oats: The phenomenon, its causes, and preventive measures. Adv. Agron. 25:209–263.

Pohlan, J.N., M. Vazquez, and A.M.E. Garcia. 1986. The influence of biotic and abiotic factors on external and internal fruit quality of Cuban orange. Hortic. Abstr. Vol. 56, no.3752. Commonwealth Agricultural Bureau, East Malling, England.

Pohronezhy, K., M. Hewitt, J. Infante, and L. Datnoff. 1992. Wind and wind-generated sand injury as factors in infection of pepper by *Xanthomonas campestris* pv *vesicatoria*. Plant Dis. 75:1036–1039.

Preez, N.D. de. 1986. The economic advantage of artificial windbreaks in plum cultivation on Tatura trellis system in a windy environment. Deciduous Fruit Grower 36:59–65.

Primault, B. 1979. Optimum climate for animals. p. 182–189. *In* J. Seemannet al. (ed.) Agrometeorology. Springer-Verlag, Berlin.

Quam, V.C., J. Gardner, J.R. Brandle, and T.K. Boes. 1991. Windbreaks for sustainable agricultural systems. Univ. of Nebraska Coop. Ext. EC 91-1772-X. Univ. of Nebraska, Lincoln.

Quam, V.C., L. Johnson, B. Wight, and J.R. Brandle. 1994. Windbreaks for livestock production. Univ. of Nebraska Coop. Ext. EC 94-1766-X. Univ. of Nebraska, Lincoln.

Raine, J.K., and D.C. Stevenson. 1977. Wind protection by model fences in simulated atmospheric boundary layer. J. Ind. Aerodyn. 2:159–180.

Rasmussen, S.D., and C.A. Shapiro. 1990. Effects of tree root-pruning adjacent to windbreaks on corn and soybeans. J. Soil Water Conserv. 45(5):571–575.

Read, R.A. 1964. Tree windbreaks for the central Great Plains. U.S. For. Serv., Rocky Mountain For. and Range Exp. Stn. Agric. Handb. 250. U.S. For. Serv., Rocky Mountain For and Range Exp. Stn., Ft. Collins, CO.

Ribaudo, M.O. 1986. Targeting soil conservation programs. Land Econ. 62(4):402–411.

Riechert, S.E., and T. Lockley. 1984. Spiders as biological control agents. Annu. Rev. Entomol. 29:299–320.

Robbins, C. 1976. Economics of windbreaks and our cattle industry. p. 107–108. *In* R.W. Tinus (ed.) Proc. of the Symp. on Windbreaks: What are they worth?, Dodge City, KS. 22–24 June 1982. GPAC Publ. no. 78. Great Plains Agric. Council For. Comm., Manhattan, KS.

Rodriquez, R., N. Del. Valle, W. Arango, R. Torres, and M. Fernandez. 1986. Effect of shelterbelts on yields in Valencia late orange [*Citrus sinensis* (L.) Osbeck] plantations. Centro. Agricola. 12:71–80. (Hortic. Abstracts Vol. 56, no. 6469.)

Rosenberg, N.J. 1966. Microclimate, air mixing, and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. Agric. Meteorol. 3:197–224.

Rosenberg, N.J. 1975. Windbreak and shelter effects. p. 108–134. *In* L.P. Smith (ed.). Progress in Biometeorology. Swets & Zeitlinger, Amsterdam.

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: The biological environment. 2nd ed. John Wiley, New York.

Scholten, H. 1988. Snow distribution on crop fields. Agric. Ecosyst. Environ. 22/23:363–380.

Schmidt, R.A., Jr. 1972. Sublimination of wind-transported snow-a model. U.S. For. Serv. Res. Pap. RM-90. U.S. For. Serv., Rocky Mountain Forest and Range Exp. Stn., Ft. Collins, CO.

