1-1-2008

Ecological Development and Function of Shelterbelts in Temperate North America

C. W. Mize
Iowa State University, Ames, Iowa

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

M. M. Schoneberger
National Agroforestry Center, USFS Southern Research Station, Lincoln, NE, USA

G. Bentrup
National Agroforestry Center, USFS Southern Research Station, Lincoln, NE, USA

Mize, C. W.; Brandle, James R.; Schoneberger, M. M.; and Bentrup, G., "Ecological Development and Function of Shelterbelts in Temperate North America" (2008). *USDA Forest Service / UNL Faculty Publications.* Paper 40.
http://digitalcommons.unl.edu/usdafsfacpub/40

Chapter 3
Ecological Development and Function of Shelterbelts in Temperate North America

C.W. Mize[1,*], J.R. Brandle[2], M.M. Schoeneberger[3], and G. Bentrup[3]

Introduction

As the world's population continues to expand, the pressure on farmland, both from expansion of urban areas (United Nations, 2002) and from a need to produce more food and fiber (Hewitt and Smith, 1995; Gardner, 1996), will increase. In direct competition with the increasing demand for more food and fiber is a growing public desire for conservation of natural systems and a focus on quality of life issues (Matson et al., 1997; Jackson and Jackson, 2002; Pimentel et al., 2004).

These two societal needs are clearly linked. Unfortunately, they are antagonistic, not complementary. The impacts of intensive agriculture, needed to increase food and fiber production, extend well beyond the field border (CAST, 1999). Similarly, many species found in natural systems, both flora and fauna, do not remain within protected reserves provided for their benefit and are impacted by land-use decisions in surrounding areas. A challenge to resource managers is to develop management strategies that support both sets of needs and lead to the "right compromise" between production agriculture, sustainability, and conservation of native floral and fauna (Mineau and McLaughlin, 1996; Swift et al., 2004).

Shelterbelts and other types of linear forest systems, such as riparian buffer strips (Benton et al., 2003), can support both sets of needs and be a link between production agriculture and protection of biodiversity. These systems, both planted and naturally occurring, provide various ecosystem services (Guertin et al., 1997). While this review focuses on shelterbelts, many of the principles discussed apply to other linear forest systems.

---

[1] Department of Natural Resource Ecology and Management, Iowa State University, Ames, IA, USA

[2] School of Natural Resources, University of Nebraska, Lincoln, NE, USA

[3] National Agroforestry Center, USFS Southern Research Station, Lincoln, NE, USA

[*] Corresponding author: E-mail: cwmize@iastate.edu

S. Jose and A.M. Gordon (eds.), *Toward Agroforestry Design: An Ecological Approach.*
Springer 2008

Shelterbelts, linear arrays of trees and shrubs planted to create a range of benefits, are a major category of agroforestry practices (Buck et al., 1999). Shelterbelts have been managed for centuries to alter environmental conditions in agricultural situations and recently have been used in rural/urban interfaces, providing numerous economic, social, and environmental benefits (Droze, 1977; Cook and Cable, 1995; Schoeneberger et al., 2001). Shelterbelts are called by different names (windbreaks, hedgerows, fence rows), depending upon their use, region, or preference of the individual. For simplicity we have chosen to use the terms interchangeably.

Shelterbelts produce a variety of economic benefits. They protect crop fields by reducing wind erosion, improving crop water use and increasing crop yields and economic returns (Kort, 1988). They protect livestock from harsh winter conditions, reducing animal stress and improving animal health. In addition, they reduce feed requirements, which reduces input costs and increases profits (Dronen, 1988). Around farm buildings they protect living and working areas, making outside work less stressful (Wight, 1988), and they reduce air exchange rates in buildings, which reduces heating and cooling costs (DeWalle and Heisler, 1988). Living snow fences can be used to manage drifting snow. Dense shelterbelts trap snow close to the shelterbelt, reducing snow removal costs from adjacent roadways and improving road safety (Shaw, 1988). Porous field shelterbelts alter windflow so that snow is distributed relatively uniformly across a field, providing critical soil moisture for next year's crop (Scholten, 1988). Urban shelterbelts are used at the rural/urban interface to provide many of the previously described services (Josiah et al., 1999), as well as serving as visual and odor barriers (Schoeneberger et al., 2001). Cook and Cable (1995) describe shelterbelts as designed corridors that add scenic beauty to agricultural landscapes. These benefits and others are well documented in numerous original articles and are summarized in a number of comprehensive reviews (Brandle et al., 1988, 2000, 2004; Burke, 1998; Caborn, 1957, 1971; Grace, 1977; Cleugh et al., 2002).

In addition to the many direct economic benefits of shelterbelts, there are numerous environmental impacts, both positive and negative, that result from shelterbelt technology. Although not easily quantified, these environmental responses often have economic implications. Issues related to wildlife habitat and biodiversity serve as examples of the difficulty in quantifying the economic value of shelterbelts. Shelterbelts provide critical habitats for many species in areas dominated by large monoculture fields of agricultural crops, which, although difficult to assign a value, is a positive value for society, but shelterbelts also provide travel corridors for encroachment of undesirable plant and animal species, which represents a difficult to assign negative value to individual landowners and society (Forman, 1995). Shelterbelts can attract bird species that feed on crop pests, reducing insecticide requirements and costs (Trinka et al., 1990; Dix et al., 1995), but they also can attract flocks of bird species that feed on crops, reducing yield and profit (Johnson and Beck, 1988; Bollinger and Caslick, 1985). Predators, including humans, recognize the advantages of hunting along a shelterbelt (Cable and Cook, 1990). Predator–prey relationships of crop pests and natural predators may be influenced, positively or negatively, by the availability of overwintering habitat (Slosser and Boring, 1980).

Control of wind and water erosion by systems of shelterbelts has far reaching consequences on the offsite costs associated with erosion, including air and water quality, which impact human health (Huszar and Piper, 1986; Williams and Young, 1999). These social and environmental effects clearly have economic values, but the values are difficult to assign with the size and direction (positive or negative) of the value often dependent on the individual.

All of these impacts arise from shelterbelt technology. The ecological role and function of shelterbelts, which produce a range of benefits and problems, are the subjects of this review. The review starts with a discussion of the three phases of a shelterbelt‘s life cycle: establishment, functional, and mature/senescent. Following that, the ecological functions of a shelterbelt as a corridor and the implications for management are discussed. Although shelterbelts are composed of trees and/or shrubs, we will, for simplicity, only refer to trees during the discussion. In most cases when we mention trees, it should be read as trees and shrubs.

Establishment Phase

The establishment phase begins with site preparation in the year prior to planting and lasts for 5–10 years, depending upon the growth rate of the species and overall growing conditions. Shelterbelts are usually established on agricultural lands, either crop fields or pastures. For crop fields, there often is no site preparation other than cultivation after the final harvest. For pastures, site preparation often involves using herbicides to kill all vegetation in the entire shelterbelt zone – the land occupied by the shelterbelt – or to kill 1–2 m wide strips into which trees will be planted. Sometimes cultivation, alone or after herbicide application, is used for site preparation of pastures. Typical site preparation results in a clean cultivated strip of bare soil or a strip of dead grass into which trees will be planted (Ritchie, 1988; Schroeder, 1988). The ecological consequences of site preparation are minimal outside of the shelterbelt zone.

As shelterbelts are generally planted into agricultural soils that usually have abundant soil seed banks (Leck et al., 1989), the shelterbelt zone can be quickly populated by annual and perennial plants, creating a diverse stand in early stages of succession. Such vegetation can shade seedlings and transpire considerable quantities of soil moisture, which will negatively affect survival and growth of a newly planted shelterbelt. As a result, weed control is an important management tool for shelterbelt establishment (Schroeder, 1988). Effective weed control reduces competition for moisture, nutrients, and light and generally results in high seedling survival and good seedling growth (Ritchie, 1988).

Each weed control technique will create different site conditions and thus different habitats for both plant and animal species. With complete weed control the microenvironment of newly planted shelterbelts tends to be hotter and drier than surrounding areas. Litter accumulation and plant diversity are minimal. Habitat niches are few, and use by wildlife is generally low (Yahner, 1983a, b). With less complete weed control, more weeds develop, and the microenvironment changes. This increases the habitat value for birds, small mammals, and insects and may result in slowed tree growth (Schroeder, 1988) and increased animal damage to young seedlings (Timm, 1988).

There are two approaches to control weeds with herbicides in newly planted shelterbelts: pre-emergents and post-emergents. Pre-emergents produce essentially bare soil, while post-emergents result in soil covered with a small amount of dead weeds. When either technique is effectively applied, the shelterbelt zone remains relatively weed free (Woeste et al., 2005).

Weed control using cultivation affects the vegetation, soil structure, and microorganisms associated with surface layers (Brady and Weil, 2000). Cultivation may add organic matter by incorporating weeds, but it also increases oxidation of soil organic matter (Lai et al., 1997). Cultivation increases evaporation from the soil surface and leads to loss of soil moisture in the shelterbelt zone.

Mowing is a commonly used, although not particularly effective, form of weed control (Schroeder, 1988). While preventing weeds from competing with trees for light, mowing does little to reduce moisture competition and can stimulate weed growth. Mowing strongly influences the species composition of weeds, favoring grass species that are well adapted to mowing, which can be very competitive with trees when mowing is stopped. Mowing reduces cover, which makes the shelterbelt zone less desirable as wildlife habitat. Reduced cover exposes rodents to predation by raptors, which often leads to reduced damage to newly planted trees. On sites where erosion is a potential problem, mowing leaves the soil protected while partially controlling weeds (Read, 1964).

Controlling weeds with mulches is probably the most environmentally safe way to provide weed control (Stepanek et al., 2002). Mulches may be inorganic, such as plastics or landscape fabrics, or organic, such as wood chips, straw, or hay. The ecological impacts of each type depend on the specific type of mulch used. Black plastic mulch controls weeds but is impervious to water and raises soil temperature (Hodges and Brandle, 1996). The color of plastic mulch affects reflectance from the surface and soil temperatures, which influences root growth (Appleton et al., 1990). Woven black fabric mulches are a better alternative, allowing water to enter the soil profile while controlling weeds. Trees respond positively to both materials.

