# Chapter 2
# Reducing Threats and Enhancing Resiliency

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## Adaptive Capacity of U.S. Agriculture

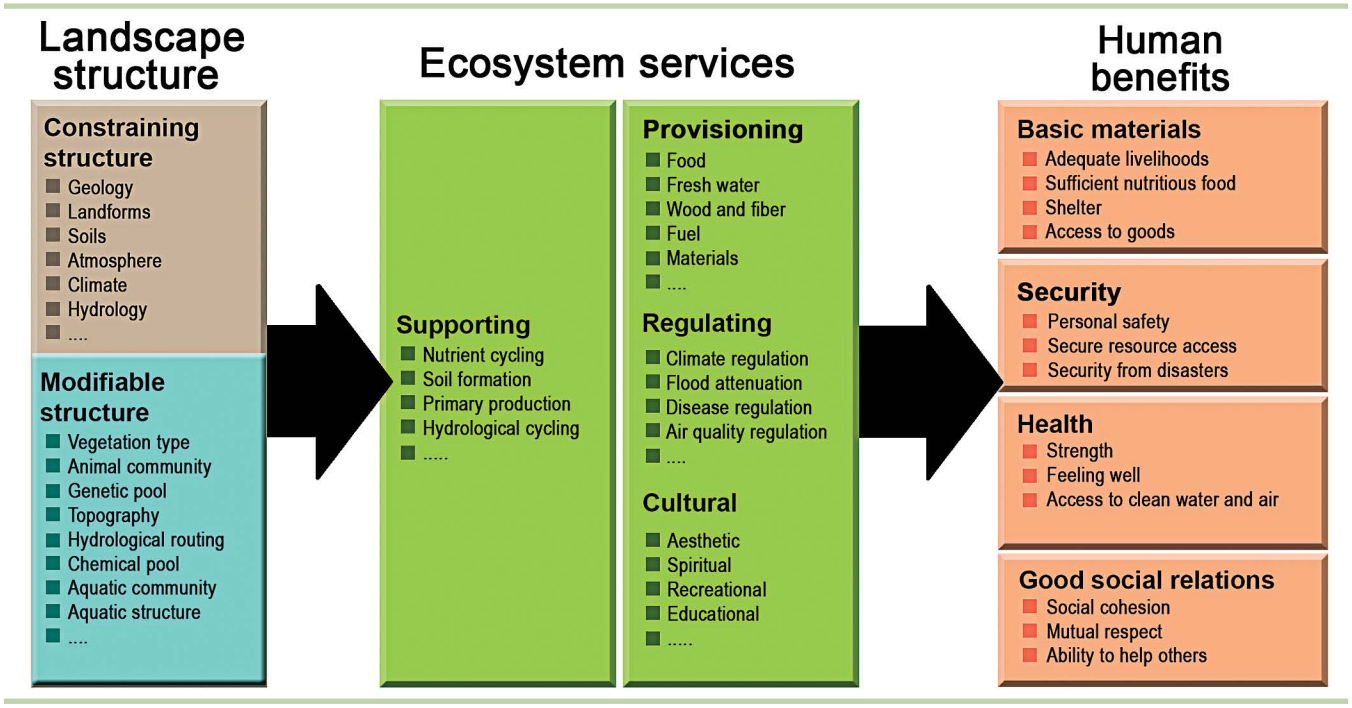
Assessments of climate change in the United States and of its impacts on U.S. agriculture (Melillo et al. 2014, Walthall et al. 2012) conclude that it is very likely that climate is changing in the United States and will continue to change throughout the 21st century. According to those assessments, temperatures will become generally warmer, but variability within seasons will become greater in some regions; precipitation patterns will change, becoming generally wetter or drier, depending on the region; and a higher incidence of extreme weather events, including drought, heat waves, and periods of intense rainfall, is likely.

Changes in climate patterns and weather variability pose substantial hazards for current U.S. agricultural systems and the resource base (fig. 2.1). According to an assessment of U.S. agriculture (Walthall et al. 2012), yield of crops and livestock will decline in some regions and increase in others due to changes in regional average climate conditions, extreme weather events outside optimum growth and reproductive ranges, and shifting ranges of damaging pests; crop growth (and that of weeds, too) may increase in response to higher atmospheric carbon dioxide ($CO_2$), but the quality of some crops may be reduced; soil erosion and water pollution will increase; and the quality of habitat for supporting beneficial biodiversity such as pollinators will decline.

The pace and complexity of changing conditions are likely to overwhelm the ability of current systems to adapt and sustain current levels of output in the long term (Walthall et al. 2012). New technologies will be needed to avoid significant disruptions in agriculture. This chapter assesses the potential for agroforestry to help adapt agriculture and agricultural lands to threats from climate change. Agroforestry practices blend trees and shrubs into the agricultural landscape to modify landscape structure in specific ways (fig. 2.2). Structure provided by agroforestry practices can be designed to modify microclimate to ameliorate direct impacts of weather extremes on production systems; to provide additional opportunities for crop production; and to protect and enhance key resources such as soil, water, and biodiversity on which agricultural production and other ecosystem services depend.

**Figure 2.1.** Agricultural productivity in the United States faces the potential for severe disruption because of climate change. To sustain a high level of productivity and a healthy resource base, agricultural systems will need to adapt to changing conditions. (A) Rice harvest in California. (Photo by Gary Kramer, USDA Natural Resources Conservation Service). (B) Cattle grazing in Alabama. (Photo by Steven Kirkpatrick, USDA Natural Resources Conservation Service).

**Figure 2.2.** Agroforestry reduces climate-related threats to agriculture by modifying the structure of agricultural landscapes. Through landscape structure, agroforestry practices modify microclimate, stabilize soil, protect water and air quality, and provide for biological diversity, including the diversity of agricultural crops. Each general type of agroforestry practice (see chapter 1) represents a different structural template for emphasizing certain benefits over others. All agroforestry practices, however, are capable of providing, and likely will provide, multiple benefits in any agricultural landscape. (Figure from Dosskey et al. 2012, as modified from MEA 2005).




## Commodity Production

Many benefits of agroforestry are derived from how it modifies local environmental conditions (e.g., air and soil temperatures, humidity, evaporation, windspeed, turbulence). Through agroforestry, local microclimate can be manipulated to enhance productivity of adjacent agricultural fields and pastures and to provide other environmental benefits.

Incorporating woody vegetation into the landscape reduces windspeed across the land surface, provides shade from solar radiation during the day, reduces radiative cooling at night, and recycles water from the soil (Brandle et al. 2009, Stigter 2010). These effects lead to physiological and ecological changes in the biological components of the agricultural landscape.

The structure of the agroforestry practice determines the magnitude of change in windspeed or radiation load (Barnes et al. 1998, Heisler and Dewalle 1988, Zhou et al. 2005). By manipulating the density and arrangement of the tree canopy, the wind flow patterns and radiation loads can be modified for the benefit of nearby crop fields and pastures (Brandle et al. 2009, McNaughton 1988). Evaporation from the soil surface is reduced, leaving more moisture for crop growth (Brandle et al. 2009). Water use efficiency is increased (Davis and Norman 1988). Soil temperatures tend to be warmer (Hodges et al. 2004) and humidity tends to be higher (McNaughton 1988). Daytime air temperatures tend to be warmer near the trees because of disruption of large-scale turbulence but tend to be cooler farther away (Cleugh 2002, McNaughton 1988). Agroforestry systems capitalize on these effects to benefit both crop and livestock production.

Future climate is expected to be warmer and drier in many agricultural regions; drought is a major concern (Walthall et al. 2012). Irrigation restrictions already are common in the Western United States (Schaible and Aillery 2012). Through microclimate modification, agroforestry practices, such as windbreaks, alley cropping, and silvopasture, can help crops and livestock use limited water more efficiently and thus ameliorate the effects of climate change.

Agroforestry practices vary in structure and design and, consequently, in their effects on microclimate. Garrett (2009) provides a comprehensive and detailed review of different agroforestry practices and their associated microclimate effects. Chapters include discussions of windbreaks (Brandle et al. 2009), silvopasture systems (Sharrow et al. 2009), and alley cropping systems (Garrett et al. 2009). The major conclusions of these chapters regarding how agroforestry practices affect crop and livestock production are presented in the following sections.

## Crop Production

The effect of windbreaks (fig. 2.3) on the yield of conventional crops has been well documented worldwide (Baldwin 1988, Brandle et al. 2009, Kort 1988). Yield improvements can be substantial, although results vary by crop, location, and year (table 2.1). For example, under windy conditions, when moisture is limited, shelter provides positive benefits for both quality and quantity of grain, forage, and vegetable crops. The yield benefit from a windbreak to crops in the field area more than offsets the decrease in yield from the area planted to trees (fig. 2.4). The precise mechanisms that produce this benefit can vary, but all are related to wind reduction and radiation control by the windbreak. For example, in Nebraska, overwintering wheat plants (*Triticum aestivum*) are protected from winter desiccation (Brandle et al. 1984, 1992). In Mediterranean environments, wheat yield increases are attributed to improvement in water use efficiency (Campi et al. 2009). In Australia,

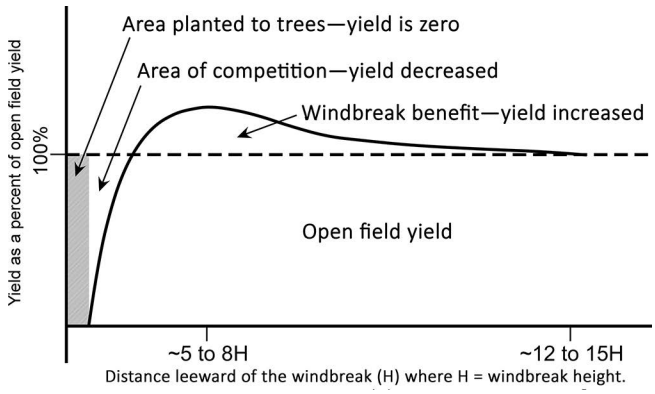
**Figure 2.3.** A windbreak of conifer trees provides year-round protection from wind for this cropland in Indiana. (Photo by Erwin C. Cole, USDA Natural Resources Conservation Service).

**Table 2.1.** Yield of many different crops can be increased by providing shelter with windbreaks.

| Crop | Average yield increase (%) |
|---|---|
| French beans | 6 |
| Oats | 6 |
| Potatoes | 6 |
| Spring wheat | 8 |
| Dry beans | 10 |
| Maize | 12 |
| Soybeans | 15 |
| Tomatoes | 16 |
| Rye | 19 |
| Grass hay | 20 |
| Winter wheat | 23 |
| Barley | 25 |
| Raspberry | 40 |
| Snap beans | 40 |
| Millet | 44 |
| Strawberry | 56 |

Source: Data from Baldwin (1988), Brandle et al. (2009), and Kort (1988).

**Figure 2.4.** The generalized profile of crop yield response to field windbreaks in the Great Plains. (Figure adapted from Read 1964 and Brandle et al. 2009).



the principle benefit of windbreaks was their ability to reduce wind erosion and subsequent crop damage (Sudmeyer et al. 2002, Sudmeyer and Flugge 2005).