Schmidt, R.A., R.L. Jairell, J.R. Brandle, E.S. Takle, and I.V. Litvina. 1995a. Windbreak shelter as a function of wind direction. p. 269–274. *In* Proc. of the 9th Meteorological Observations and Instrumentation Symp., Charlotte, NC. 27–31 Mar. 1995. Am. Meteorological Soc., Charlotte, NC.

Schmidt, R.A., E.S. Takle, J.R. Brandle, and I.V. Litvina. 1995b. Static pressure at the ground under atmospheric flow across a windbreak. p. 517–520. *In* Proc. 11th Symp on Boundary Layers and Turbulence, 27–31 Mar. 1995. Am. Meteorological Soc., Charlotte, NC.

Shah, S.R.H. 1970. The influence of windbreak on the development and yield of horticultural crop (genus *Fragaria*). Agric. Pakistan 21(2):137–158.

Shaw, D.L. 1988. The design and use of living snowfences in North America. Agric. Ecosyst. Environ. 22/23:351–362.

Shaw, D.L., 1991. Living snow fences: Protection that just keeps growing. Colorado Interagency Living Snow Fence Program. Colorado State Univ., Ft. Collins, CO.

Shi, Z., and Z. Gao. 1986. On the ecological efficiency of shelterbelt network and its yield increasing effect in paddy fields. J. Ecol. 5(2):10–14.

Simons, J.N. 1957. Effects of insecticides and physical barriers on field spread of pepper veinbanding mosaic virus. Phytopathology 47:139–145.

Skidmore, E.L. 1966. Wind and sandblast injury to seedling green beans. Agron. J. 58:311–315.

Skidmore, E.L., L.J. Hagen, D.G. Maylor, and I.D. Teare. 1974. Winter wheat response to barrier-induced microclimate. Agron. J. 66:501–505.

Slosser, J.E., and E.P. Boring, III. 1980. Shelterbelts and boll weevils: a control strategy based on management of overwintering habitat. Environ. Entomol. 9:1–6.

Solomon, M.G. 1981. Windbreaks as a source of orchard pests and predators. p. 273–283. *In* J.M. Thresh (ed.) Pests, pathogens, and diseases. Pitman Books Ltd., London.

Southwood, T.R.E., and M.J. Way. 1970. Ecological background to pest management. p. 6–29. *In* R.L. Rabb and F.E. Guthrie (ed.) Proc. of the Conf. on Concepts of Pest Management, Raleigh, NC. 25–27 Mar. 1970. North Carolina State Univ., Raleigh, NC.

Stoeckeler, J.H. 1962. Shelterbelt influence on Great Plains field environment and crops. USDA For. Serv. Prod. Res. Rep. no. 62. U.S. Gov. Print. Office, Washington, DC.

Stoeckeler, J.H., and R.A. Williams. 1949. Windbreaks and shelterbelts. p. 191–199. *In* A. Stefferud (ed.) Trees Yearbook of Agriculture. U.S. Gov. Print. Office, Washington, DC.

Strupl, M. 1953. Zebne kulisy na polich J.Z.D. a CSSR (Green windbreaks on the fields of the State Farms of the Czech. S.S.R. [in Czech.] Cited in van Eimern et al., 1964).

Sturrock, J.W. 1981. Shelter boosts crop yield by 35 percent: Also prevents lodging. NZ J. Agric. 143:18–19.

Sturrock, J.W. 1984. The role of shelter in irrigation and water use. p. 79–86. *In* J.W Sturrock (ed.) Shelter research needs in relation to primary production. The Report of the National Shelter Working Party Ministry of Works and Dev., Water and Soil Misc. Publ. no. 94. National Shelter Working Party Ministry of Works and Dev., Water and Soil, Wellington, New Zealand.

Sturrock, J.W. 1988. Shelter: Its management and promotion. Agric. Ecosyst. Environ. 22/23:1–13.

Suratman, M.N. 1996. Growth and yield of snap beans (*Phaseolus vulgaris* L.) as affected by shelterbelts and planting dates. M.S. thesis. Univ. of Nebraska, Lincoln.