Using organic mulches (basically litter) will add organic matter to soil, but may reduce available nitrogen if incorporated into the soil (Borland, 1990; Gouin, 1992). Organic mulches improve soil structure and serve as a food source for microorganisms. In contrast to plastic mulch, organic mulches act as insulation and reduce soil temperature fluctuations. In temperate regions of North America this usually means an increase in root activity and growth, especially in the summer and fall. At more northern latitudes (e.g. in the boreal forest region) or at high elevations (alpine systems) lower soil temperatures in the spring may delay root growth and reduce overall tree height (Lahti et al., 2005; Landhausser et al., 2001). In some cases, however, root growth may be shallow, occurring primarily in the litter or mulch layer, decreasing the ability of roots to tap deeper water resources and potentially increasing susceptibility to extended drought periods (Stuckey, 1961; Watson, 1988).

The type of organic mulch can be critical. Grass or crop residue mulches break down quickly and need to be replenished on a regular basis. A layer of larger bark or wood chips, 8–12 cm deep will last 3–5 years. Mulching with grass or crop residue tends to favor small rodents, which may result in girdling of trees. Mulching with larger pieces of bark or wood chips reduces the impact of rodent populations (Borland and Weinstein, 1989).

In some areas, trees are irrigated until they are well established. Using drip irrigation may encourage localized root systems and lead to reduced root biomass (Klepper, 1991), leaving a large tree with an unfavorable root to shoot ratio when the water source is removed, i.e. the root system may be too small to support the aboveground portion (Romero et al., 2004). Sprinkle irrigation applies water to the entire shelterbelt zone, leading to additional weed competition and potentially to reduced tree growth.

During the establishment phase, the trees in a shelterbelt develop from small seedlings to trees that are 3–5 m tall. Individual trees are clearly evident at the beginning of the establishment period but will begin to grow together by the end of the period. Spacing between trees determines how soon closure occurs and influences the degree of competition between trees and the amount of radiation reaching the surface. If spacing and weed control are adequate, trees will have crowns that extend from the top of the tree to near the ground. Consequently, shelterbelt trees tend to have a very different morphology from most forest grown trees. Forest grown trees often grow in more crowded conditions, which results in shading and death of lower branches and individual trees. For a given soil and climate, forest grown trees will tend to be taller, have shorter crowns and smaller diameters than comparably aged shelterbelt trees (Zhou et al., 2002; 2005). Unlike forest grown trees, shelterbelt trees retain their lower branches due to the linear nature of the planting and the greater availability of radiation.

Spacing between trees within the row varies with design objective and local site conditions, but in general, spacings of 2–5 m for most tree species and 1–2 m for most shrub species are typical. Closer spacings reduce the time necessary for development of a barrier or until canopy closure but may shorten the overall life span of the windbreak. In contrast, wider spacings increase the length of time required to form a barrier and increase the life span of the shelterbelt.

In either case, as the canopy closes and the barrier forms, light penetration into a shelterbelt decreases. In multiple row shelterbelts, interior branches begin to die back, similar to a forest situation but remain an important part of overall windbreak structure until they abscise (Brandle et al., 2004). Branch death is affected by the shade tolerance of the tree species and spacing of the trees (Kozlowski and Pallardy, 1997).

Initially, biodiversity in the shelterbelt zone is controlled by what is planted and the extent and type of weed control. Most shelterbelts are composed of several species (2–5), but sometimes will be a single species and occasionally more than five species. Depending upon the level of weed control, this low level of diversity may be retained for 5–10 years. More routinely, weed control is not perfect, and numerous herbaceous species will become established within the shelterbelt zone. Most will originate from the soil seed bank, but others will be blown in by wind or carried in by birds or small mammals. These species will be typical weeds of the local area, including both annual and perennial grasses and broadleaf species. With these weeds will come associated insects and their predators (Dix and Leatherman, 1988; Showler and Greenberg, 2003; Wilson et al., 2004).

The abundance and species composition of the understory will change over time, due to decreasing light levels and increasing moisture competition from trees. As the shelterbelt grows, shade-intolerant species will be replaced with more shade-tolerant species (Hiller, 2004; Sutton, 1992). The understory can be ideal habitat for certain wildlife species and can provide numerous niches for various types of insects (Pasek, 1988). As the understory and tree canopy develop, a litter layer will form, and soil microorganisms occupying the site will change to reflect the changing soil conditions. The formation of a barrier affects windflow, and plant material from adjacent fields may collect in the shelterbelt zone, adding to the litter under the shelterbelt (Johnson and Beck, 1988).

In the typical monoculture field of annual crops, a shelterbelt in the first several years of establishment provides minimal habitat for most wildlife. By the end of the establishment phase, some birds, primarily edge species or generalists, will begin to utilize shelterbelt trees for nesting and for perches (Yahner, 1982; Jobin et al., 2001). As this occurs, seeds from other areas will be carried in and become established in the understory (McArthur and McArthur, 1961). As the understory continues to develop, rodents and other small mammals may begin to utilize the windbreak (Yahner, 1983b; Timm, 1988).

A few thoughts on shelterbelt species selection are in order at this time. Obviously, the species chosen for a shelterbelt will have a large role in determining the ecological impact of the shelterbelt. Soil and climate conditions are usually the most limiting environmental factors in species selection, but other factors, such as landowner preferences and local regulations, may also influence species choice.

Native species are usually best because they are adapted to the growing conditions of the area. There are, however, a number of introduced species that have been used successfully in shelterbelts throughout North America. For example, within the Great Plains region, native conifer species are limited and several European pine species, notably *Pinus sylvestris* and *P. nigra*, are naturalized and used widely. In contrast, most regions have an adequate number of native hardwood species for use in shelterbelts.

Genera, such as spruce (*Picea* spp.) and cedar (either *Juniperus* spp. or *Thuja* spp.), produce dense shade, limiting understory vegetation. Pine (*Pinus* spp.) produces moderate shade, while deciduous species generally produce light to moderate shade depending on canopy structure (Larcher, 1995).

Species composition of a shelterbelt determines the nature of the litter layer, which along with canopy structure, influences understory species composition and use by various insect and small mammal species.

Regardless of the species chosen, each species or group of species has a specific growth form which helps determine shelterbelt structure. Similarly, canopy structure influences windflow and light climate in and around the shelterbelt zone. A single row of conifers will have a very different structure than a single row of deciduous hardwoods (Brandle et al., 2004). Similarly, spacing between trees will influence structure, for example, trees planted on a 2 m spacing will create a different canopy structure than those on a 3 m or 4 m spacing. And multiple row shelterbelts produce an entirely different understory microenvironment than a single row shelterbelt. Most of these differences are minor during the establishment phase, especially early in the establishment phase. As a shelterbelt matures and canopy structure becomes more defined, initial species composition plays a larger row in determining conditions within and around the shelterbelt zone (Heisler and DeWalle, 1988; Zhou et al., 2002, 2005).

Functional Phase

At the transition from establishment to functional phase, crowns of the developing shelterbelt trees will begin to touch, forming a barrier that increases in height with age. Individual trees begin to compete for space, light, moisture, and nutrients. As in a typical forest situation, those species and individuals with the best genetics will be able to most efficiently utilize the resources of the site. But unlike a forest in which the species and individuals that most efficiently utilize resources become dominant, trees in shelterbelts are spaced so that all have adequate space to survive and the potential to develop into large trees. However, like the forest, shelterbelt trees will vary in size, depending on their individual genetics and ability to compete. In addition, soil variations across the landscape will influence tree growth. As the number of rows in the shelterbelt increases, the shelterbelt responds more like a forest. While individual tree growth and survival are important, it is the structure of the shelterbelt as a barrier to windflow that is generally the most important characteristic of a successful shelterbelt (Wang et al., 2001; Zhou et al., 2005).

Shelterbelt structure determines the amount of wind speed reduction that occurs in the vicinity of a shelterbelt. As a result of changes in wind speed and turbulence created by a shelterbelt, microclimate within the sheltered area is altered. In general, exchange rates between the atmosphere and soil and plant surfaces are reduced, and as a result, average daily temperature and humidity are increased slightly in the sheltered area. Detailed discussions of the microclimatic impacts of shelterbelts and the crop responses to these changes have been presented elsewhere (McNaughton, 1988; Brandle et al., 2000, 2004) and are not repeated here. Our focus remains on development of a shelterbelt and its ecological impacts in the shelterbelt zone and within the agroecosystem at the landscape scale.

For single row shelterbelts, canopy structure and shelterbelt orientation are the primary factors determining the light climate near the shelterbelt. For east–west oriented shelterbelts, the north side of the shelterbelt receives primarily diffuse light and will have a lower total radiation load than the south side. On the south exposure, radiation reflected by the shelterbelt will result in slightly higher radiation loads immediately adjacent to the shelterbelt than in areas away from the shelterbelt. The area immediately adjacent to the north side of the shelterbelt is shaded most of the day and tends to be cooler and wetter than the south side, which receives direct sunlight essentially all day. As a result, understory species on the north side tend to more shade tolerant species, while species on the south tend to be shade intolerant and more adaptable to drier sites (Hou et al., 2003; Nieto-Cabrera, 1998).

Single row shelterbelts oriented north–south receive morning sun on the east side and afternoon sun on the west side. A study of soybean response to these conditions indicated greater yields on the east side of the shelterbelt (Nieto-Cabrera, 1998). He attributed the greater yield response on the east side to increased radiation availability during the morning hours when temperatures and water stress levels were lower as opposed to the higher radiation loads on the west side during the afternoon hours when temperatures were higher and water stress levels greater. The understory species along the west edge of the shelterbelt were more drought tolerant than ones on the east side (Brandle and Hiller, unpublished data).