Modeling studies by Easterling et al. (1997) using the Erosion-Productivity Impact Calculator and Mize et al. (2008) using the Shelterbelt Agroforestry Modeling System indicate that windbreaks have the potential to increase yields over unprotected fields under all but the most extreme scenarios predicted by climate models. Lower nighttime temperatures resulting from reduced windspeed, less mixing of the air, and reduced evapotranspiration are thought to account for most of the yield gains in sheltered crops (Easterling et al. 1997, Hatfield et al. 2011).

High winds during drought periods can also decrease yields because of abrasion to crop plants from blowing soil (Armbrust 1982, Finch 1988, Sudmeyer et al. 2002, Sudmeyer and Flugge 2005). Under a future warmer and drier climate, drought periods are expected to become more frequent and more extreme (Vose et al. 2016). Abrasion damage is a particular problem with production of fruit and vegetable crops (Norton 1988). In many cases, replanting becomes necessary, requiring additional inputs and expense. Wind control by agroforestry practices (windbreaks, riparian buffers, and alley cropping systems) can be effective at minimizing blowing soil. Properly designed windbreaks, for example, are effective to a distance from the windbreak of 10 times the height of the trees (USDA-NRCS 2014). Windblown soil particles in the air (dust) also degrade air quality and can create serious health issues for people, livestock, and wildlife (Williams and Young 1999), as explained in the section on Air Quality in this chapter.

In the longer term, erosion of soil by wind removes the finer soil particles, organic matter, and nutrients, which leads to reduced soil health. Furthermore, soil that is blown off site is deposited in lakes, reservoirs, and road ditches, requiring mitigation efforts. The economic costs associated with offsite impacts of blown soil can exceed the onsite costs of yield reduction from crop damage and soil loss (Huszar and Piper 1986).

Shade from agroforestry practices can help limit heat stress and improve yields of some crops. Crops such as cotton (*Gossypium hirsutum*) and soybean (*Glycine max*) have higher rates of field emergence when grown under moderated temperatures. Cotton exhibits earlier germination and higher survival rates when grown in the shade of pecan trees, where conditions are cooler and moister (Jose et al. 2004). Moderate shade can also improve growth in some crops; for example, two species of woody ornamentals, American beautyberry (*Callicarpa americana* var. *lactea*) and parsley hawthorn (*Crataegus marshallii*) have higher survival and faster growth under pecan alley cropping compared with monoculture (Fletcher et al. 2012). Warm-season legumes, hoary ticktrefoil (*Desmodium canescens*) and panicledleaf ticktrefoil (*D. paniculatum*) produce significantly greater dry weight and some forage species contain more crude protein when grown at 50 percent and 80 percent shade than in full sunlight (Lin et al. 1999, 2001). Shading and competition with trees for water and nutrients, however, can also negatively affect the yield of some crops. On the balance, Gillespie et al. (2000) saw no effect on corn yield in two alley cropping systems in Indiana. To adapt to future hotter climate, it will be important to identify and select effective combinations of agroforestry tree and crop species that capitalize on microclimate modification.

## Livestock Production

Predicted higher temperatures may pose a significant challenge in animal production systems. Elevated temperatures, especially when combined with high humidity, will reduce weight gain, pregnancy rates, and milk production and will also lower overall animal health (Walthall et al. 2012). In beef cattle operations, heat is a significant factor in biological efficiency (Gaughan et al. 2010, Tucker et al. 2008). For example, a reduction in deep body temperature of beef cattle by as much as 0.77 °C can improve gain rates by as much as 0.57 kilograms per day during summer heat stress periods (Higgins et al. 2011).

Providing shade is a recommended strategy for reducing summertime heat stress on livestock under a warming climate (Rowlinson 2008). Shade also helps improve milk yields, increase conception rates, and decrease mastitis in dairy cattle (Gregory 1995, Tucker et al. 2008). Shade is important for reducing heat load from direct sunlight, particularly in cattle with dull, dark hair coats (da Silva et al. 2003). Provision of shading using agroforestry practices may offset the effects of projected temperature increases on livestock production. By providing shade, silvopasture and livestock windbreaks can reduce the energy expended for thermoregulation, leading to higher feed conversion and weight gain (Brandle et al. 2009, Sharrow et al. 2009). Mitlöhner et al. (2001) found that cattle provided with shade reached their target body weight 20 days earlier than those without shade.

Increasing atmospheric $CO_2$ concentration may reduce the quality of livestock forages produced on grazing and pasture lands (Walthall et al. 2012). Higher levels of $CO_2$ will increase forage production but reduce overall forage quality because of the effects on plant nitrogen and protein content (Morgan et al. 2004). Shading, however, can increase forage quality, depending on the forage species (Lin et al. 2001). For instance, the shading component in silvopasture systems has been shown to improve forage quality in cool-season grasses by increasing protein content while reducing fiber (Bambo et al. 2009, Kallenbach et al. 2006). Higher forage quality combined with

shading to reduce animal heat stress suggests that silvopasture systems can be a viable strategy to sustain livestock production under climate change (Schoeneberger et al. 2012).

In some regions, such as the Central United States, periodic winter cold events are likely to become more extreme under a future climate (Kim et al. 2014) and threaten livestock production. Low temperatures, especially when combined with wind, decrease livestock production efficiency by requiring greater feed intake to maintain body temperature. The consequences of extreme cold events can create challenges to producers, exemplified by the October 2013 storm that resulted in the deaths of more than 45,000 livestock in South Dakota (Edwards et al. 2014). Reducing windspeed in winter by using agroforestry practices, particularly windbreaks, can lower livestock stress, improve livestock health, and increase feeding efficiency (Brandle et al. 2009, Gregory 1995). Winter protection can be especially critical for young lambs and calves during lambing or calving season. Cattle producers in Kansas indicate, on average, calving success increases by 2 percent if a windbreak protects the cows (Quam et al. 1994).

### Key Findings

Agroforestry practices can improve the productivity of conventional agricultural crops and livestock by enhancing the microclimate around them and, thereby, may ameliorate negative effects of climate change on agricultural production.

### Key Information Needs

- Improved models for predicting effects of agroforestry practices on crop yields under future climate scenarios.
- Identification of agroforestry tree and crop combinations that capitalize effectively on microclimate modification.
- Better documentation of forage and livestock yield responses in silvopasture systems.
- Revised agroforestry designs tailored to modern field geometries and management practices.

## Crop Diversity

Annual grain and oil-seed crops comprise the bulk of U.S. food and feed crop production and will continue to do so for much of the 21st century (Malcolm et al. 2012). In response to climate change, shifts in acreages for specific crops, changes in management decisions, and expansion of irrigation may compensate for some loss in yields in the short term (Walthall et al. 2012). Advances in plant breeding and development of genetically modified crops offer opportunities to develop crops more tolerant of drought and heat stress; however, most of our annual crops will remain particularly vulnerable. Maintaining annual crop production will become increasingly problematic, and the combined stresses associated with climate change are expected to decrease overall agricultural productivity in the second half of this century (Pryor et al. 2014, Walthall et al. 2012) (table 2.2).

**Table 2.2.** Percent change in U.S. production (averaged across climate change scenarios) relative to reference conditions.

| Crop | Average percent change in production | | | |
|---|---|---|---|---|
| | 2020 | 2040 | 2060 | 2080 |
| Barley (bushels) | – 1.9 | – 0.6 | – 3.5 | 1.0 |
| Corn (bushels) | – 8.1 | – 8.7 | – 13.8 | – 16.2 |
| Cotton (bales) | – 7.9 | – 6.1 | – 5.6 | – 5.9 |
| Hay (dry ton) | – 4.0 | – 0.6 | 2.7 | 4.2 |
| Oats (bushels) | – 8.7 | – 10.7 | – 16.1 | – 20.8 |
| Rice (cwt) | – 2.2 | – 2.5 | – 4.2 | – 6.1 |
| Silage (dry ton) | – 6.9 | – 9.5 | – 13.1 | – 14.4 |
| Sorghum (bushels) | – 15.1 | – 5.4 | – 14.0 | – 17.0 |
| Soybeans (bushels) | – 8.1 | – 8.8 | – 11.9 | – 14.3 |
| Wheat (bushels) | – 2.8 | 1.3 | 5.6 | 11.6 |

cwt = hundredweight.

Source: USDA-ERS (2015b).

Agroforestry practices may be capable of both mitigating the negative impacts of climate stressors on annual crop production and serving as resilient food production systems (Lin 2011, Matocha et al. 2012, Schoeneberger et al. 2012, Van Noordwijk et al. 2014, Verchot et al. 2007). Agroforestry food crops offer opportunities to replace production of annual grain and oil-seed crops on acres converted to agroforestry practices (fig. 2.5).

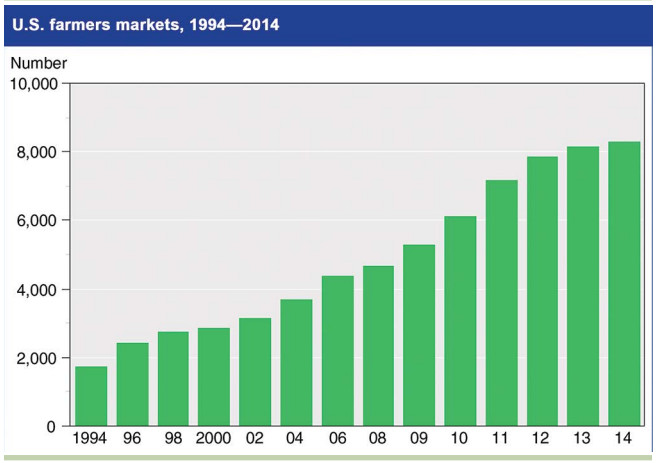
Agroforestry systems are multispecies mixes of perennials and annuals that are inherently more resilient to environmental stresses than annual-only cropping systems (Leakey 2014, Malézieux 2012, Smith et al. 2013). They have a higher degree

**Figure 2.5.** Agroforestry practices providing protection for annual crops and natural resources can be implemented with species that produce an additional crop, like this cherry crop in Michigan. (Photo by Lynn Betts, USDA Natural Resources Conservation Service).

of species diversity, larger root systems that hedge against climate extremes, and the ability to tolerate increased disturbance (Helzer 2010, Jose et al. 2009). Where winter chilling requirements do not become limiting, food-producing perennial crops such as fruits, nuts, and berries can provide resilience to climate extremes. Species mixes spread biological and financial risks across crops and seasons. Many agroforestry crops are also better suited to being grown on marginal lands than are annual crops (MacDaniels and Lieberman 1979, Molnar et al. 2013, Smith et al. 2013).