Tabler, R.D. 1975. Estimating the transport and evaporation of blowing snow. p. 85–104. *In* Proc. of the Symp. on Snow Management on the Great Plains, Bismark, ND. 29 July 1975. GPAC Publ. 73. Great Plains Agric. Council, Res. Comm., Lincoln, NE.

Tabler, R.D., and K.L. Johnson. 1971. Snow fences for watershed management. p. 116–121. *In* Proc. of the Symp. on Snow and ice in relation to wildlife and recreation, Ames, IA. 11–12 Feb. 1971. Iowa Coop. Wildlife Res. Unit, Ames, IA.

Takle, E.S., H. Wang, R.A. Schmidt, J.R. Brandle, and R.L. Jairell. 1997. Pressure perturbation around shelterbelts: Measurements and model results. p. 563–564. *In* 12th Symp. on Boundary Layers and Turbulence, Vancover, BC. July 1997. Am. Meteorol. Soc., Vancouver, BC.

Taksdal, G. 1992. Windbreak effects on the carrot crop. Acta Agric. Scand. 42:177–183.

Tibke, G. 1988. Basic principles of wind erosion control. Agric. Ecosyst. Environ. 22/23:103–122.

Ticknor, K.A. 1988. Design and use of field windbreaks in wind erosion control systems. Agric. Ecosyst. Environ. 22/23:123–132.

Timofeev, V.P. 1951. Russian experience in field-protecting afforestation. Sbornik AN SSSR no. 1. p. 5–37. Translated from Russian by the Israel Program for Scientific Translations. PST Cat. no. 181 (OTS 61-11428). U.S. Dep. of Commerce, Washington, DC.

Umland, E.R., 1979. Root pruning as a management technique. p. 101–111. *In* R.J. Gavit (ed.) Proc. of the Windbreak Management Workshop, Norfolk, NE. 23–25 Oct. 1979. GPAC Publ. 92. Great Plains Agric. Council, Lincoln, NE.

van Eimern, J., R. Karschon, L.A. Razumava, and G.W. Robertson. 1964. Windbreaks and shelterbelts. Tech. Note no. 59. WMO no.147.TP.70. World Meteorological Organization, Geneva, Switzerland.

van Emden, H.F. 1965. The role of uncultivated land in the biology of crop pests and beneficial insects. Sci. Hortic. 17:121–136.

van Gardingen, P., and J. Grace. 1991. Plants and wind. Adv. Bot. Res. 18:189–253.

Waister, P.D. 1972a. Wind as a limitation on the growth and yield of strawberries. J. Hortic. Sci. 47:411–418.

van Gardingen, P., J. Grace, and C.E. Jeffree. 1991. Abrasive damage by wind to the needle surfaces of *Picea sitchensis* (Bong.) Carr. and *Pinus sylvestris* L. Plant Cell Environ. 14:185–193.

Waister, P.D. 1972b. Wind damage in horticultural crops. Hortic. Abstr. 42:609–615.

Wang, H., and E.S. Takle. 1994. Mesoscale and boundary-layer flows over inhomogeneous surfaces consisting of porous obstacles. p. 262–265. *In* 6th Conf. on Mesoscale Processes. Am. Meteorol. Soc., Portland, OR. 18–22 July 1994. Am. Meteorological Soc., Boston.

Wang, H., and E.S. Takle. 1995a. A numerical simulation of boundary-layer flows near shelterbelts. Boundary-Layer Meteor. 75:141–173.

Wang, H., and E.S. Takle. 1995b. Numerical simulations of shelterbelt effects on wind direction. J. Appl. Meteor. 34:2206–2219.

Wang, H., and E.S. Takle. 1996a. On shelter efficiency of shelterbelts in oblique wind. Agric. For. Meteor. 81:95–117.