The effects of orientation on multiple row shelterbelts are similar to those of single row shelterbelts. In addition, multiple row shelterbelts have the added dimension of the space between rows. Within a shelterbelt, light level between the rows is the primary limiting ecological factor that controls understory development. Canopy structure directly affects light penetration into the canopy, and thus controls the amount of light reaching the soil or litter surface (Larcher, 1995).

Species composition of the understory for both single and multiple row shelterbelts is limited by the availability of seed. Harvey (2000) indicated that native species tend to have an advantage due to a greater availability of seed. Available soil moisture and type of litter are also factors in determining the successful germination and establishment of individual plant species. Sutton (1992) examined woody plant occurrence in hedgerows and fencerows in eastern Nebraska. Native woody species with fleshy fruits (*Morus alba, Celtis occidentalis, Prunus americana*, and *Ribes missouriense*) dominated the reproduction within these linear forests. Only five species with wind dispersed seeds were present. The implication is that bird use of the shelterbelts was the major seed dispersal method. He noted that in the shelterbelts examined, nearly half of the common components of the deciduous forest of eastern Nebraska were missing.

A recent study of 40–year-old, two-row field shelterbelts in Nebraska identified 29 woody species that had been recruited into the shelterbelts (Hiller, 2004). While a taxonomic survey of herbaceous species was not conducted, observations during the sampling for woody species indicated a wider variety of species in the hardwood shelterbelts than in the conifer shelterbelts. For the most part, these differences reflected the density of the canopy and the different light regimes; however, the nature of the litter also may have influenced germination and survival of some species.

An earlier study of these same windbreaks indicated that the type of litter influenced the types of insects that were capable of overwintering in the litter of the shelterbelt (Danielson et al., 2000). Hardwood litter was more conducive to overwintering success than conifer litter. Similarly, the boll weevil (*Anthonomus grandis*) successfully overwintered in hardwood litter but not in conifer litter (Bottrell et al., 1972; Slosser and Boring, 1980).

Shelterbelts contribute to improved soil moisture relationships within the crop field protected by the shelterbelt in two ways: (1) reductions in wind speed reduce evaporation from the soil surface, leaving more water for crop development and (2) low-density field shelterbelts create a broad zone of increased snow deposition across the field on the leeward side of a shelterbelt, leading to an increase in available soil moisture (Kort, 1988; Scholten, 1988). Snow that accumulates within the shelterbelt zone contributes to the growth and development of the shelterbelt.

Dense windbreaks and living snow fences create a deep drift of snow in a narrow band near their leeward sides. They also can be used to create small stock ponds in rangeland areas by depositing snow in low, depressed areas (Jairell and Schmidt, 1990). In both cases, snow management by shelterbelts captures wind blown snow for use within an agroecosystem.

The shelterbelt zone is managed differently from the adjacent cropland. Cropland is cultivated, fertilized, planted, and sprayed with various pesticides annually, but the shelterbelt zone is not cultivated and receives no intentional fertilizer or pesticide inputs. However, limited inputs from adjacent field applications may accumulate within the shelterbelt zone as a result of being deposited via wind erosion, surface water flow or drift. With no cultivation, litter builds up in the shelterbelt zone, increasing soil organic matter and porosity, resulting in changes in soil structure and a shift in populations of various microorganisms (Heal and Dighton, 1986; Juma and McGill, 1986; Bharati et al., 2002). The degree of litter buildup is a function of species composition and environmental conditions, particularly temperature, available moisture, and length of growing season. Forests in the northern latitudes of the USA have slower rates of production of biomass and decomposition of litter compared to those in lower latitudes, and shelterbelts should show similar patterns (Barnes et al., 1998).

If conifers are part of the shelterbelt, their needles will contribute to a deepening litter layer due to their slow decomposition. Litter structure under conifers is more porous than under hardwoods and offers few niches for various types of overwintering insects (Slosser and Boring, 1980). Leaves of most hardwoods break down more rapidly than conifer litter and contribute less to the depth of a litter layer but result in a more rapid build up of soil organic matter (Barnes et al., 1998). Nutrient cycling in these linear forests will start to approximate that of local native forest systems, although the balance of nutrients will depend upon inputs from adjacent cropland and outflows of nutrients due to leaves being blown out of the zone and branches being removed.

As a shelterbelt develops and forms a continuous barrier with more vertical structure, more and different wildlife species will be attracted to the shelterbelt (Best, 1983; Cassel and Wiehe, 1980). Birds that nest, sing, or forage in the shelterbelt will be found more commonly (Johnson and Beck, 1988; Johnson et al., 1994). Given the limited size of most shelterbelts, most bird species that use shelterbelts are edge species; however, the presence of shelterbelts has extended the range of a number of generalist species (Podoll, 1979). A comprehensive review of shelterbelts and wildlife by Johnson and Beck (1988) remains the signature work in this area, and the reader is referred to the original review for more details.

As the barrier and understory communities continue to develop, more non-avian species will begin to use a shelterbelt as a corridor. As shelterbelts age, some predators, both bird and mammal, may increasingly use them for hunting (Gates and Gysel, 1978; Yahner, 1982; Johnson and Beck, 1988). As a narrow forest, large mammalian predators, such as coyote (*Canis latrans*) and red fox (*Vulpes vulpes*), find shelterbelts good hunting grounds; however, rodent and snake predators are not common in these types of habitats. The commonly accepted belief that predators selectively hunt along corridors may only be a concern with larger ground-nesting birds, such as ring necked pheasants (*Phasianus colhicus*) (Shalaway, 1985). A notable exception is the use of field shelterbelts by upland game bird hunters who have found that the number of pheasant or quail taken along shelterbelts is greater than in open fields. A Kansas study indicated significant economic benefits (US$30 million annually) could be attributed to hunters using shelterbelts for upland game bird hunting (Cable and Cook, 1990). The relationship between predator, prey, and shelterbelt habitat needs more study (Johnson and Beck, 1988).

Similarly, the belief that an increase in wildlife abundance will increase the likelihood of damage to adjacent crops needs further examination. Again, the impact appears to apply under certain circumstances. Flocking birds, such as red-wing blackbirds (Agelaius phoeniceus) and European starlings (Sturnus vulgaris), may damage ripe corn (Zea mays) or sunflower (Helianthos spp.) (Bollinger and Caslick, 1985), but in most cases damage can be minimized by timing planting so that crop maturity occurs prior to the appearance of migrating flocks (Johnson and Beck, 1988).

Shelterbelts influence the distribution of both crop pests and their natural enemies (Mineau and McLaughlin, 1996). In addition, more pollinating insects are found in sheltered areas than open areas. For example, honey bee (*Apis mellifera*) flight is inhibited at wind speeds of 6.7–8.9 m/s (Norton, 1988). A number of insects, such as aphids (Homoptera: Aphididae), are carried by wind (Pasek, 1988), and shelterbelts, which reduce wind speed, can reduce the damage associated with aphid-transmitted viruses (Simons, 1957).

Shelterbelts reduce wind erosion and thus reduce damage to the crop. Wind-blown soil can abrade plant tissue, as well as carry inoculum for bacterial and fungal diseases (Pohronezhy et al., 1992). The abrasion causes loss of water control integrity of the epidermal surfaces and potential entry points for pathogens (Hodges and Brandle, 1996). Soil erosion also reduces cropland productivity, and shelterbelts help prevent that reduction. Additionally, shelterbelts, acting as a barrier to flow, can reduce overland flow of water, a cause of rapid, localized erosion. Assuming the soil in the shelterbelt zone is similarly influenced by perennial vegetation as the soil in riparian buffer strips (Bharati et al., 2002), it has a much higher infiltration rate and surface roughness than adjacent cropland, so more water percolates into the soil, benefiting the shelterbelt as well as reducing overland flows.

While these erosion effects are important, the offsite costs of erosion on ecosystems are far greater than the onsite damage (Huszar and Piper, 1986) and include damage to water storage facilities, irrigation systems, road ditches, and other facilities (Ribaudo, 1986). The impacts on air quality and human health (Williams and Young, 1999) are more difficult to quantify but more universal in scope.

Mature Phase

Older shelterbelts continue to provide many of the same ecological functions as younger shelterbelts. As long as they maintain their integrity (forming a uniform and contiguous barrier), they continue to provide the many benefits of shelter described earlier. In fact, the greater height of the older shelterbelt provides an advantage as the extent of the protected zone is enlarged. From a wildlife perspective, mature shelterbelts are more diverse than younger shelterbelts and provide a greater variety of niches for plants, insects, birds, mammals, and other organisms. A shelterbelt enters the mature phase when mortality begins to reduce the integrity of the shelterbelt.

As individual trees within a shelterbelt or a forest approach maturity, their health and vigor begin to decline and eventually the trees die. In a natural forest, dying trees are replaced by trees of the same species or other species, depending upon the age structure of the forest and the species originally present (Barnes et al., 1998). As trees die within a shelterbelt, they might be replaced by other trees, shrubs, or annual and perennial weeds, or the shelterbelt might be cut down and replanted or not. The replacement of trees in a shelterbelt depends upon the management that has been practiced during its lifespan, specifically whether invading trees are removed or not and plans for managing the shelterbelt as the originally planted trees begin to die.

Shelterbelt trees often have shorter life spans than forest grown trees because there are more sources of stress for a tree in an agricultural field than in a natural forest (Fewin and Helwig, 1988; Dix and Leatherman, 1988). Modern agriculture uses many chemical inputs. Fertilizer is one that is commonly used, and trees should benefit from some access to fertilizer applied to adjacent fields. But herbicides also are commonly applied to the same fields, often with multiple sprayings per year, and trees have considerable potential for repeated damage from herbicides. Shelterbelts of any age can be severely damaged or killed by application of herbicides during windy conditions. Additionally, agricultural fields are often cultivated, and the root systems of trees that grow into the field are repeatedly damaged.