The production of specialty crops that can be grown in agroforestry systems is increasing in direct response to increasing demand for locally sourced foods (Johnson 2014, Low and Vogel 2011, USDA-ERS 2015a). Fruit, nut, and vegetable farms are eight times more likely to sell locally than are other farms (Low and Vogel 2011). According to statistics collected by the USDA Agricultural Marketing Service, the number of farmers markets has increased from 1,755 to more than 8,284, reflecting a 372-percent increase since 1994 (fig. 2.6) (USDA-ERS 2014). Agroforestry food crops can contribute to increasingly popular direct-to-consumer food systems.

**Figure 2.6.** Growth of local farmers markets are increasing the demand for specialty food crops, including agroforestry crops, and creating new marketing opportunities. (From USDA Economic Research Service using USDA Agricultural Market Service's Farmers Market Survey).




Agroforestry food systems are notable historically for their sustainability and resilience. For example, multistory food-producing systems have sustainably produced fruit, nuts, leafy vegetables, and other staple foods since ancient times (Ewel 1999, Wiersum 2004); tropical and subtropical agroforestry homegardens have demonstrated sustainable production for thousands of years (Torquebiau 1992, Vandermeer et al. 1998); and multistory agroforestry homegardens have been traditionally cultivated in temperate environments for at least two millennia (Clark and Nicholas 2013, Lelle and Gold 1994, Smith 1950).

Agroforestry is a form of multifunctional agriculture (Jose 2012, Leakey 2014, McIntyre et al. 2009, Picasso et al. 2011, Quinkenstein et al. 2009, Robertson et al. 2014, Van Noordwijk et al. 2011). When properly designed and maintained, food-producing agroforestry systems can simultaneously provide ecological services that annual crops do not, such as reducing nonpoint source pollution, sequestering carbon, sustaining long-term soil fertility, and enabling biological control through crop and ecosystem diversity (Batello et al. 2014, Clough et al. 2011, Davis et al. 2012, Ewel 1999, Jose 2012, Robertson et al. 2014, Schoeneberger et al. 2012).

The integration of food- and commodity-producing perennials into agroforestry practices has the potential to add millions of hectares to the production base of the United States without loss of protection of environmentally sensitive lands (Jose et al. 2012). Agroforestry practices like alley cropping, windbreaks, and riparian forest buffers can be designed to include food-producing species (e.g., fruits, nuts) (Schultz et al. 2009, Smith et al. 2013). Nonfood crops such as floriculture, biomass, and timber crops can also be incorporated into these practices (Schultz et al. 2009). Agroforestry production systems can produce greater total yields per unit area as compared with monocultures of the individual crops they include (Dupraz et al. 2005). The combination of diversified food and commodity production and provision of ecosystem services can impart greater economic and biological resilience to the effects of climate change than can conventional annual cropping systems.

If widely deployed, agroforestry practices scattered across the agricultural landscape can function as a patchwork of mosaics at different stages of maturity (early, mid, late) (Robertson et al. 2014, Subler and Uhl 1990), adding further resilience to the agroecosystem. Well-designed landscape mosaics can further spread economic and ecological risk and may lower some costs of production (Clark and Nicholas 2013, Smith et al. 2013).

## Key Findings

- Agroforestry systems incorporating appropriate species can be significant food production systems.
- Food-producing agroforestry systems are more resilient to climate stressors than are annual cropping systems.
- Agroforestry systems can diversify farm portfolios, spread risk, and increase both the economic and environmental resilience of farms.

## Key Information Needs

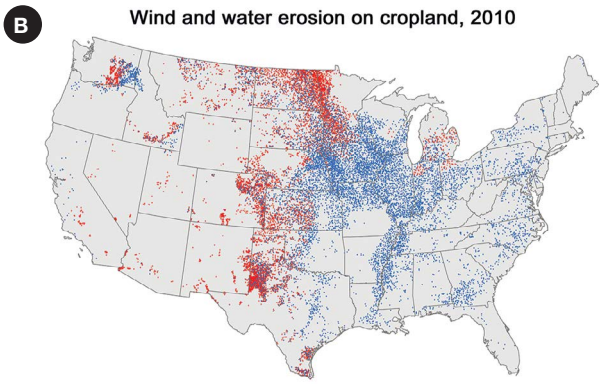
- Improved agroforestry systems for marginal and degraded lands.
- Identification of agroforestry tree and crop combinations that maximize positive interactions while minimizing competitive interactions between crops and trees.

- Better strategies for producing, distributing, and marketing food and nonfood products from agroforestry systems.

## Soil Resources

Climate change is predicted to include more frequent extreme rainfall events and longer drought periods, which would affect soil resources (Melillo et al. 2014). Increased precipitation intensity will lead to an exponential increase in the potential for soil erosion by water runoff (Garbrecht et al. 2014). Longer drought periods will increase the period of susceptibility of soils to erosion by wind (Nordstrom and Hotta 2004). Topsoil loss to erosion will reduce the health and productivity of the remaining soil resource and threaten the sustainability of agricultural production (Walthall et al. 2012) (fig. 2.7).

**Figure 2.7.** Soil erosion by water and wind jeopardizes soil health and the sustainability of agricultural productivity. Climate change is predicted to exacerbate conditions that lead to soil erosion. (A) Severe sheet and rill erosion on highly erodible soils in Iowa after heavy rains. The spring rains fell on soils that had no protection against soil erosion. (Photo by Lynn Betts, USDA Natural Resources Conservation Service). (B) Some agricultural regions currently experience high rates of soil erosion by water (blue dots) and wind (red dots). Each dot represents 100,000 tons per year. Soil erosion is expected to accelerate in response to climate change in most regions. (Data and map from 2010 USDA National Resources Inventory, USDA Natural Resources Conservation Service).




Appropriate agroforestry practices can reduce these threats by protecting soils from water and wind erosion and by rebuilding soil health in eroded soils (Jose 2009, Young 1989).

### Soil Erosion

Most soil erosion in agricultural fields occurs during large rainfall events. When the rainfall rate exceeds the infiltration capacity of soil, the excess water drains overland, dislodging topsoil and carrying it off the field. Soil erosion is accentuated by annual tillage that loosens the topsoil, reduces infiltration capacity, and removes surface debris that protects soil from being dislodged by raindrops and overland flow. Under current climate conditions, the average rate of soil erosion from tilled agricultural fields is much greater than the rate of soil regeneration leading to a substantial net loss of soil (Montgomery 2007). Under a future climate, greater frequency of extreme rainfall events will exacerbate this problem. At a national scale, soil erosion by rainfall is estimated to increase between 16 and 58 percent during the 21st century because of climate change (Nearing 2001, Nearing et al. 2004). Others have predicted similarly large increases in erosion rate (O'Neal et al. 2005, Segura et al. 2014).

Agroforestry practices such as alley cropping can markedly reduce the rate of soil erosion from crop fields and potentially counteract the increasing risk of erosion posed by climate change. An alley cropping system can be oriented and designed to stabilize soil and promote infiltration within the tree strips and to reduce the erosive force of overland flow across the cultivated field. Sediment outflow from fields with alley cropping has been measured to be 28 to 30 percent less than from fields without alley cropping (Udawatta et al. 2011b).

In drier regions of the United States, like the Great Plains, soil erosion by wind can be significant during drought periods. This region historically has experienced severe soil loss by wind erosion, such as experienced during the Dust Bowl years in the 1930s. The prospect of increasing length and severity of drought periods due to climate change raises the risk that periods of severe wind erosion may recur with greater frequency.

Of all the potential benefits of a windbreak agroforestry practice, wind erosion control is the most widely recognized and accepted (Brandle et al. 2009). The link between windspeed and wind erosion is well established. Properly designed windbreaks reduce windspeed near the ground surface (as described previously in the Commodity Production section) and significantly reduce wind erosion. In response to the Dust Bowl experience, soil conservation efforts established nearly 19,000 miles of windbreaks in the Great Plains (Droze 1977) (box 2.1). The success of that program led to similar efforts elsewhere in the United States and Canada and also in Argentina, Australia, China, New Zealand, and Russia (Cleugh et al. 2002, Mattis

1988, Miller et al. 1995, Peri and Bloomberg 2002, Sturrock 1984, Zhao et al. 1995). In the United States, however, most of the original windbreaks have been, and continue to be, removed as modern fields have increased in size and have changed shape to accept pivot irrigation systems. Where windbreaks have been removed, other techniques, such as conservation tillage and residue management, would be needed to limit wind erosion on a short-term basis, but they cannot replace the benefits of long-term perennial plantings.

## **Box 2.1.** Prairie States Forestry Project

Current wind erosion and airborne dust problems are likely to increase under climate change (see Soil Resources and Air Quality sections). The U.S. Government used agroforestry to address these same issues during the Dust Bowl period of the 1930s on the Great Plains, when millions of acres of farmland were literally being blown away. The persistent drought, poor soil management, and subsequent wind erosion in the region had far-reaching social, economic, and environmental impacts. Soil was lost at a tremendous rate and many farmers and ranchers were forced from their land, leading to the largest human migration in American history within a short period of time. Between 1930 and 1940, approximately 3.5 million people moved away from the Plains States (Worster 1979). Dust pneumonia, a form of lung disease, affected many residents in the region. The worst duststorms reached the east coast and blanketed cities such as Chicago and New York in "black snow."

In 1935, President Franklin D. Roosevelt initiated the Prairie States Forestry Project to combat the severe soil erosion. For the next 8 years, the U.S. Department of Agriculture, Forest Service, working with the Works Progress Administration (WPA) and Civilian Conservation Corps (CCC), planted windbreaks throughout the Great Plains States of Kansas, Nebraska, North Dakota, Oklahoma, South Dakota, and Texas. Although WPA and CCC workers planted the trees and shrubs, landowners were responsible for long-term care and maintenance of the windbreaks. Most of these windbreaks were 10 to 16 rows wide and a mile long. Even under the dry conditions of the time, most seedlings survived and, for the next 30 to 40 years, provided protection to the agricultural lands of the region. Nearly 220 million seedlings were planted, creating 18,600 miles of windbreaks occupying 240,000 acres on 30,000 farms (Williams 2005). Although many of these original windbreaks still exist around farmsteads, most of the wide-row field windbreaks have been removed to make way for center-pivot irrigation systems or field consolidation.

The Prairie States Forestry Project represents one of the largest and most focused efforts of the U.S. Government to address an environmental problem and is considered by some as a potential model for an effective climate change strategy (Sauer 2010). Viewed by modern standards, the project was conceived, designed, and implemented in a short period of time and incorporated effective top-down and bottom-up management styles. Although climate change is a more complex and global phenomenon than was the Dust Bowl, this past experience may hold important lessons for the current climate change problem.