Wang, H., and E.S. Takle. 1996b. On three-dimensionality of shelterbelt structure and its influences on shelter effects. Boundary-Layer Meteorol. 79:83–105.

Wang, H., and E.S. Takle. 1997. Model simulated influences of shelterbelt shape on wind sheltering efficiency. J. Applied Meteorol. 36:695–704.

Webster, A.J.F. 1970a. Direct effects of cold weather on the energetic efficiency of beef production in different regions of Canada. Can. J. Anim. Sci. 50:563–573.

Webster, A.J.F. 1970b. Effects of cold outdoor environments on the energy exchanges and productive efficiency of beef cattle. p. 30–38. *In* Annual Feeder's Day Report. Univ. of Alberta, Alberta, Canada.

Wight, B. 1988. Farmstead windbreaks. Agric. Ecosyst. Environ. 22/23:261–280.

Wight, B., T.K. Boes, and J.R. Brandle. 1991. Windbreaks for rural living. Univ. of Nebraska Ext. EC 91-1767-X,. Univ. of Nebraska, Lincoln.

Williams, J.R., L. Lyles, and G.W. Langdale. 1981. Soil erosion effects on soil productivity: A research perspective. J. Soil Water Conserv. 36:82–90.

Wilson, J.D. 1985. Numerical studies of flow through a windbreak. J. Wind Eng. Ind. Aerodyn. 21:119–154.

Winchester, C.F. 1964. Symposium on growth: Environment and growth. J. Anim. Sci. 23:254–264.

Woodruff, N.P., L. Lyles, L. Siddoway, and D.W. Fryrear. 1972. How to control wind erosion. USDA-ARS Agric. Info. Bull. 354. USDA, Washington, DC.

Woodruff, N.P., and A.W. Zingg. 1953. Wind tunnel studies of shelterbelt models. J. For. 53:173–178.

Woodruff, N.P., and A.W. Zingg. 1955. A comparative analysis of wind-tunnel and atmospheric air-flow patterns about single and successive barriers. Trans. Am. Geophys. Union 36:203–208.

Yahner, R.H. 1982a. Avian nest densities and nest-site selection in farmstead shelterbelts. Wilson Bull. 94:156–175.

Yahner, R.H. 1982b. Avian use of vertical strata and plantings in farmstead shelterbelts. J. Wildl. Manage. 46:50–60.

Yahner, R.H. 1982c. Microhabitat use by small mammals in farmstead shelterbelts. J. Mammal. 63(3):440–445.

Young, B.B. 1983. Ruminant cold stress: Effect on production. J. Anim. Sci. 57:1601–1607.

Young, B.A., and R.J. Christopherson. 1974. Some effects of winter on cattle. p. 3–6. *In* Annual Feeder's Day Report. Univ. of Alberta, Alberta, Canada.

Zachar, D. 1982. Soil erosion. Elsevier, Amsterdam.

Zhang, D. 1994. Response of cantaloupe to wind protection: Evaluations and modelling. M.S. thesis. Univ. of Nebraska, Lincoln.

Zhang, H., and J.R. Brandle, 1997. Leaf area development of corn as affected by windbreak shelter. Crop Sci. 37:1253–1257.

Zhang, H., J.R. Brandle, G.E. Meyer, and L. Hodges. 1995. The relationship between open windspeed and windspeed reduction in shelter. Agrofor. Syst. 32:297–311.

Zhao, Z., L. Xiao, T. Zhao, and H. Zhang. 1995. Windbreaks for agriculture. China Forestry Publ. House, Beijing (in Chinese).

Zohar, Y., and J.R. Brandle. 1978. Shelter effects on growth and yield of corn in Nebraska. Israel For. Assoc. 28:1–4 (in Hebrew).

From: Garrett, H.E., W.J. Rietveld and R.F. Fisher (eds). 2000, North American Agroforestry: An Integrated Science and Practice, American Society of Agronomy, Inc. Madison Wisconsin. 402 pages.