As mature shelterbelt trees die, gaps will begin to appear in the shelterbelt. If site conditions are suitable and seed sources are available, these gaps will be filled by new tree or shrub species in a process similar to forest succession if the management of the shelterbelt does not call for the removal of the new trees and shrubs. If conditions are less than ideal, aggressive annual species or perennial grass species, often smooth brome (*Bromus inermis*) in the Midwestern USA, may begin to invade the site, creating greater stress on the trees and increasing the rate of shelterbelt decline.

Nutrients in forest trees are recycled within the forest but that does not often happen with shelterbelt trees. The sequence of regeneration, growth and senescence may or may not occur in a shelterbelt, depending on local conditions and management.

Old shelterbelts have at least three fates. The most common is that they are removed and not replaced. The second fate is removal and replacement. Sometimes a new shelterbelt will be established in the same area immediately after the old one is removed. For producers who are very concerned with maintaining shelter, a new shelterbelt will be established adjacent to an old one some years before the old one is removed (Fewin and Helwig, 1988).

A third fate befalls those shelterbelts that contain an adequate number of trees that became established after the original shelterbelt was planted and are owned by individuals who want to keep the shelterbelt. These shelterbelts are like mixed species, multi-aged forests in which the older trees die out and are rapidly replaced by younger trees that have been waiting in the understory to fill holes in the canopy. These shelterbelts can remain effective for many years but generally require some intervention to control the composition and density of trees that replace the originally planted trees. In England some hedgerows have been dated to be at least 1000 years old (LERC, 2004).

Shelterbelts as a Component of the Landscape

Like all agroforestry practices, shelterbelts represent an intentional addition of woody plants into agricultural landscapes. Shelterbelts are a designed landscape feature in that they are deliberately composed and arranged on the landscape to create specific ecological impacts that we deem valuable. While some of their ecological foundations have been discussed in general (see Olson et al., 2000), shelterbelts have an ecology unique to built ecosystems that we are only now beginning to comprehend in terms of agroecosystem dynamics and sustainability (Paoletti, 2001).

To landscape ecologists, the landscape is composed of three elements: a matrix, which is the predominant plant and animal community; patches, which are plant and animal community areas surrounded by areas with different community structure; and corridors, which are narrow plant and animal communities that connect patches (Figure 3.1) (Forman, 1995). Shelterbelts are corridors – introduced buffers – placed into a matrix, which is usually an agroecosystem characterized by intense human intervention. The ecological interactions between shelterbelts, as corridors, and the other two landscape elements defines the targeted or intended services being sought from shelterbelts, as well as the many unintended impacts that may or may not be considered beneficial (Schoeneberger et al., 1995; Schmucki et al., 2002).

Although shelterbelts generally comprise a very small portion of the landscape, the impact of their structural diversity in the highly simplified and massive agricultural matrices is many times greater than the small portion of land they occupy (Guertin et al., 1997). Placement of shelterbelts and other introduced corridors, such as riparian buffer strips, into the agricultural matrix alters numerous ecological functions that translate into impacts at the site level, aggregating upwards to the farmscape, and beyond (Figure 3.2a–b). Managing these impacts to our benefit requires an understanding of how the five main corridor functions – habitat, conduit, filter/barrier, sink, and source – change over a shelterbelt's life (Tables 3.1 and 3.2) (Hess and Fischer, 2001). Operating simultaneously, these five functions vary seasonally and with the weather, and change dramatically over a shelterbelt's life span.

Figure 3.1 Shelterbelts, as a designed corridor within the agricultural landscape

While this approach oversimplifies the many and highly complex interactions that take place, it does provide a scientific framework for guiding shelterbelt design and management over time. We can create or manage the ecological functions of shelterbelts by making decisions on shelterbelt design, location, and orientation at the time of establishment and/or by deliberately manipulating the structure throughout its life span. Manipulating the width, connectivity, architecture, length, composition, and the edge-to-interior ratio changes the biological and physical characteristics of a shelterbelt.

Because the dominant use of shelterbelts is as a filter/barrier for microclimate modification, the first scale of consideration is at the practice (field) or individual corridor level. The architecture or structure of a corridor is the primary concern. Structure is defined as the amount and arrangement of the solid and open portions of a shelterbelt and for microclimate modification is often expressed in terms of shelterbelt density (percentage of the solid portion) or porosity (percentage of the open portion). The relationship between structure and function is the subject of current research, and a detailed discussion can be found in Zhou et al. (2005) and Brandle et al. (2004). In general, dense shelterbelts create large wind speed reductions over short distances and are used to protect buildings, livestock, and roads, while more porous shelterbelts create moderate wind speed reductions but over greater distances and are used to protect fields and crops.

Maximizing the filter/barrier function of shelterbelts, therefore, entails design decisions at establishment regarding species selection and planting arrangement (length, width, and orientation) and management practices as needed throughout the life span to maintain the appropriate density. Examples of other important corridor functions and their implications for management are briefly listed in Table 2.2 and were discussed in the section on the three phases of a shelterbelt's life. It is critical to note that many of the functions created by shelterbelts operate at scales larger than an individual property or practice and must be taken into account if the overall impacts from these plantings are to have a net benefit to the landowner or larger stakeholder group. For example, the conduit function of corridors for large wildlife occurs at landscape scales (See Box 3.1).

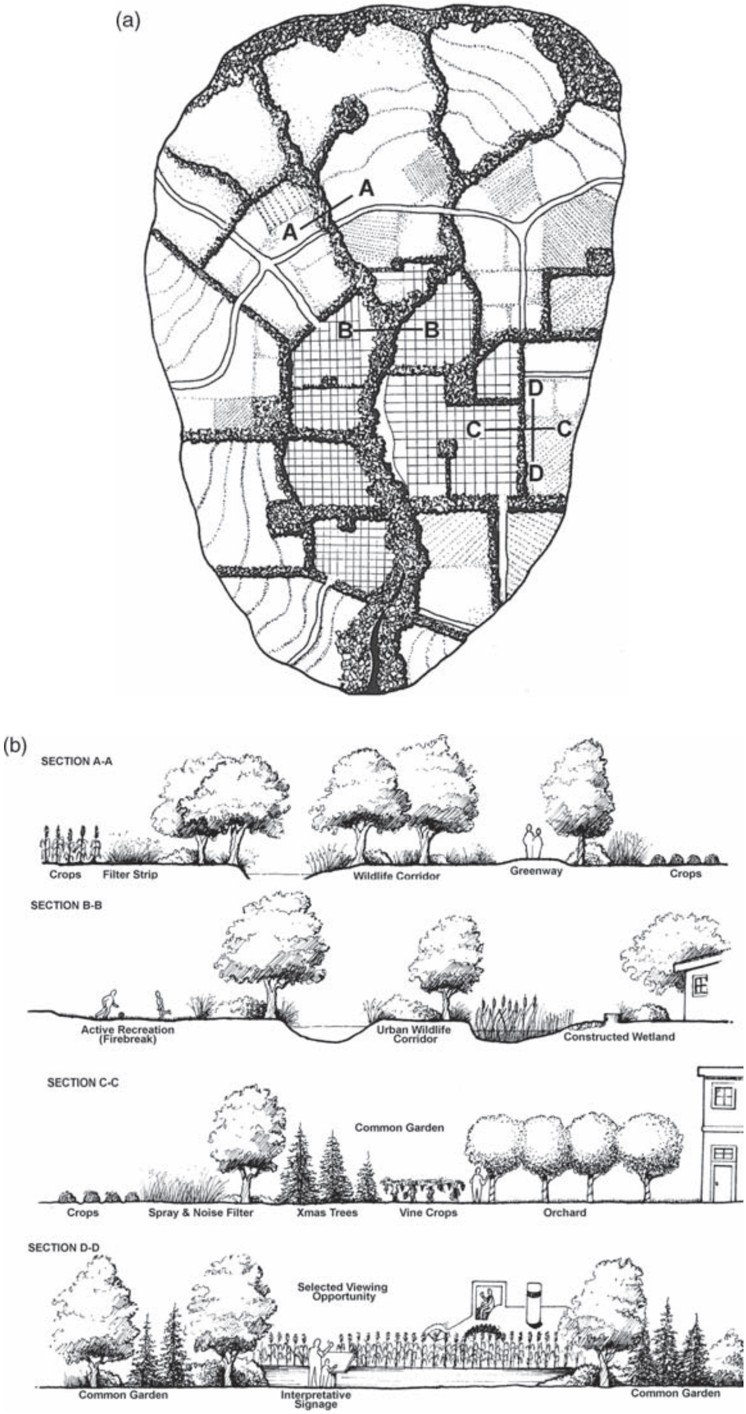
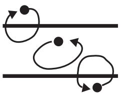
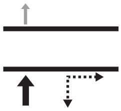
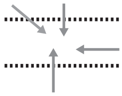
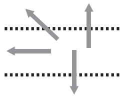


Figure 3.2 a, b Overview of ecological impacts throughout a farmscape created by shelterbelts and other agroforestry plantings. (Modified from Forman and Baudry, 1984)

Table 3.1 General description of main corridor functions. (Adapted from Schoeneberger et al., 2001.)

Corridor function	Description	Application to shelterbelts
 Habitat	Provides resources (e.g., food, shelter, reproductive cover) to support an organism's needs	Provide critical wildlife habitat oasis for numerous wildlife species within the dominant agricultural ecosystem.
 Conduit	Conveys energy, water, nutrient, seeds, organisms, and other elements within the linear elements.	Travel corridors that enable movement of wildlife across agricultural landscape – either between critical patches or as an oasis along migratory pathways.
 Filter/Barrier	Intercepts wind, wind-blown particles, surface and subsurface water, water-carried materials (e.g. nutrients, pesticides, sediments), genes, and animals.	The dominant function managed for in shelterbelts. Shelterbelts are constructed to serve as barriers predominantly to wind and wind-carried particles. They filter dust, agrochemical drift, odors, and other particulates.
 Sink	Receives and retains objects and substances that originate in the adjacent matrix of land.	Windbreaks tend to serve as sinks for many agricultural products and by-products, including eroded and wind-blown top soil, fertilizers, pesticides and other chemicals, seeds, and animals.
 Source	Releases objects and substances into the adjacent matrix of land.	Windbreaks may serve as a source of weed seed and other pests, such as deer and other animals that damage crops. They may also serve as a source of beneficial organisms, both insects and birds that can serve as natural enemies to crop pests.