*A giant duststorm rolls across eastern Colorado during the 1930s. (Photo by USDA Natural Resources Conservation Service).*

*Workers planting a windbreak in the Great Plains during the mid-1930s. (Photo by USDA Forest Service).*

*Landowners tending to their windbreak planted as part of the Prairie States Forestry Project during the 1930s. (Photo by USDA Forest Service).*

### Soil Health and Productivity

The erosion of fertile topsoil reduces soil productive capacity. Eroded topsoil consists of fine soil particles containing organic matter and nutrients. What remains is subsoil that has poorer physical, chemical, and microbiological properties for crop growth (Pimentel et al. 1995, Williams et al. 1981). Trees, shrubs, and grasses within agroforestry systems affect properties of soil directly beneath and adjacent to them. Compared with monocultured annual crops, perennial agroforestry vegetation can more quickly build and sustain higher levels of soil organic matter and nutrient content and create more favorable soil physical conditions for plant growth (Berg and Laskowski 2006, Cadisch and Giller 1997, Udawatta and Anderson 2008, Udawatta et al. 2009). All these soil improvements link to recycling of organic matter provided by plant litter, roots, and root exudates and to decomposition processes influenced by agroforestry shading and wind reduction that alter soil temperature and water regimes.

Soils in agroforestry systems often have better structure for infiltration and water storage capacity than do soils in annually cultivated fields (Bharati et al. 2002; Seobi et al. 2005; Udawatta et al. 2006, 2011a). These characteristics will be critically important under a drier and warmer climate. Improved soil porosity is consistently observed within agroforestry systems that include riparian buffers, field windbreaks, alley cropping, and silvopasture practices (Bharati et al. 2002, Kumar et al. 2010, Sauer et al. 2007, Seobi et al. 2005). Improved soil pore size distribution associated with perennial vegetation increases infiltration and water-holding capacity (Udawatta and Anderson 2008, Udawatta et al. 2011a). These changes in soil structure and porosity are resilient to disturbances such as raindrop impact (Amezketa 1999, Bronick and Lal 2005).

Soil fertility and nutrient-use efficiency of crops can be improved by the presence of nearby agroforestry trees. Nutrients are captured from the subsoil by roots of trees and recycled to the soil surface through tree litter and, along with additional nitrogen fixed by leguminous agroforestry trees, can be recaptured by nearby crops (Blazier et al. 2008, Karki et al. 2009, Nair 1993). This process can reduce the need for intensive and frequent fertilizer additions. Reestablishment of nutrient-cycling processes creates a more diverse and resilient soil fertility system.

Microbial communities and soil enzymes under trees are functionally different than those under annual crops, which may improve nutrient availability and plant growth in alley cropping systems (Lacombe et al. 2009, Mungai et al. 2005, Rivest et al. 2010, Udawatta and Anderson 2008, Udawatta et al. 2009). Emerging research suggests that agroforestry systems can support higher microbial diversity than annual monocropped fields (Unger et al. 2013) and may have a positive effect on soil biochemical properties and microbial resilience that results in higher crop productivity and tolerance to severe water stress (Rivest et al. 2013).

### Key Findings

- Agroforestry practices such as alley cropping and windbreaks can reduce soil erosion by water and wind and, thereby, protect long-term soil productivity.
- Agroforestry systems can enhance soil health by improving soil physical condition and fertility and by diversifying soil biological functions.

### Key Information Needs

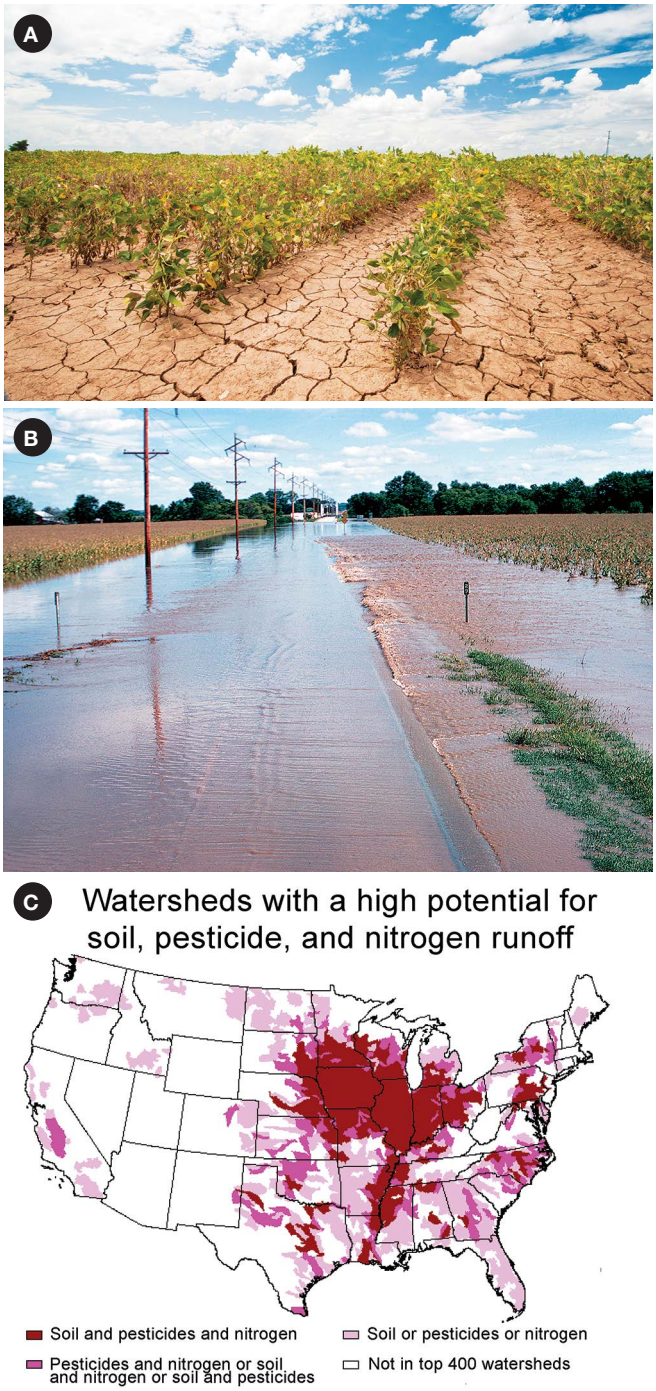
- Identification of optimal combinations of tree and crop species and spatial configurations for improving soil health, particularly on marginal or degraded lands.
- Better understanding of how to capitalize on below-ground structure and processes for improving water and nutrient uptake, especially under drought conditions.
- Documentation of crop productivity responses to agroforestry-related soil improvements.

## Water Resources

Water resources support crop and livestock production, and agricultural lands supply water for other uses, including wildlife and aquatic species, domestic consumption, energy production, and industrial and recreational purposes. Predicted increases in weather variability, including increasing frequency and intensity of heavy rainfall events and extended heat and drought periods, will affect water supply in ways that directly threaten agricultural production, infrastructure, and environmental quality (Melillo et al. 2014). Major impacts will include increasing drought stress on crops and livestock while water supplies for irrigation diminish, increasing flood and erosion damage to crops and supporting infrastructure, increasing water pollution by sediments and agricultural chemicals, accelerated sedimentation and diminishing water storage capacity in reservoirs for supply during drought and for flood control during storm events, and increasing water temperatures that degrade aquatic habitats (Bates et al. 2008, Brewer et al. 2014, Kundzewicz et al. 2014,Walthall et al. 2012, Whitehead et al. 2009, Wilbanks and Fernandez 2012) (fig. 2.8).

Agroforestry practices can reduce drought stress and demand for irrigation water by moderating water use by crops and livestock, lessen the severity of flooding and stream channel erosion by moderating stream discharge and peak stormflows, reduce water pollution by sediments and agricultural chemicals by protecting soils in fields from erosion and by filtering these

**Figure 2.8.** Water resources are expected to be affected by climate change in several ways. (A) Drought and heat stress in crops is expected to increase in severity. (Photo by Bob Nichols, USDA Office of Communications). (B) With climate change, flood damage to crops and transportation infrastructure is expected to become more frequent and severe. (Photo by Keith McCall, USDA Natural Resources Conservation Service). (C) Risk for water pollution by sediment, pesticides, and nutrients is high in many agricultural areas and is expected to increase with climate change. (Map by USDA Natural Resources Conservation Service, Resource Assessment and Strategic Planning Division, Map ID:BMW.1731, October 1997).




pollutants out of runoff from agricultural fields, and moderate excessively high stream temperatures that threaten aquatic biota by providing shade to stream channels (Schoeneberger et al. 2012, Walthall et al. 2012). Each of these benefits is described in more detail in the following sections.

## Drought

Agroforestry practices can reduce agricultural demand for water during drought. Windbreaks reduce crop water stress and conserve soil moisture by reducing windspeed across adjacent crop fields, thereby reducing evaporation losses from soil and transpiration by crops (Brandle et al. 2009). Silvopastures provide wind control and shade for livestock, thereby reducing heat stress and water needs (Sharrow et al. 2009). The benefits of wind control are described in greater detail in the Commodity Production section in this chapter.

Tree crops are more drought hardy than most herbaceous annual crops (Atkinson 2011, Fereres 1984). Drought hardiness is attributed to better stress tolerance and to extensive root systems that explore more soil for water (Chaves et al. 2002, Turner and Kramer 1980,). Agroforestry practices can increase soil porosity, reduce runoff, and increase soil cover, leading to increased water infiltration and retention in the soil profile, which can reduce moisture stress during low rainfall years (Anderson et al. 2009, Udawatta and Anderson 2008, Udawatta et al. 2002, Verchot et al. 2007). Under certain conditions, trees interspersed with crops can make more water available for use by adjacent crop plants. Through a process called hydraulic lift, deeper rooted trees can redistribute deep soil water supplies upward into the crop root zone and sustain crop plants during drought (Horton and Hart 1998, Yu et al. 2013). Under less extreme conditions, however, trees growing in close proximity to crop plants, such as along the edges of windbreaks or in closely spaced alleys, will compete with the crop plants for soil moisture and limit crop yield (fig. 2.4).

In many northern semiarid areas, such as the northern Great Plains, snow is a critical source of soil moisture for crop and forage production during the following growing season (Brandle et al. 2009). Without windbreaks, much of windblown snow is blown off the field and deposited in road ditches and gullies or behind fence rows or other obstructions (Greb 1980). Field windbreaks can help capture the moisture available in snow by slowing the wind and distributing the snow across the field. Snow capture and protection of crop plants from winter desiccation by windbreaks can increase wheat yields by 15 to 20 percent (Brandle et al. 1984, Kort 1988, Lehane and Nielson 1961).

## Flooding

Increasing rainfall intensities will produce larger stormflows in streams and rivers (Vose et al. 2016). In response, flooding

will increase and stream channels and banks will experience accelerated erosion as waterways adjust to the new flow regime. Flooding and stream channel erosion will damage crops and nearby transportation infrastructure such as roads, railways, and bridges (Kundzewicz et al. 2014, Walthall et al. 2012, Whitehead et al. 2009, Wilbanks et al. 2012).