Shelterbelts: A Component in Sustainable Land-use Management

Shelterbelts in North America came into early prominence primarily as a filter/barrier tool to combat the Dust Bowl of the 1930s. Today, society's demand for more sustainable agricultural production systems and landscapes is placing new requirements on shelterbelts. No longer should shelterbelts be established for one benefit. They must be designed to perform multiple corridor functions and provide several services (Lassoie and Buck, 2000).

Shelterbelts, along with other agroforestry practices, are being promoted globally as a means to create critical environmental and economic linkages across the agricultural, urban, and forest continuum (Ruark et al., 2003). For the strategic

Table 3.2 Examples of corridor functions of shelterbelt and their management implications

Corridor Function	Examples	Management implications
Habitat	Habitat for bird and bat species that feed on crop pests (Johnson and Beck, 1988)	Increase corridor width to minimize nest parasitism by cowbirds Leave dead trees standing for snags habitat
	General habitat for parasitoids and other beneficial insects (Marino and Landis, 1996)	Establishment of structurally diverse shelterbelts. Provide specific plant species necessary for maintaining beneficial insects
Conduit	Movement corridors for desirable species at risk (Anderson, 1997)	Use the shelterbelt to connect other habitat patches Use similar species and structure found in the habitat patches
	Movement corridors for undesirable species	Avoid connecting patches that are colonized by undesirable species
	Integrate shelterbelt into regional pedestrian trail system where appropriate	Increase corridor width to accommodate the range of desired functions
Filter/Barrierv	Concentration of wind dispersed weed seeds on windward side	Minimize area required for active weed treatment and management
	Visual screen separating land uses or undesirable views	Use species that provide screening benefits year around
	Interception and concentration of pollutant laden runoff	Provide understory vegetation to trap and retain pollutants
	Provide energy savings for human-based structures (DeWalle and Heisler, 1988)	Establish appropriate species to provide solar and wind protection
	Trap airborne chemical drift and odors from affecting adjacent areas	Use species on outside edge that are tolerant of chemical drift Silvicultural treatment to maintain a dense barrier
	Reduction of noise from agricultural fields and roads	Establish shelterbelt close to noise source Use dense, branching species, particularly evergreens
Sink	Weed proliferation during establishment phase	Use appropriate mulches or cultivation to control weeds
	Storage of carbon in woody biomass	Provide long term management of vegetation to sequester carbon
	Capture and deposit snow to protect structures, roads, and livestock	Silvicultural treatment to maintain 60–80% porosity to accumulate snow
Source	Insect pests of crops: boll weevils (*Anthonomus gradis*) and alfalfa weevils (*Hypera postica*)	Silvicultural treatment of shelterbelt to destroy pest habitat Use of pesticides to control pests
	Animal pests of crops: deer, elk, rabbits, and rodents	Minimize proximity to other travel corridors Alter interior structure to create less favorable habitat
	Natural enemies of crop pests (Altieri and Letourneau, 1982)	Manipulation of edge-to-interior ratio in shelterbelt "forest" Manage species composition and density
	Provide alternative economic products (i.e. medicinal herbs and woody florals)	Integrate marketable species into planting design

Box 3.1 Louisiana Black Bear Use of Corridors. (From Anderson, 1997; Johnson et al., 2000.)

The Louisiana black bear *(Ursus americanus luteolus)* was once abundant in east Texas, southern Mississippi and all of Louisiana. Habitat loss and fragmentation have diminished the range of the black bear by 90–95%. In January 1992, the US Fish and Wildlife Service designated the Louisiana black bear as threatened under authority of the Endangered Species Act.

In 1994, wildlife biologists at the University of Tennessee initiated a study of corridor use and feeding ecology of black bears in the Tensas River Basin in northern Louisiana. The 350 km^2 privately owned study area contained four major isolated woodland patches, some linked by wooded corridors. The patches were surrounded by agricultural fields of corn, soybeans, cotton, wheat, and other small grains. Corridors in the study area ranged from 50 m to 73 m in width. The height and density of vegetation in most corridors was sufficient to conceal bear movements.

Radio collars were placed on 19 Louisiana black bears, and their movement was tracked over 18 months. Analysis of telemetry data indicated that bears preferred corridors to agricultural fields when outside of a forest track. Fifty-two percent of the male bear patch-to-patch movement and 100% of the female bear movement was between patches connected by corridors. Adult male bears used the corridors most intensively in June and July, the breeding season. Sub-adult bears used the corridors for dispersal from their natal home range.

This study suggests that wooded corridors between forested tracts may be vital to the survival for the Louisiana black bear in highly fragmented landscapes. Long-term management should include maintenance, enhancement and implementation of wooded corridors that link forested patches. Shelterbelts and other woody corridors provide a means to maintain agricultural production while providing other key environmental services.

incorporation of shelterbelts and similar plantings to occur, two different scales of considerations and planning must be melded: (1) the sustainable agriculture level, where whole-farm resource use is balanced with whole-farm productivity and (2) the sustainable landscape level, where agroecosystems, along with public and urban lands, are components of a larger watershed (Barrett et al., 1999).

Because 50% of the USA (approximately 360 million hectares) is in agricultural production, the importance of agricultural lands in determining the health of land in the USA is evident (USDA, 1996). Strategies at this scale entail a more holistic approach and require a broader consideration of concerns, land uses, and stakeholders within the larger watershed encompassing agricultural activities. Ultimately, shelterbelts will need to be integrated with other corridor types for societies to achieve the range of goals and services desired from their lands (Figure 3.3).

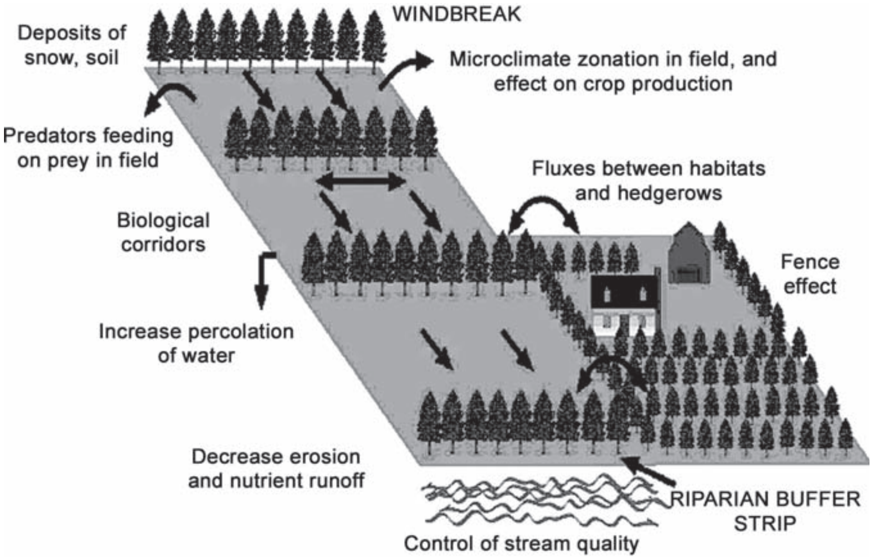


Figure 3.3 Integration of shelterbelts with other corridor systems to achieve landowner and community-based goals

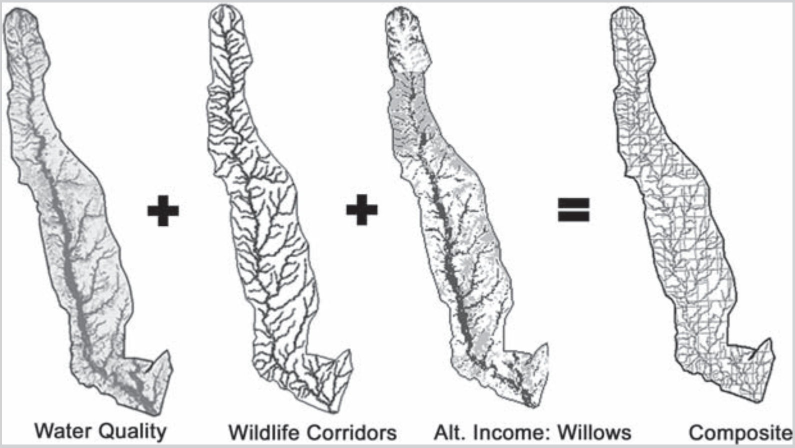
In this conceptual example, shelterbelts and other corridors and patches are purposely designed and linked together in a manner that promotes the desired landowner and community-driven goals. In Section A-A, the corridor is designed to treat runoff by filtering runoff through a dense vegetative buffer that also provides habitat and a conduit for wildlife. This corridor also allows for passive recreation through a greenway trail, allowing urban residents to experience agricultural environments. In contrast, Section B-B illustrates a corridor in a more urbanized section of the watershed. Because stormwater flow is more concentrated, a constructed wetland is designed in the shelterbelt system to treat the stormwater before it flows into a stream. A more active recreation area is included in the corridor, which also serves as a firebreak to protect homes.

A shelterbelt between an agricultural field and residential area is presented in Section C-C. In addition to improving the mircoclimate for the adjacent crop field, the area also serves as a common garden for local residents and is protected from noise and spray by a vegetative buffer. Section D-D illustrates how this same shelterbelt can provide views and awareness of conservation measures being applied to protect natural resources.

This example demonstrates how the objective of the shelterbelt or corridor will play a key role in determining the location and design parameters for a particular segment of the corridor system. The next step is then determining strategic arrangements within the context of the working landscape. Geographic Information Systems (GIS) provide an effective and efficient means to analyze landscape characteristics (i.e. slope, soil type, land cover) in the identification of suitable shelterbelt and other corridor locations that can address the desired objectives (See Box 3.2). GIS-based assessments developed at a state or multi-county level

Box 3.2 Soldier Creek Watershed: Achieving Multiple Objectives with GIS. (From Bentrup and Leininger, 2002; Bentrup and Kellerman, 2004.)

The Soldier Creek watershed, a 500 km^2 region in northeast Kansas, is typical of many watersheds in the western Corn Belt ecoregion. Once covered with tallgrass prairie, over 90% of the ecoregion is now used extensively for cropland and pasture. Landowners and community leaders in the Soldier Creek area are interested in using wooded buffers to help mitigate water quality problems while providing benefits to wildlife. GIS was used to identify the best locations for implementing buffers to treat runoff and provide wildlife habitat and movement corridors. Because these proposed plantings would take land out of traditional agricultural production, landowners were concerned about losing income. Another GIS assessment was developed to determine where non-timber specialty products could be grown to diversify landowners' enterprises and replace the potential loss in income. In the illustration below, suitable locations for growing willows for the decorative floral industry were determined. By combining the three individual GIS assessments, sites were identified where buffers could achieve water quality, wildlife, and economic goals, allowing planners to prioritize efforts on private lands.



can be valuable in preparing technology transfer programs and for prioritizing resources and projects, while county-level assessments can be useful in the site specific design process (Bentrup and Kellerman, 2004).

More extensive discussion on this topic is beyond this review; however, we can point out other publications and efforts that are addressing the need for tools and approaches to help guide the incorporation of agroforestry plantings, like shelterbelts, into the larger spatial context. One such effort in the USA is *Conservation Corridor Planning at the Landscape Level – Managing for Wildlife Habitat Manual*

(Johnson et al., 2000), developed in response to the nationwide promotion of buffers through the National Conservation Buffers Initiative. Directed at managed corridors in agriculturally dominated landscapes, this handbook serves as a source for ideas and planning principles for wildlife corridor planning at site and landscape scales.

Because every application of shelterbelts and other plantings is based upon a unique mix of biophysical, social, and economic considerations, a suite of flexible tools is needed to accommodate the range of considerations and each individual's or group's unique decision-making process (Bentrup et al., 2003; Ellis et al., 2004) (Box 3.3). The Comprehensive Conservation Buffer Planning Methodology being developed at the USDA National Agroforestry Center (www.unl.edu/nac) facilitates this process and dialog among stakeholders, while providing information on

Box 3.3 Shelterbelt Planning and Design Tools. (From Bentrup et al., 2005.)

This list provides a sample of tools and publications available for planning and designing multifunctional shelterbelts at site and landscape scales to achieve landowner and community-based goals.

Conservation Planning Atlas: An internet-based atlas of over 100 national and regional-scale resource maps. http://www.unl.edu/nac/conservation/

BUFFER$: An economic analysis spreadsheet tool for evaluating the installation or removal of buffers in a crop field. http://www.unl.edu/nac/conservation/

WBECON: A tool that calculates the economics of windbreaks by taking into account various factors, such as windbreak species, windbreak design, soil and climate factors, crop rotation, windbreak costs, crop costs, and crop prices. http://waterhome.brc.tamus.edu/NRCSdata/models/Forests and Windbreaks/WB/

Visual Simulation Kit: A two CD collection containing a photo-editing software program and a how to guide for creating visual simulations of proposed conservation design and management scenarios. http://www.unl.edu/nac/simulation/

Habitat Suitability Index Model: Wildlife Species Richness in Shelterbelts: A simple model for evaluating species richness based on structural parameters of a shelterbelt.
http://www.nwrc.usgs.gov/wdb/pub/hsi/hsi-128.pdf

Conservation Corridor Planning at the Landscape Level – Managing for Wildlife Habitat Manual: *http://www.wsi.nrcs.usda.gov/products/tools.html*

PLANTS: A national plant database maintained by the USDA. http://plants.usda.gov/

USDA National Agroforestry Center: A multi-agency organization promoting agroforestry in rural and urban environments. http://www.unl.edu/nac/

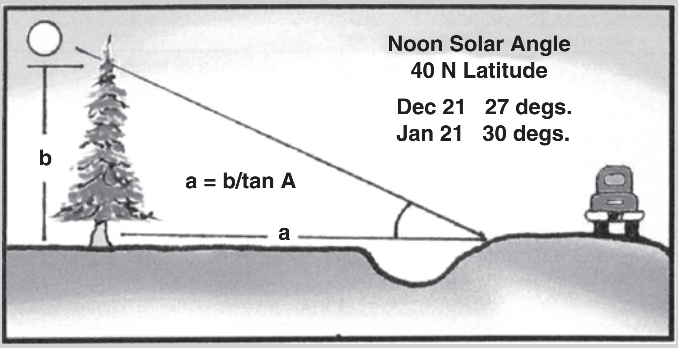
PFRA Shelterbelt Centre: A Canadian organization that promotes the integration of trees in agroecosystems. http://www.agr.gc.ca/pfra/shelterbelt.htm the dynamic interactions and potential tradeoffs of tree-based buffers, such as shelterbelts. This loosely coupled suite of tools is being developed to address multiple issues and ranges from the *Conservation Planning Atlas* and GIS-guided suitability assessments addressing water quality, wildlife habitat, and income diversification to *BUFFER$* (a conservation buffers economic analysis tool) and a computer-based visual simulation tool (*www.unl.edu/nac/conservation/index.html*).

Central to the planning effort is the simply illustrated and written *Conservation Buffers: Planning and Design Principles* manual that facilitates landowner and stakeholder discussion regarding the ecological principles that can be applied in the design and management of agroforestry plantings (see Box 3.4).

Shelterbelts and other agroforestry plantings are not a panacea for addressing sustainability issues, but with appropriate tools that integrate and balance site,

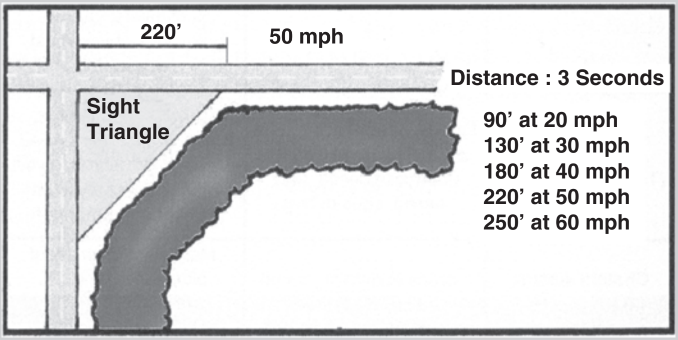
Box 3.4 Conservation Buffers: Planning and Design Principles. (From Bentrup et al., 2005.)

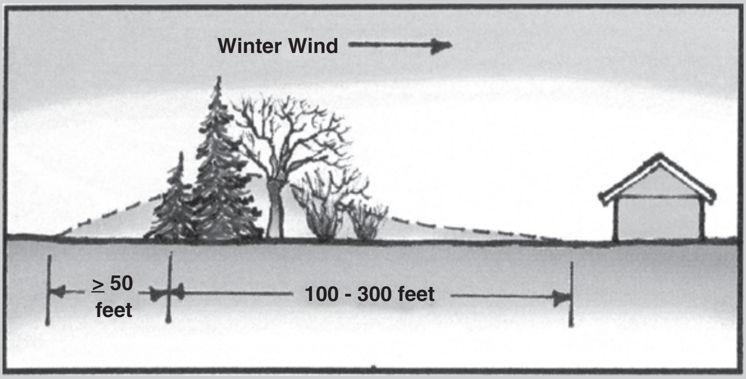
Over 80 illustrated planning and design concepts for shelterbelts and other corridors are presented in this guide gleaned from a diffuse body of research and literature. Information was synthesized from landscape ecology, conservation biology, agricultural engineering, agronomy, economics, social sciences, and other disciplines. The principles were organized into seven resource categories: water quality, species and habitats, productive soils, economic opportunities, protection and safety, aesthetics and visual quality, and outdoor recreation. By providing an easy way to incorporate current research into the design of multifunctional buffers at landscape and site-scales, this guide should facilitate the considerations of landowners and/or community issues in the buffer planning process. Below is an example page from this guide.

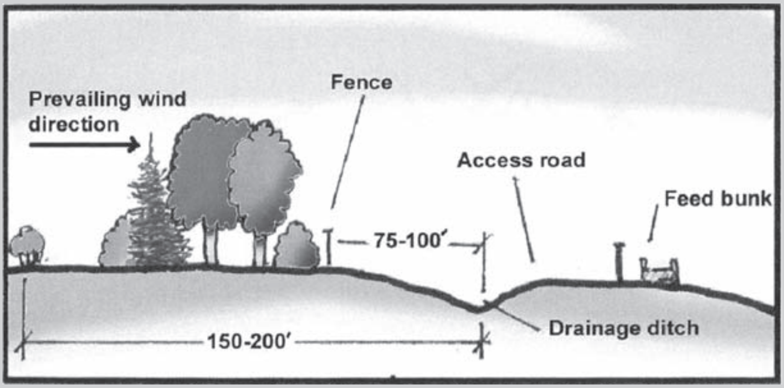


(continued)

Box 3.4 (continued)







landscape, and even regional-level concerns, we can begin to design strategic systems that create more sustainable landscapes.

Summary

Shelterbelts are linear forests established on the landscape to address various conservation goals. These designed corridors provide protection from wind to crops and livestock, store carbon, and offer habitat to numerous insects, birds, and small mammal. As we better understand their function, we will be able to utilize them more efficiently to create more stable landscapes. Shelterbelts are not panaceas, but as our understanding of their function at the landscape level increases, they will become a significant part of the tools used to create healthier agroecosystems in North America and other parts of the world.

References

Altieri M. and Letourneau D. (1982) Vegetation management and biological control in agroecosystems. Crop Protection 1:405–430.

Anderson D. (1997) Corridor use, feeding ecology, and habitat relationships of black bears in a fragmented landscape in Louisiana. Masters thesis, University of Tennessee, Knoxville.