Increasing forest cover in watersheds can reduce the total amount of runoff and lessen peak stormflows (Vose et al. 2016). Forest clearing increases total stream discharge and peak stormflows (Andréassian 2004, Bosch and Hewlett 1982, Mao and Cherkauer 2009, Twine et al. 2004). Reestablishing forest cover reverses this trend by a combination of increasing rainfall interception and evapotranspiration, increasing rainfall infiltration, and retarding the velocity of overland runoff flow toward stream channels (Anderson et al. 2009, Bartens et al. 2008, Johnson 1998, Kumar et al. 2008, Seobi et al. 2005, Trimble et al. 1987). This watershed-scale effect can be significant, even if trees are reestablished only in narrow strips in uplands or in streamside riparian zones (Salemi et al. 2012; Smith 1992; Udawatta et al. 2002, 2011b). In arid regions such as the desert Southwestern United States, however, establishment of streamside forest can reduce critical summer base flows because water uptake and transpiration rates by trees is greater than by other types of vegetative cover (Scott et al. 2000, Shafroth et al. 2005, Wilcox et al. 2007).

Forest vegetation on streambanks and floodplains provides better protection from the erosive forces of stormflow than do annual crops and natural herbaceous cover. Forested banks and floodplains experience much lower rates of erosion than those that are unforested (Allen et al. 2003; Beeson and Doyle 1995; Geyer et al. 2000; Hession et al. 2003; Laubel et al. 2003; Micheli et al. 2004; Thorne 1990; Zaimes et al. 2004, 2006). Along unstable streams, forest is more effective than herbaceous vegetation alone at reducing high bank erosion rates (Geyer et al. 2000; Harmel et al. 1999; Simon and Collison 2002; Zaimes et al. 2004, 2006). Computer models can reveal specific sites along stream courses where bank erosion is more likely to occur and where establishment of riparian forest buffers would be most effective at controlling the erosion (Tomer et al. 2003).

Streamside trees can have some negative local effects on flooding and erosion. Debris from trees can clog small streams and drainage ways, retarding storm drainage and worsening farmland flooding. Toppling of large trees can be a localized source of accelerated bank erosion (Montgomery 1997, Thorne 1990). The conversion of herbaceous vegetation on streambanks to forest may cause some limited channel widening (Davies-Colley 1997, Lyons et al. 2000, Stott 1997, Sweeney et al. 2004, Trimble 1997).

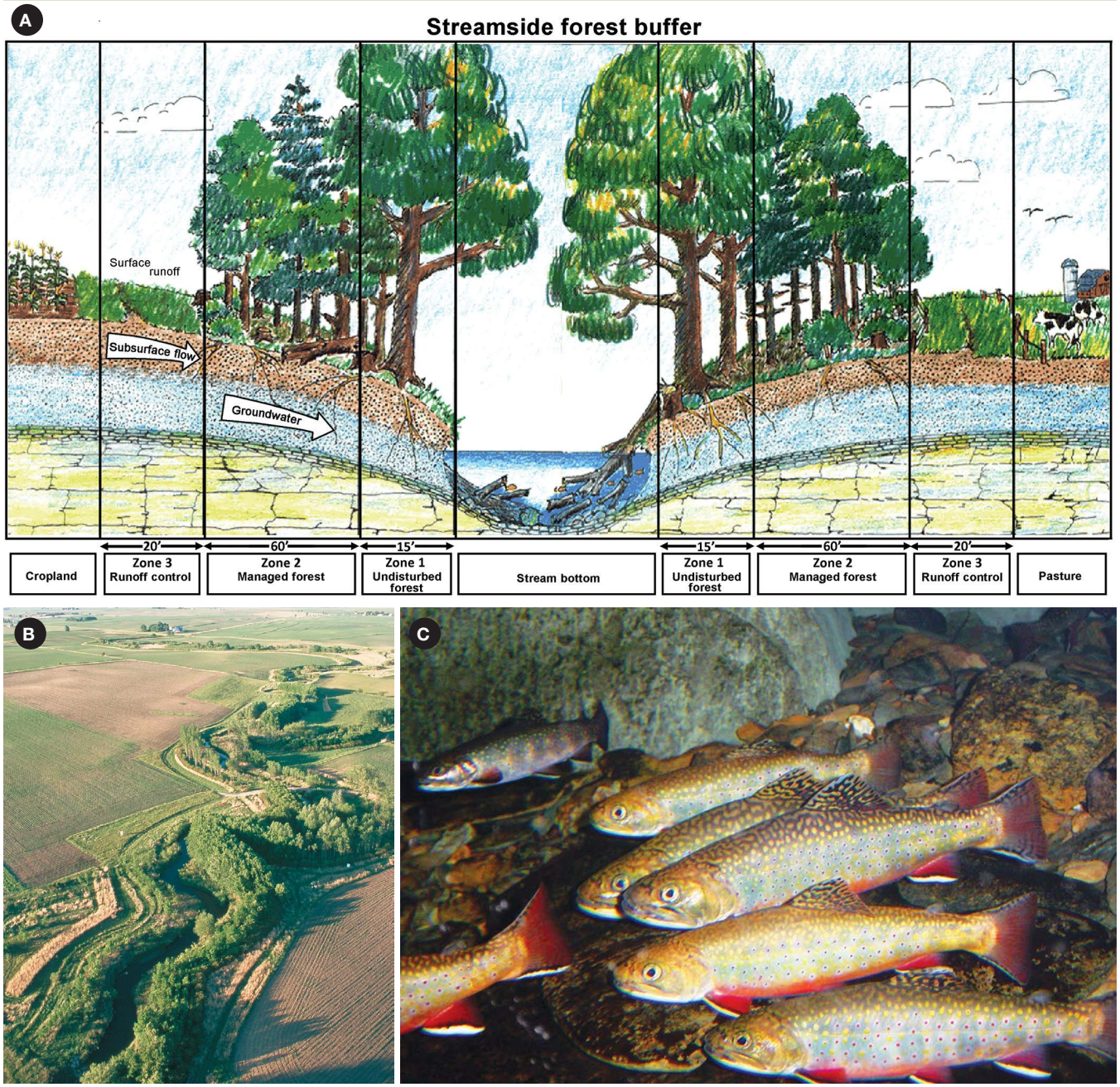
## Water Pollution

Nonpoint source water pollution by eroded sediments, fertilizers, and other agricultural chemicals contributes substantially to the impairment of U.S. waters (EPA 2013). Increasing rainfall intensities under climate change will produce even greater amounts of runoff, leading to accelerated soil erosion and chemical transport from agricultural fields and also from streambanks and channels (Walthall et al. 2012).

Establishing permanent vegetation in and around annually cultivated crop fields can reduce the amount of runoff and associated erosion from the fields (Dosskey 2001; Reeder and Westerman 2006; Renard et al. 1997; Udawatta et al. 2002, 2011b) and function to filter sediments and chemicals from runoff before they reach waterways (Baker et al. 2006; Dosskey 2001, 2010; Helmers et al. 2008; Lin et al. 2011; Lowrance et al. 1997; Mayer et al. 2007). The impact of permanent vegetation, such as in agroforestry practices, on pollutant runoff can be substantial. For example, nitrogen removal by a riparian forest buffer (fig. 2.9) can be as high as 90 percent or more of the runoff load from an adjacent crop field (Anderson et al. 2014, Dosskey 2001, Lowrance et al. 1997, Mayer et al. 2007). Similar levels of sediment removal are also possible (Dosskey 2001). Phosphorus removal will be somewhat less than that for sediment (Dosskey 2001, Hoffman et al. 2009, Lowrance et al. 1997, Schmitt et al. 1999). The level of impact achieved, however, depends strongly on where buffers are planted relative to agricultural source areas (Dosskey et al. 2002, 2013; Tomer et al. 2003; Walter et al. 2000, 2007). Greater reduction will be achieved where permanent cover is interspersed with crops (e.g., alley cropping) on more erodible lands and where positioned in the path of runoff flow (e.g., riparian forest buffer). Technical tools have been developed that can identify the most effective sites in cultivated watersheds for pollution control using agroforestry practices (e.g., Dosskey et al. 2011, 2013). Even greater impact can be achieved by converting marginal cultivated land to a permanent silvopasture agroforestry system.

Several agricultural practices, however, can lead to underperformance of agroforestry practices for pollution control. Agricultural drainage practices, such as building ditches and subsurface tile drains, transport pollutants directly from fields into streams without the benefit of filtering through riparian forest buffers (Dosskey et al. 2002, McClellan et al. 2014). Special buffer designs have been developed for these pathways and also for redirecting such flows back into a riparian buffer system (Schultz et al. 2009). Filtering of large amounts of pollutants by riparian buffers, whether sediments or nutrients, cannot continue indefinitely without maintenance actions because sediment and nutrient accumulation can eventually saturate the retention capacity of a buffer (Dillaha et al. 1989,

**Figure 2.9.** Riparian forest buffer is an agroforestry practice that protects water quality and aquatic habitat. (A) A generic design for a riparian forest buffer was developed in the early 1990s by the USDA Forest Service. (Welsch 1991). This model was later modified and adopted as a conservation practice by the USDA Natural Resources Conservation Service. (B) A riparian forest buffer recently established among cropland in central Iowa. (Photo by Lynn Betts, USDA Natural Resources Conservation Service). (C) A clear stream with healthy brook trout. (Photo by U.S. Fish and Wildlife Service, Southeastern Region).




Dosskey et al. 2010). Maintenance actions include the periodic removal of accumulated sediments and the harvest and removal of vegetation and its accumulation of nutrients.

Increasing sediment loads under climate change likely will produce a compounding negative effect on water supply in irrigation-dependent agricultural regions such as the Great Plains. More intense rainfall events will accelerate soil erosion and subsequent sedimentation in water storage reservoirs and more quickly diminish the capacity to supply water during intervening drought periods (Kundzewicz et al. 2014, Whitehead et al. 2009, Wilbanks et al. 2012). Longer, hotter drought periods will reduce soil cover by crop and pasture vegetation and leave the soil increasingly vulnerable to accelerated erosion (Walthall et al. 2012) and sedimentation during subsequent rainfall events. Permanent vegetative cover in the form of drought-hardy agroforestry practices can maintain soil

protection through drought periods and storm events and can filter sediments from runoff, thereby maintaining the functional lifespans of water supply reservoirs.

### Water Temperature

A predicted rise in stream water temperature may be one of the more significant effects of climate change on stream biota (Mohseni et al. 1999, Rieman et al. 2007, Wenger et al. 2011b, Wu et al. 2012). Elevated water temperature threatens the sustainability of existing aquatic communities, particularly cold-adapted fish species such as salmon and trout (Caissie 2006; Dunham et al. 2007; Mohseni et al. 2003; Poole and Berman 2001; Rieman et al. 2007; Wenger et al. 2011a, 2011b). Higher water temperature can also spur the growth of toxin-producing algal species (Whitehead et al. 2009).

Shade provided by riparian forest buffers can moderate increases in stream water temperature. Removal of the streamside forest, which is common in agricultural landscapes, is a major stressor of stream health in the United States (EPA 2013, Sweeney and Newbold 2014). Unshaded streams, especially smaller streams, experience higher summer temperatures than those under full shade (Sweeney and Newbold 2014). Streamside forested buffers of at least 30 meters (m) in width may be sufficient for providing maximum thermal protection in small streams (Sweeney and Newbold 2014). The degree to which a rise in water temperature can be moderated, however, will also depend on other factors, such as the size of the stream, relative contribution of groundwater to total streamflow, other land uses in the watershed, and their cumulative effects throughout the stream network (Beschta and Taylor 1988, Callahan et al. 2014, Groom et al. 2011, Luce et al. 2014, Sweeney and Newbold 2014). Mathematical modeling has been used to integrate effects of multiple factors and to predict stream temperatures under future climate scenarios (e.g., Arismendi et al. 2014, Daraio and Bales 2013, Luce et al. 2014).