Appleton B., Derr J., and Ross B. (1990) The effect of various landscape weed control measures on soil moisture and temperature, and root growth. Journal of Arboriculture. 16:264–268.

Barnes B., Zak D., Denton S., and Spurr S. (1998) Forest Ecology, 4th edn. Wiley, New York, 774 pp.

Barrett G., Barrett T., and Peles J. (1999) Managing agroecosystems as agrolandscapes: reconnecting agricultural and urban landscapes. In: Collins W. and Qualset C. (eds) Biodiversity in Agroecosystems. CRC Press, Boca Raton, FL, pp. 197–213.

Benton T., Vickery J., and Wilson J. (2003) Farmland biodiversity: is habitat heterogeneity the key? Trends in Ecology and Evolution 18:182–188.

Bentrup G., Schoeneberger M., Dosskey M., and Wells G. (2005) Conservation buffers: planning and design principles. USDA National Agroforestry Center, Lincoln, NE.

Bentrup G., Schoeneberger M., Dosskey M., and Wells G. (2003) The fourth p: planning for multi-purpose riparian buffers. In: Proceedings of the 8th North American Agroforestry Conference. Corvallis, OR, June 23–25.

Bentrup G. and Kellerman T. (2004) Where should buffers go? – modeling riparian habitat connectivity in northeast Kansas. Journal of Soil and Water Conservation 59:209–213.

Bentrup G. and Leininger T. (2002) Agroforestry: mapping the way with GIS. Journal of Soil and Water Conservation 57:148a–153a.

Best L. (1983) Bird use of fencerows: Implications of contemporary fencerow management practices. Wildlife Society Bulletin 11:343–347.

Bharati L., Lee K., Isenhart T., and Schultz R. (2002) Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agroforestry Systems 56:249–257.

Bollinger E. and Caslick J. (1985) Factors influencing blackbird damage to field corn. Journal of Wildlife Management 49:1109–1115.

Borland J. (1990) Examining the facts and fallacies behind the uses and benefits of mulch. American Nurseryman, August 15, 1990, pp. 131–132, 135, 137–141.

Borland J. and Weinstein G. (1989) Mulch: Is it always beneficial? Ground Maintenance 24:10–12, 120–121.

Bottrell D., White J., Moody D., and Hardee D. (1972) Overwintering habitats of the boll weevil in the rolling plains of Texas. Environmental Entomology 1:633–638.

Brady N. and Weil R. (2000) The Nature and Properties of Soils, 11th edn. Prentice Hall, New Jersey, 740 pp.

Brandle J., Hintz D., and Sturrock J. (eds). (1988) Windbreak Technology. Elsevier Science, Amsterdam, The Netherlands, 598 pp.

Brandle J., Hodges L., and Wight B. (2000) Windbreak practices. In: Garrett, H.E., Rietveld, W.J., and Fisher, R.F. (eds) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, WI, pp. 79–118.

Brandle J., Hodges L., and Zhou X. (2004) Windbreaks in North American agricultural systems. Agroforestry Systems 61:65–78.

Buck L., Lassoie J., and Fernandes E. (1999) Agroforestry in Sustainable Agricultural Systems. CRC Press, Boca Raton, FL, 416 pp.

Burke S. (1998) Windbreaks. Inkata Press, Port Melbourne, Australia, 129 pp.

Cable T. and Cook P. (1990) The use of windbreaks by hunters in Kansas. Journal of Soil and Water Conservation 45:575–577.

Caborn J. (1957) Shelterbelts and Microclimate. Faber & Faber, London, 135 pp.

Caborn J. (1971) The agronomic and biological significance of hedgerows. Outlook Agriculture 6:279–284.

Cassel J. and Wiehe J. (1980) Uses of shelterbelts by birds. In: Workshop Proceedings, Management of Western forests and Grasslands for Nongame Birds. USDA Forest Service General Technical Report INT-86, Ogden, UT, pp. 78–87.

CAST (1999) Gulf of Mexico Hypoxia: Land and Sea Interactions. Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA, 44 pp.

Cleugh H., Prinsley R., Bird R., Brooks S., Carberry P., Crawford M., Jackson T., Meinke H., Mylius S., Nuberg I., Sudmeyer R., and Wright A. (2002) The Australian national windbreaks program: overview and summary of results. Australian Journal of Experimental Agriculture 42:649–664.

Cook P. and Cable T. (1995) The scenic beauty of shelterbelts on the Great Plains. Landscape and Urban Planning 32:63–69.

Danielson S., Brandle J., Hodges L., and Srinivas P. (2000) Bean leaf beetle (Coleoptera: Chrysomelidae) abundance in soybean fields protected and unprotected by shelterbelts. Journal of Entomological Science 35:385–390.

DeWalle D. and Heisler G. (1988) Use of windbreaks for home energy conservation. Agriculture, Ecosystems, and Environment 22/23:243–260.

Dix M., Johnson R., Harrell, M., Case R., Wright R., Hodges L., Brandle J., Schoeneberger M., Sunderman N., Fitzmaurice R., Young L., and Hubbard K. (1995) Influence of trees on abundance of natural enemies of insect pests: a review. Agroforestry Systems 29:303–311.

Dix M. and Leatherman D. (1988) Insect management in windbreaks. Agriculture, Ecosystems and Environment 22/23:513–537.

Dronen S. (1988) Layout and design criteria for livestock windbreaks. Agriculture, Ecosystems and Environment 22/23:231–240.

Droze W. (1977) Trees, Prairies, and People: A History of Tree Planting in the Plains States. USDA Forest Service and Texas Woman's University, Denton, TX, 313 pp.

Ellis E., Bentrup G., and Schoeneberger M. (2004) Computer-based tools for decision support in agroforestry: current state and future needs. Agroforestry Systems 1:1–19.

Fewin R. and Helwig L. (1988) Windbreak renovation in the American Great Plains. Agriculture, Ecosystems and Environment 22/23:571–582.

Forman R. (1995) Land Mosaics. Cambridge University Press, Cambridge, UK.

Forman R. and Baudry J. (1984) Hedgerows and hedgerow networks in the landscape ecology. Environmental Management 8:495–510.

Gardner G. (1996) Shrinking Fields: Cropland Loss in a World of Eight Billion. Worldwatch Paper 131. Worldwatch Institute, Danvers, MA, 56 pp.

Gates J. and Gysel L. (1978) Avian nest dispersion and fledging success in field-forest ecotones. Ecology 59:871–883.

Grace J. (1977) Plant Response to Wind. Academic Press, London, 204 pp.

Gouin F. (1992) Mulch Mania. American Nurseryman, October 1, 1992, pp. 97–99.

Guertin D., Easterling W., and Brandle J. (1997) Climate change and forest in the Great Plains – Issuse in modeling fragmented woodlands in intensively managed landscapes. BioScience 47:287–295.

Harvey C. (2000) Colonization of agricultural planted windbreaks by forest trees: effects of connectivity and remnant trees. Ecological Applications 10:1762–1773.

Heal O. and Dighton J. (1986) Nutrient cycling and decomposition in natural terrestrial ecosystems, pp. 14–73. In: Mitchell, M.J. and Nakas, J.P. (eds) Microfloral and Faunal Interactions in Natural and Agro-Ecosystems. Martinus Nijhoft/DR W. Junk Publishers, The Netherlands, 505 pp.

Heisler G. and DeWalle D. (1988) Effects of windbreak structure on wind flow. Agriculture, Ecosystems and Environment 22/23:41–69.

Hess G. and Fischer R. (2001) Communicating clearly about conservation corridors. Landscape and Urban Planning 55:195–208.

Hewitt I. and Smith K. (1995) Intensive agriculture and environmental quality. Henry A. Wallace Institute for Alternative Agriculture. http://www.winrock.org/wallacecneter/documents/laeg.pdf.

Hiller J. (2004) Woody plant recruitment in planted windbreaks: Saunders County, Nebraska. MS thesis, University of Nebraska – Lincoln, Lincoln, NE, 73 pp.

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

Hou Q., Brandle J., Hubbard K., Schoeneberger M., Nieto C., and Francis C. (2003) Alteration of soil water content consequent to root-pruning at a windbreak/crop interface in Nebraska, USA. Agroforestry Systems 57:137–147.

Huszar P. and Piper S. (1986) Estimating the off-site costs of wind erosion in New Mexico. Journal of Soil and Water Conservation 41:414–416.

Jackson D. and Jackson L. (2002) The Farm as Natural Habitat - Reconnecting food Systems with Ecosystems. Island Press, Washington, 297 pp.

Jairell R. and Schmidt R. (1990) Snow fencing near pit reservoirs to improve water supplies. Proceedings, 58th Annual Western Snow Conference, Sacramento, CA, April 17–19, 1990, pp. 156–159.

Jobin B., Choiniere L., and Belanger L. (2001) Bird use of three types of field margins in relation to intense agriculture. Agriculture, Ecosystems and Environment 84:131–143.

Johnson R. and Beck M. (1988) Influence of shelterbelts on wildlife management and biology. Agriculture, Ecosystems, and Environment 22/23:301.

Johnson R., Beck M., and Brandle J. (1994) Windbreaks for people: the wildlife connection. Journal of Soil and Water Conservation 49:546–550.

Johnson C., Bentrup G., and Rol D. (2000) Conservation corridor planning at the landscape level: managing for wildlife habitat. USDA Natural Resources Conservation Service, Part 190 of the National Biology Handbook.

Josiah S., Gordon L., Streed E., and Joannides J. (1999) Agroforestry in Minnesota: A Guide to Resources and Demonstration Sites. University of Minnesota Extension Service, St. Paul MN.

Juma N. and McGill W. (1986) Decompostion and nutrient cycling in agro-ecosystems. Pages 74–136. In: Mitchell, M.J. and Nakas, J.P. (eds) Microfloral and Faunal Interactions in Natural and Agro-Ecosystems. Martinus Nijhoft/DR W. Junk Publishers, The Netherlands, 505 pp.

Klepper B. (1991) Crop root system response to irrigation. Irrigation Science 12:105–108.

Kort J. (1988) Benefits of windbreaks to field and forage crops. Agriculture, Ecosystems and Environment 22/23:165–190.

Kozlowski T. and Pallardy S. (1997) Growth Control in Woody Plants. Academic Press, San Diego, CA, 641 pp.

Lahti M., Aphalo P., Finer L., Ryyppo A., Lehto T., and Mannerkoski H. (2005) Effects of soil temperature on shoot and root growth and nutrient uptake of 5-year-old Norway spruce seedlings. Tree Physiology 25:115–122.

Lai R., Kimble J., and Follet R. (eds). (1997) Soil Properties and Their Management for Carbon Sequestration. USDA-Natural Resources Conservation Service: National Soil Survey Center, Lincoln, NE, pp. 150.

Landhausser S., DesRochers A., and Lieffers V. (2001) A comparison of growth and physiology in *Picea glauca* and *Populus tremloides* at different soil temperatures. Canadian Journal of Forest Research 31:1922–1929.

Larcher W. (1995) Physiological Plant Ecology, Ecophysiology and Stress Physiology of Functional Groups, 3rd edn. Springer, Berlin, pp. 506.

Lassoie J. and Buck L. (2000) Development of agroforestry as an integrated land use management strategy. pp. 1–29. *In:* Garrett, H.E., Rietveld, W.J., and Fisher, R.F. (eds) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, WI.

Leck M., Parker V., and Sampson R. (1989) Ecology of soil seed banks. Academic Press, London.

LERC. (2004) Ageing Hedgerows. Leicestershire Environmental Resources Centre. http:www.lboro.org/~wwatch/Intro%20pages/Hedgerow%fact%sheet/Ageing%20Hedgerows.htm.

Matson P., Parton W., Power A., and Swift M. (1997) Agricultural intensification and ecosystem properties. Science 277:504–509.

Marino P. and Landis D. (1996) Effect of landscape structure on parasitoid diversity and parasitism in agroecosystems. Ecological Applications 6:276–284.

McArthur R. and McArthur J. (1961) On bird species diversity. Ecology 42:594–598.

McNaughton K. (1988) Effects of windbreaks on turbulent transport and microclimate. Agriculture, Ecosystems and Environment 22/23:17–39.

Mineau R. and McLaughlin A. (1996) Conservation of biodiversity within Canadian agricultural Landscapes: Integrating habitat for wildlife. Journal of Agricultural and Environmental Ethics 9:93–113.

Nieto-Cabrera C. (1998) Above and below-ground competition for solar radiation and soil moisture in a windbreak-soybean system. Ph.D. Dissertation, Department of Agronomy, University of Nebraska, Lincoln, NE, 193 pp.

Norton R. (1988) Windbreaks: Benefits to orchard and vineyard crops. Agriculture, Ecosystems and Environment 22/23:205–213.

Olson R., Schoeneberger M., and Aschmann S. (2000) An ecological foundation for temperate agroforestry, pp. 31–61. *In:* Garrett, H.E., W.J. Rietveld, and Fisher, R.F. (eds) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, WI.

Paoletti M. (2001) Biodiversity in agroecosystems and bioindicators of environmental health. pp. 11–44. In: Shiyomi, M. and Koizumi, H. (eds) Structure and Function in Agroecosystem Design and Management. CRC Press, Boca Raton, FL.

Pasek J. (1988) Influence of wind and windbreaks on local dispersal of insects. Agriculture, Ecosystems and Environment 22/23:539–554.

Pimentel D., Berger B., Filberto D., Newton M., Wolfe B., Karabinakis E., Clark S., Poon E., Abbett E. and Nandagopal, S. (2004) Water resources: Agricultural and environmental issues. BioScience 54:909–918.

Podoll E. (1979) Utilization of windbreaks by wildlife. In: Windbreak Management, Great Plains Agricultural Council Publ. No. 92, Lincoln, NE, 132 pp.

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

Read R. (1964) Tree windbreaks for the central Great Plains. USDA Forest Service, Agriculture Handbook No. 250, Washington, DC, 68. pp.

Ribaudo M. (1986) Targeting solid conservation programs. Land Economics 62:402–411.

Ritchie K. (1988) Shelterbelt plantings in semi-arid areas. Agriculture, Ecosystems and Environment 22/23 425–440.

Romero P., Botia P., and Garcia F. (2004) Effects of regulated deficit irrigation under subsurface drip irrigation conditions on vegetative development and yield of mature almond trees. Plant and Soil 260:169–181.

Ruark G., Schoeneberger M., and Nair P. (2003) Agroforestry – helping to achieve sustainable forest management. pp. 240–253. In: The Role of Planted Forests in Sustainable Forest Management: Reports and Papers of the United Nations Forum on Forests Intersessional Experts Meeting, 25–27 March 2003, Wellington, New Zealand (ISBN-0478-07758-0). Available at: http://www.maf.govt.nz/mafnet/unff-planted-forestry-meeting/conference-papers/roles-for-agroforestry.htm.

Schmucki R., De Blois S., Bouchard A., and Domon G. (2002) Spatial and temporal dynamics of hedgerows in three agricultural landscapes of southern Quebec, Canada. Environmental Management 30:651–664.

Schoeneberger M., Dix M., and Dosskey M. (1995) Agroforestry-enhanced biodiversity: The good, the bad and the unknown, pp. 207–216. In: Rietveld, W.J. (tech. ed.) Proceedings, Agroforestry and Sustainable Systems Symposium, August 7–10, 1994. Fort Collins, CO. USDA Forest Service General Technical Report RM-GTR-261, 276 pp.

Schoeneberger M., Bentrup G., and Francis C. (2001) Ecobelts: Reconnecting agriculture and communities. In: Flora, C. (ed.) Interactions between agroecosystems and rural human communities. Adv. in Agroecology. CRC Press, Boca Raton, FL, pp. 239–260.

Schroeder W. (1988) Planting and establishment of shelterbelts in humid sever-winter regions. Agriculture Ecosystems and Environment 22.23:441–463.

Scholten H. (1988) Snow distribution on crop fields. Agriculture, Ecosystems and Environment 22/23:363–380.

Shalaway S. (1985) Fencerow management for nesting birds in Michigan. Wildlife Society Bulletin 13:302–306.

Shaw D. (1988) The design and use of living snow fences in North America. Agriculture, Ecosystems and Environment 22/23:351–362.

Showler A. and Greenberg S. (2003) Effects of weeds on selected arthropod herbivore and natural enemy populations, and on cotton growth and yield. Environmental Entomology 32:39–50.

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

Slosser J. and Boring III, E. (1980) Shelterbelts and boll weevils: a control strategy based on management for overwintering habitat. Environmental Entomology 9:1–6.

Stepanek L., Brandle J., and Harrell M. (2002) Assessment of microenvironmental conditions related to the use of synthetic sheet mulches for protecting newly planted trees in semi-arid environments. Journal of Sustainable Agriculture 19:15–34.

Stuckey I. (1961) Root growth of *Taxus*. American Nurseryman 114:14, 117–118.

Sutton R. (1992) Landscape ecology of hedgerows and fencerows in Panama Township, Lancaster County, Nebraska. Great Plains Research 2:223–254.

Swift M., Izac A., and van Noordwijk M. (2004) Biodiversity and ecosystem services in agricultural landscapes – are we asking the right questions? Agriculture, Ecosystems and Environment 104:113–134.

Timm R. (1988) Vertebrate pest management in windbreak systems. Agriculture, Ecosystems and Environment 22/23:555–570.

Trinka P., Rozkosny R., Gaisler J., and Houskova L. (1990) Importance of windbreaks for ecological diversity in agricultural landscapes. Ekologia 9:241–257.

United Nations (2002) World Urbanization Prospects. Economic and Social Affairs Working Paper 173, United Nations, Population Division, New York.

US Department of Agriculture, Natural Resources Conservation Service (1996) America's private land – a geography of hope. Program Aid 1548.. Department of Agriculture, Natural Resources Conservation Service, Washington, DC, 80 pp.

Wang H., Takle E., and Shen J. (2001) Shelterbelts and windbreaks: Mathematical modeling and computer simulation of turbulent flows. Annual Review of Fluid Mechanics 33:549–586.

Watson G. (1988) Organic mulch and grass competition influence tree root development. Journal of Arboriculture 14:200–203.

Wight B. (1988) Farmstead windbreaks. Agriculture, Ecosystems and Environment 22/23:261–280.

Williams P. and Young M. (1999) Costing dust. How much does wind erosion cost the people of south Australia? Final Report, Policy and Economic Research Unit. CSIRO Land and Water, South Australia, Australia.

Wilson A., Hough-Goldstein J., Vangessel M., and Pesek J. (2004) Effects of varying weed communities in corn on European corn borer, *Ostrinia nubilalis* (Hubner) (Lepidoptera: Crambidae), oviposition, and egg mass predation. Environmental Entomology 33:320–327.

Woeste K., Seifert J., and Selig M. (2005) Evaluation of four herbicides and tillage for weed control on third year growth of tree seedlings. Weed Science 53:331–336.

Yahner R. (1982) Avian nest densities and nest-site selection in farmstead shelterbelts. Wilson Bulletin 94:156–175.

Yahner R. (1983a) Seasonal dynamics, habitat relationships, and management of avifauna in farmstead shelterbelts. Journal of Wildlife Management 47:85–104.

Yahner R. (1983b) Small mammals in farmstead shelterbelts: habitat correlates of season abundance and community structure. Journal of Wildlife Management 47:74–84.

Zhou X., Brandle J., Takle E., and Mize C. (2002) Estimation of the three-dimensional aerodynamic structure of a green ash shelterbelt. Agricultural and Forest Meteorology 111:93–108.

Zhou X., Brandle J., Mize C., and Takle E. (2005) Three-dimensional aerodynamic structure of a tree shelterbelt: definition, characterization and working models. Agroforestry Systems 63:133–147.