Most water resource benefits of agroforestry have a lag time between installation and impact. Functions such as providing shade, wind protection, restoring soil permeability, and developing surface debris will accrue slowly as trees grow (Dosskey et al. 2010). As a consequence, many benefits to water supply and to pollution, flood, and temperature control likewise will accrue slowly. Furthermore, benefits to streamflow, pollution control, and temperature accrue at the watershed scale so that their level of benefit will depend largely on the extent of land coverage by appropriately designed agroforestry practices.

### Key Findings

Implementation of agroforestry practices on otherwise cultivated annual cropland and herbaceous pastures can offset threats to water resources by—

- Reducing water stress in nearby crops and livestock through microclimate (wind, shade) modification.
- Protecting streambanks and engineered infrastructure from erosion damage during stormflows.
- Moderating water pollution.
- Moderating high stream temperatures and protecting cold water-dependent biota.

### Key Information Needs

- Enhanced planning tools to assist managers with optimum placement and design of agroforestry practices for effective control of erosion and water pollution.
- Documentation of impacts of agroforestry implementation on water resources at the watershed scale.

## Air Quality

Weather and climate factors such as temperature, humidity, and wind influence the emissions, transport, dilution, transformation, and eventual deposition of air pollutants (Kinney 2008). Changes in these variables due to climate change will influence air quality, contributing to potential impacts on public health, safety, and quality of life. For instance, more than 20 million people in the Midwestern United States experience air quality that fails to meet national ambient air-quality standards (Pryor and Barthelmie 2013). Climate change is expected to exacerbate human health problems by increasing air pollution (Melillo et al. 2014).

Agricultural operations can be a significant source of air pollutants (Aneja et al. 2009). For example, particulate matter emitted from agricultural lands in the Columbia Plateau region of the Pacific Northwest is a major contributor to poor air quality (Sharratt et al. 2007). Other air pollution concerns arising from agriculture include odor and ozone. Agroforestry may reduce the effects of climate change on ambient air quality by buffering and protecting agricultural lands. The capacity for these services is described in the following sections for each type of air pollutant.

### Dust

Particulate matter (PM) emissions from agriculture in the United States contribute about 14 percent of $PM_{2.5}$ emissions and approximately 22 percent of $PM_{10}$ emissions (EPA 2011). A significant portion of these emissions consists of dust from cropping systems and livestock operations (EPA 2011). Airborne dust is a human health concern across many agricultural areas in the United States (Gares et al. 2006, Sharratt et al. 2007, Stout 2001) (fig. 2.10). Elevated dust in the atmosphere

**Figure 2.10.** Blowing dust is a continuing air-quality problem in semiarid regions and is likely to worsen with climate change. A duststorm engulfs Brownfield, TX, on June 22, 2006, reducing air quality and harming public health. This storm caused several traffic accidents, resulting in a fatality and several injuries. (Photo by David Drummond).

can lead to skin and eye irritations, shortness of breath, asthma, and other respiratory disorders that contribute to significant healthcare costs (Clausnitzer and Singer 2000, Smith and Lee 2003, Williams and Young 1999). Poor visibility due to windblown dust also contributes to highway accidents and traffic fatalities.[1] Dust can be transported from regional to intercontinental scales, creating problems and hazards well beyond the source (Chin et al. 2007).

Predicted hotter, drier summers under climate change will likely lead to increased drying of soils, wind erosion, and airborne dust (Lee et al. 1996, Zobeck and Van Pelt 2006). Under higher greenhouse gas emission scenarios, drought is projected to become more common throughout most of the Central and Southern United States, contributing to higher airborne dust levels due to a reduction in vegetative cover (Lee et al. 1996, Melillo et al. 2014). Bioaerosols, such as fungal spores and endotoxins, are likely to be more of a problem under drier conditions (Boxall et al. 2009). Duststorms associated with drought conditions have been associated with increased incidence of Coccidioidomycosis (an infection referred to as valley fever, which is caused by a soil-borne fungal pathogen) in Arizona and California (Comrie 2005). Although the capacity of current climate models to predict future windspeeds is limited, estimated reduction in windspeeds in some U.S. regions due to climate change may offset some of the increased wind erosion potential (Breslow and Sailor 2002, Sailor et al. 2008, Segal et al. 2001).

Windbreaks, through a variety of physical processes, can reduce windspeed over the land surface and thereby reduce the mobilization and transport of dust and associated particulates (Heisler and Dewalle 1988, Tibke 1988). The zone of reduced windspeed typically extends a distance equivalent to 10 to 20 tree heights downwind of a windbreak, so multiple barriers are often required to effectively control wind erosion from large fields (Tibke 1988). Trees can also filter the air by intercepting airborne particles (Hill 1971). Trees have been observed to reduce dustfall by 30 to 42 percent and total suspended particles by 11 to 13 percent (Dochinger 1980) (see box 2.1 describing agroforestry's role in mitigating the 1930s Dust Bowl). The perennial vegetation used in agroforestry practices can also reduce the area of farm soil exposed to erosion (Asbjornsen et al. 2014).

## Odor

Odor emitted from livestock and poultry production facilities can be a significant problem for human health, quality of rural life, and local economies (Donham et al. 2007, Palmquist et al. 1997, Wing and Wolf 2000). Odors from these facilities can be offensive and cause eye, nose, and throat irritations; headaches; nausea; palpitations; and other symptoms (Heederik et al. 2007, Schiffman and Williams 2005, Thu 2002). Odors arise primarily from manure decomposition and consist of a complex mixture of gaseous and particulate compounds (Bottcher 2001). Depending on weather conditions, odorous compounds can be perceived by residents more than 5.5 kilometers (km) from their source (Guo et al. 2005).

Predicted warmer temperatures will increase the production of odorous compounds through faster anaerobic decomposition of manure (Miner 1995). Odor transport is also favored by stable atmospheric conditions, low windspeed, and high ambient temperature (Xing et al. 2007), conditions likely to increase under projected climate scenarios (Melillo et al. 2014).

Evidence suggests that windbreaks located adjacent to livestock production facilities can help mitigate odors through a mix of physical and social dynamics. Trees and shrubs can filter and intercept odor-causing particulates and gases, in part, because of the large surface area provided by plant foliage (Hill 1971, Khan and Abbasi 2000). Windbreaks can lift the odor plume into the lower atmosphere, aiding in dilution and dispersion (Lin et al. 2006). Land deposition of odorous particulates and aerosols can occur downwind of the windbreaks due to reduced windspeeds (Laird 1997, Thernelius 1997). Trees may serve as a biological sink for the chemical constituents of odor after interception (Hill 1971, Tyndall and Colletti 2007). Enhancing

[1] KOAA Channel 5: January 13, 2014. http://www.koaa.com/news/blowing-dust-causes-multiple-accidents-on-i-25/. *Lincoln Journal Star*: April 29, 2014. http://journalstar.com/news/local/dust-storm-chokes-i--traffic-in-panhandle/article_f92ddcd6-b48f-5469-a462-1c5dcab11355.html?comment_form=true. KSAL: April 30, 2014. http://www.ksal.com/drought-wind-causing-big-dust-storms/.

the aesthetics of livestock production sites with vegetation such as windbreaks has also been shown to reduce the perception of odor (Kreis 1978, Mikesell et al. 2001, Tyndall and Colletti 2007).

Odor concentrations can be reduced by 6 to 66 percent when measured downwind from windbreaks (Hernandez et al. 2012, Lin et al. 2006, Malone et al. 2006, Parker et al. 2012). Although windbreaks can contribute to reducing concentrations of odorous compounds, it is recommended that windbreaks be viewed as complementary technology to be used with a suite of odor management strategies (Tyndall and Colletti 2007).

### Ozone

Ground-level ozone causes respiratory problems for humans and damages sensitive vegetation, including crops and forests. Climate change is expected to increase summertime ground-level ozone in polluted regions by 1 to 10 parts per billion during the coming decades (Jacob and Winner 2009). Nonattainment of ozone air-quality standards is typically an issue in urban areas; however, some U.S. agricultural regions, such as the San Joaquin Valley in California, also suffer from high ozone levels (Yates et al. 2011). Although ozone is not emitted directly from agricultural operations, it is formed through the chemical reactions of nitrogen oxides (NOx) and volatile organic compounds (VOCs) that are considered to be ozone precursors. These ozone precursors can be produced by agricultural processes such as decomposition of plant and animal wastes, combustion engines in farm equipment, burning of crop residue, and applications of pesticides and nitrogen fertilizer (Yates et al. 2011).

Agroforestry can help reduce ground-level ozone indirectly by reducing NOx and VOC emissions. Agricultural pesticide applications are a significant source of VOC emissions and methods to reduce the number of applications will reduce the concentration of VOC emissions (Yates et al. 2011). Biological pest control provided by agroforestry practices may reduce pesticide applications that contribute to VOC emissions. Agroforestry practices can facilitate beneficial insect dispersal into fields and predation on pest species, reducing pesticide use (Bianchi et al. 2006, Chaplin-Kramer and Kremen 2012, Griffiths et al. 2008, Holland and Fahrig 2000, Morandin et al. 2014) (see Biodiversity section for additional information). Increasing the area occupied by woody vegetation can reduce the number of equipment passes, reducing fuel use and emissions (Brandle et al. 1992). Vegetation can intercept and serve as a sink for VOCs and NOx (Nowak et al. 2000, 2006); however, trees can also emit VOCs and may offset some of the trapping benefit (Nowak et al. 2000). Selecting tree species that are low emitters of VOCs may reduce this effect (Taha 1996). The overall net impact of agroforestry on ozone precursors is still unknown and requires further investigation.

### Key Findings

- Agroforestry practices are an effective means to reduce human health impacts from windblown dust and other particulate matter.
- Windbreaks can aid in reducing odors from livestock production facilities.
- Agroforestry practices can decrease ozone precursors.

### Key Information Needs

- Enhanced tools for locating and designing agroforestry practices to improve air quality.
- Better understanding of how to reduce odor using agroforestry practices.
- Documentation of the effectiveness of agroforestry practices on mitigating ground-level ozone.

## Biodiversity

Biodiversity provides the fundamental building blocks for the many goods and services that are derived from agroecosystems (Altieri 1999). Declines and changes in biodiversity can have direct or indirect impacts on ecosystem function, persistence, and services (Cardinale et al. 2012). Many stressors, such as habitat loss and degradation, invasive species, overuse, pollution, and disease, currently are impacting biodiversity (MEA 2005). Climate change is another stressor that will exacerbate many of these problems, affecting the services that biodiversity provides to society (Staudinger et al. 2012). Climate change likely will reduce crop pollination by animals by increasing phenological mismatching between pollinators and plants (Kjøhl et al. 2011, Polce et al. 2014), compound existing stressors on managed honey bee colonies (Reddy et al. 2013), displace native pollinator species by invasion of incompatible alien plants (Staudinger et al. 2012), and result in other impacts (Melillo et al. 2014, Staudinger et al. 2012). Climate change is expected to accelerate insect resistance to pesticides because of longer growing seasons yielding more generations per year (Walthall et al. 2012). Habitat conditions, both terrestrial and aquatic, will be altered by changes in precipitation and temperatures (Staudinger et al. 2012). Species that are unable to shift their geographic distributions or have narrow environmental tolerances will be at an increased risk of extinction (Mantyka-Pringle et al. 2012, Staudinger et al. 2012).

Agroforestry has the capacity to conserve biodiversity while promoting agricultural production (Jose 2012) and can be used to enhance resilience to climate change (Schoeneberger et al. 2012). Agroforestry plays five major roles in conserving biodiversity by providing (1) perennial habitat for species in

otherwise monocultured annual croplands; (2) preservation of germplasm for sensitive species; (3) a productive alternative to land clearing for monocultured annual crops; (4) corridors between habitat remnants needed for conservation of area-sensitive plant and animal species; and (5) erosion control and water quality protection, among other services, that prevent the degradation and loss of habitat (e.g., Jose 2009, 2012). The following sections summarize the important benefits and tradeoffs of using agroforestry practices to mitigate some climate change impacts on biodiversity.

## Pollination

More than 30 percent of food production relies on insect pollination, overwhelmingly provided by both European honey bees and wild native bees (Klein et al. 2007). Pollination services by managed honey bee colonies are expected to decline under predicted climate change scenarios due to impacts on their biology, behavior, and distribution (Reddy et al. 2013). Given the challenges facing managed honey bee colonies, it is important to diversify the pollinators on which growers rely. Wild native bees, which number more than 4,000 species in North America, pollinate crops worth at least $3 billion annually in the United States (Losey and Vaughan 2006). Conserving a diverse assemblage of pollinators, with different traits and responses to ambient conditions, is considered one of the best ways to minimize risk due to climate change (Kjøhl et al. 2011, Rader et al. 2013, Winfree et al. 2007). Native bees and other pollinators can benefit from agroforestry in several ways.

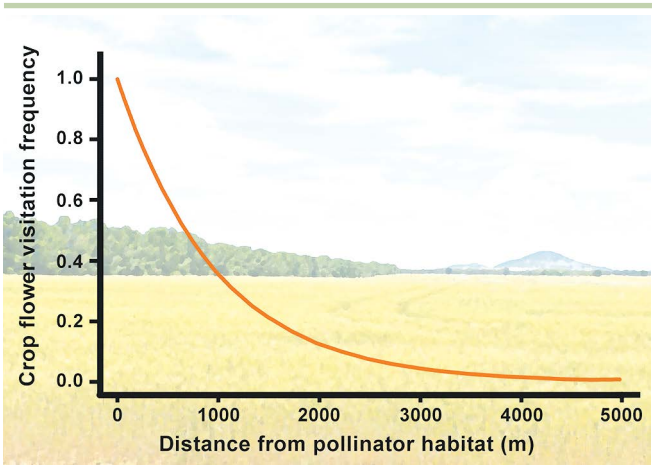
When appropriate tree and shrub species are used in agroforestry practices, these woody plants can provide important sources of pollen and nectar for pollinators, especially when crops are not in flower (Hannon and Sisk 2009, Miñarro and Prida 2013). These species can provide flowers of various sizes, shapes, and colors that support a diverse community of bees and other pollinators (Nicholls and Altieri 2013, Potts et al. 2003, Roulston and Goodell 2011). Enhancing plant diversity through agroforestry can alleviate the potential spatial and phenological mismatch between pollinators and plants by offering a variety of resources to enhance pollinator stability under climate variation (Kjøhl et al. 2011, Polce et al. 2014). Providing substantial floral resources throughout the growing season is critical to sustaining an adequate population of pollinators that can effectively pollinate a crop (Morandin and Kremen 2013, Morandin et al. 2011). For instance, agroforestry practices incorporating early flowering species like willows (*Salix* spp.) can provide some of the first pollen and nectar resources of the season, boosting early-season pollinator populations (Ostaff et al. 2015).

Agroforestry practices can provide nesting habitat for native bees. Approximately 30 percent of native bees are solitary woodnesters that require trees and shrubs for nesting (Cane et al. 2007, Grundel et al. 2010, Potts et al. 2005). Some build their nests inside hollow tunnels provided by soft, pithy centers of branches or tunnels left behind by wood-boring beetle larvae; others excavate their own tunnels. About 70 percent of native bee species create nests under ground and require undisturbed ground such as that under trees and shrubs not subject to tillage or soil disturbance (Cane et al. 2007, Potts et al. 2005). Bumble bees (*Bombus* sp.), some of the most effective native pollinators, often construct ground-level nests at the interface between fields and linear woody habitat such as hedgerows and windbreaks (Kells and Goulson 2003, Svensson et al. 2000). Bumble bee nest densities can be twice as high in these linear woody habitats compared with grassland and woodland habitats (Osborne et al. 2008).

Agroforestry practices can offer habitats with favorable microclimate conditions for pollinator activity. The practices can provide numerous niches that allow pollinators to find suitable sites for thermal regulation (Kjøhl et al. 2011, Pollard and Holland 2006). Windbreaks and other practices reduce windspeeds in fields, minimizing the desiccation of petals and loss of pollen viability (Wilcock and Neiland 2002) while also allowing pollinators to forage during high wind events that would normally reduce or prohibit foraging (Brittain et al. 2013).

Agroforestry practices can provide pollinator habitat close to crops. Pollinator visits to a crop drop off dramatically when the pollinator habitat is not located nearby (Dramstad 1996, Klein et al. 2012, Morandin and Kremen 2013, Morandin et al. 2014, Ricketts et al. 2008) (fig. 2.11). Fruit set of pollinator-dependent crops is estimated to decrease by 16 percent at 1 km distance from the nearest pollinator habitat (Garibaldi et al. 2011). Reducing the distance between pollinator habitat at the field and landscape scales can result in greater pollination and yield production (Benjamin et al. 2014, Holzschuh et al. 2012).

**Figure 2.11.** The effectiveness of pollination declines with increasing distance that pollinators must travel from their natural habitat. Agroforestry practices such as hedgerows and windbreaks can provide the critical habitat at field margins that native pollinators require. (Data from Ricketts et al. 2008).



Pollinators, particularly bumble bees, use linear habitat features to travel from field to field, increasing pollination activity and seed set (Cranmer et al. 2012, Van Geert et al. 2010). Agroforestry practices can provide pollinator habitat and travel corridors at these spatial scales while simultaneously offering other services, such as microclimate benefits, to crops and soil protection.

Bees can be negatively affected by exposure to many agricultural pesticides, ranging from direct contact to inadvertent spray drift (Arena and Sgolastra 2014). Agricultural spray drift is predicted to rise due to increased pesticide volatility under predicted warmer temperatures (Bloomfield et al. 2006). Windbreaks, hedgerows, riparian forest buffers, and alley cropping can reduce pesticide spray drift from coming onto or leaving a farm. Branches, leaves, and stems of woody plants can capture pesticide particles, and the windspeed reduction at the application site can reduce movement of pesticides off their target (Kjær et al. 2014, Lazzaro et al. 2008, Otto et al. 2009, Richardson et al. 2004). Spray drift reductions of 80 to 90 percent can be achieved with woody buffers; however, because data gaps for using this method accurately still exist and buffer vegetation can be harmed by pesticides, plant species selection is critical (Ucar and Hall 2001). Agroforestry practices can also serve as safe havens for pollinators if adequately protected from spray drift (Davis and Williams 1990, Lazzaro et al. 2008, Longley et al. 1997).

## Biological Pest Control

Insect pests are responsible for 18 percent of the loss in crop production globally (Oerke 2006), and this loss is expected to increase under a warmer climate (Walthall et al. 2012). Beneficial insects, such as arthropod predators and parasitoids, suppress populations of insect pests in agricultural crops, an ecosystem service that has been estimated at $4.5 billion annually in the United States (Losey and Vaughan 2006). Supporting biological pest control through agroecosystem diversification may be a strategy for suppressing pest outbreaks under a changing climate (Lin 2011). Diversification at the farm and landscape level has been shown to increase beneficial insect abundance and diversity in crops, although the overall impact on pest control is less well documented (Chaplin-Kramer and Kremen 2012, Chaplin-Kramer et al. 2011, Shackelford et al. 2013). Increasing habitat diversity with agroforestry practices can support biological pest control in several ways.

Agroforestry practices can provide a food supply for beneficial insects when crop pests are not available (Gareau et al. 2013, Morandin et al. 2011, Stamps and Linit 1998). In annual cropping systems, beneficial insects lack continuous sources of alternative prey. Agroforestry practices also offer stable habitat that benefits reproduction, overwintering, and refuge from perturbations of farming practices (Pywell et al. 2005, Varchola and Dunn 2001).

Agroforestry practices within fields (e.g., alley cropping) or adjacent to fields (e.g., windbreaks, hedgerows, riparian forest buffers) facilitate beneficial insect dispersal into fields (Bianchi et al. 2006, Chaplin-Kramer and Kremen 2012, Griffiths et al. 2008, Holland and Fahrig 2000). Pest control from parasitism has been found to extend 100 m from hedgerows (Morandin et al. 2014). Reducing wind in fields can also significantly aid beneficial insects in finding and consuming pests. Wind barriers can improve crop pest reduction by beneficial insects by up to 40 percent (Barton 2014). In some cases, however, trees and shrubs may inhibit movement of certain beneficial insects, potentially limiting their effectiveness for controlling crop pests (Mauremooto et al. 1995).

Birds also use the woody habitat in agroforestry practices and can contribute to pest control, although the impact of this service is still unquantified (Kirk et al. 1996, Puckett et al. 2009, Tremblay et al. 2001). Bats may also provide pest control (Boyles et al. 2011), but this service has been explored primarily in tropical regions (Maas et al. 2013). The role of birds and bats in controlling pests warrants further investigation.

In some cases, agroforestry practices may exacerbate pest problems by protecting insect pests, allowing them to maintain and rebuild populations to reinvade crop areas (Slosser et al. 1984). Certain plant species might also provide a host for crop pests. For example, European buckthorn (*Rhamnus cathartica*), a species historically used in agroforestry plantings, has proven to be invasive and an overwintering host for the Asian soybean aphid (*Aphis glycines*) (Heimpel et al. 2010). Choosing the right practice for a particular location and carefully selecting and managing plants will be critical to minimize potential problems (Griffiths et al. 2008).

## Corridors

Climate change is intensifying the negative cumulative effects of habitat loss and fragmentation on biodiversity (Staudinger et al. 2012). Habitat fragmentation will likely impede the ability of many species to respond, move, and/or adapt to climate-related impacts (Mantyka-Pringle et al. 2012). Enhancing connectivity between remaining habitat fragments across landscapes may reduce population fluctuations and extinction risk and promote gene flow and adaptation (Heller and Zavaleta 2009, Mawdsley et al. 2009). Connectivity can be enhanced by establishing corridors and stepping-stone reserves or by taking management actions that enhance landscape permeability (Krosby et al. 2010). Although corridor benefits are species dependent, corridors are most likely to benefit species with slow-growing populations that have low survivorship when dispersed through fragmented landscapes (Hudgens and Haddad 2003).

Agroforestry practices such as windbreaks, hedgerows, and riparian forest buffers can function as forest corridors in the agricultural landscape (e.g., Haas 1995, Hilty and Merenlender 2004). Corridors can be effective for species movement although evidence for supporting population viability is currently limited (Davies and Pullin 2007, Gilbert-Norton et al. 2010). Minimal migrations (i.e., one individual per generation) between habitat patches, however, may minimize loss of genetic diversity (Mills and Allendorf 1996). For example, in the intensely farmed Tensas River Basin, threatened Louisiana black bears (*Ursus americanus luteolus*) use riparian forest buffers to travel between forest patches to forage and breed (Anderson 1997) (fig. 2.12). Agroforestry practices like alley cropping, silvopasture, and forest farming also create landscape structure similar to natural forest and increase permeability of agricultural landscapes to animal movement and population persistence (Eycott et al. 2012, Watling et al. 2011). In some regions, however, forest corridors and habitats may be detrimental to grassland species (Pierce et al. 2001).

Farmers often view corridors and other noncropped habitat as a reservoir for problem species, such as weeds, that can invade their fields—a perception that may increase due to the prediction that weed populations will increase under climate change (Walthall et al. 2012). Corridors can provide habitat for weed species and may function as invasion conduits, but they are not a major source of weeds in agricultural fields (Boutin et al. 2001, Devlaeminck et al. 2005, Reberg-Horton et al. 2011, Wilkerson 2014). Through management such as mowing and maintaining perennial vegetative cover, potential weed issues can be minimized and, in some cases, corridors may serve as barriers to weed invasion (Boutin et al. 2001, Wilkerson 2014). Some have expressed concern that providing wildlife corridors such as riparian forest buffers and hedgerows in the vicinity of fruit and vegetation fields can increase food safety risks if wildlife is a disease vector for pathogens such as *Escherichia coli* O157:H7 (Beretti and Stuart 2008). Current evidence, however, suggests wildlife is not a significant source of food-borne pathogens and that wildlife habitat adjacent to fields does not increase food safety risks (Ferens and Hovde 2011, Ilic et al. 2012, Karp et al. 2015, Langholz and Jay-Russell 2013).

## Key Findings

- Agroforestry practices can support crop pollination and biological pest control by providing the habitat needs of native pollinators and beneficial insects.
- Pollinators, beneficial insects, and other flora and fauna species can be protected from pesticide applications through the use of agroforestry practices.
- Habitat connectivity may be augmented with agroforestry practices, potentially enabling flora and fauna species to adapt to climate change.

**Figure 2.12.** The Louisiana black bear was once abundant in East Texas, southern Mississippi, and all of Louisiana. Forest clearing for agricultural and urban development diminished the bear's habitat by 90 to 95 percent, leading the U.S. Fish and Wildlife Service to designate the bear as threatened in 1992 under the Endangered Species Act. Wildlife biologists studying the bears in the Tensas River Basin in northern Louisiana determined that wooded corridors along rivers and ditches enable the bears to move between isolated patches of favorable forest habitat and have played an important role in sustaining the species in a landscape dominated by corn, soybeans, and cotton. (Source and photos from USDA Natural Resources Conservation Service 2004).

## Key Information Needs

- Better understanding of how agroforestry practices can support biological pest control by bats, birds, and other natural enemies.
- Improved models for designing agroforestry practices to mitigate pesticide impacts on flora and fauna species.
- Documentation of the effect of corridors on crop pests (i.e., weeds, insects, and diseases) and on beneficial flora and fauna populations under climate change.
- Increased capacity to manage agroforestry practices at landscape scales for enhancing pollination and biological pest control.

## Adaptable Plantings

To be an effective adaptation strategy, agroforestry plant materials must themselves be adaptable to climate change effects. Changing climatic conditions will impact plant survival and function, which, in turn, determines agroforestry's utility as an adaptation and mitigation option. Tree and shrub species have multiple points of climate vulnerability: winter chilling requirements, springtime freeze risk, heat and water stress, pollination constraints, and disease and pest damage (Winkler et al. 2013). Winter warming trends predicted for many regions of the United States (Melillo et al. 2014) may reduce chilling hours, which, along with changes in frost, drought, and heat events, will influence quality and yield from many fruit/nut-producing species (Winkler et al. 2013). Disease and pest dynamics are expected to shift and escalate, which, when combined with abiotic tree stress, will further impact performance and survival of many woody species (Ayres and Lombardero 2000).

The selection of plant materials will need to take into account changing climatic conditions altering the geographical distribution of plants (Iverson et al. 2008a, McKenny et al. 2007b). Geographic ranges where species naturally reproduce, survive, and grow will shift as thresholds of tolerance are exceeded in some current locations and new locations come to within tolerable thresholds. Planted crops and agroforestry tree species will experience a similar effect—perhaps even more so as many agroforestry species are introduced and not necessarily locally well adapted. Given that woody plant material is long lived, the success of an agroforestry practice will depend on the adaptability of the planted trees and shrubs to both current and future climate regimes (fig. 2.13). Several tools are available for identifying agroforestry species that are adaptable in specific regions.

Through informed decisions on plant selection, agroforestry may offer a way to facilitate assisted migration of plant species (Dawson et al. 2011). For temperate forest species, it has been estimated that migration rates of more than 1 km per year may be needed for tree species to keep pace with current temperature and precipitation changes, a speed of migration tenfold greater than that observed in the past under natural climate change for key taxa (McLachlan et al. 2005, Pearson 2006, Petit et al. 2008). Assisted migration is an approach to lessen climate change impacts by intentionally moving species to more climatically suitable locations (Pedlar et al. 2012, Williams and Dumroese 2013). This approach can carry potential risks, such as the creation of invasive species, hybridization with new species, and the introduction of disease to other species; therefore, strategies to minimize risks need to be considered (Pedlar et al. 2012). Species-selection frameworks and other tools are available to support decisionmaking with considerations for assisted migration (Williams and Dumroese 2013).

**Figure 2.13.** Successful agroforestry must include trees that are adapted to both present and future climatic conditions. Tree death will compromise the long-term effectiveness of this windbreak in Nebraska. Windbreak renovation, in which maladaptive trees are replaced over time, will be key in maintaining healthy and functioning plant materials. (Photo by Nebraska Forest Service).

### Model Prediction

Significant changes to plant distribution patterns are expected to occur during the next century in response to climate change. The 2007 Intergovernmental Panel on Climate Change (IPCC) predicted a mean global temperature rise of 2.4 to 6.4 °C by the end of the 21st century (IPCC 2007), an increase that has been estimated to place 20 to 30 percent of species at high risk of extinction (McKenney et al. 2007b, Warren et al. 2013). Numerous studies during the past decade have tried to predict what shifts may occur in distribution patterns and to determine what species will be lost from a particular region (Iverson et al. 2008b, van Zooneveld et al. 2009, Warren et al. 2013). Studies of native North American trees predict the future natural habitats for 134 species in the Eastern United States (Iverson et al. 2008a). Unlike natural forest lands, cultivated urban and agroforestry trees are intentionally planted and may consist

of native and nonnative species. Useful lifespans of 50 years or more may be expected. Therefore, trees planted today may be coping with the altered climatic conditions predicted in the decades to come.

Many studies have used Climate Envelope Models (CEMs) to predict plant species distributions as influenced by climate change. CEMs represent a refinement of the traditional USDA Plant Hardiness Zone maps (USDA 2012) and can project distribution impacts of climate change (McKenney et al. 2007a). For example, based on climate scenarios developed by the IPCC in 2000, the Chicago Botanic Garden recently determined that many commonly planted species would become less suitable for climatic conditions that are predicted in future decades and that other species would become more suitable (Bell 2014). Although critics have raised concerns about the CEM technique, other studies have validated the results of some case studies using CEMs (Hijmans and Grahman 2006).

## Plant Evaluation Trials

Climate extremes typically limit the suitability of cultivated tree species for certain regions (McKenney et al. 2007a). Plant evaluation trials are used to test the suitability of tree species and cultivars developed from breeding and selection programs (Braun et al. 2010). These evaluations can be informative when conducted in locations frequently challenged by extremes that are expected in other regions under future climate regimes. For example, the continental climate of the Great Plains region is known for hot summers, cold winters, and rapid temperature fluctuations (Kunkel et al. 2013). Heavy rains interrupt seasonal and prolonged droughts. These conditions are expected to be accentuated by climate change and extended into adjacent regions (Karl et al. 2009, Kunkel et al. 2013). The John C. Pair Horticultural Center near Wichita, KS, conducts tree evaluations in this harsh climate. A 2-year period (2011 through 2012) brought some of the warmest temperatures on record to the Wichita area and only 75 percent of average precipitation. Under these conditions, not unlike what is predicted in future decades, a test of various cultivars of sugar maple (*Acer saccharum*), elm (*Ulmus* spp.), and assorted conifers identified some species and cultivars that are more tolerant of these conditions than others (Pool et al. 2013). In previous trials, one particular ecotype of maple native to western Oklahoma, "Caddo" maple, proved to be particularly hardy under extreme heat and drought conditions (Griffin 2005, Pair 1995). Trials with Caddo maple conducted in other regions, however, determined its suitability is geographically restricted from higher rainfall and humidity climates farther to the east because of susceptibility to disease.

A regional project to evaluate several seed sources of baldcypress (*Taxodium distichum*) from Texas and Mexico identified some genotypes having potentially better cold hardiness (Arnold et al. 2012). In addition, some baldcypress genotypes performed well during the historic heat and drought of the southern Great Plains in 2011 and 2012. Seed collected from the southwestern most populations of baldcypress in Central Texas are performing well on sites in Oklahoma and Kansas. They are cold hardy, heat and drought tolerant, and adapted to the high pH soils common in the Great Plains region (Denny et al. 2008).

Long-term, multi-State trials can produce locally relevant information regarding the geographic suitability of new cultivars. For example, the National Elm Trial is a 15-State effort to evaluate Dutch elm disease-resistant elm cultivars across the United States (Jacobi 2014). Often, cultivars that perform well in one region of the country fail to survive in another.

Conifers continue to be a challenge to grow successfully in parts of the agriculturally important Great Plains. Although they often serve as windbreaks, protect against soil erosion, and provide wildlife habitat, disease and environmental stress take their toll. Species that are known for heat and drought tolerance may not be sufficiently cold hardy. Transplant survival can also be a problem for species and cultivars that do not exhibit rapid root growth (Pool et al. 2012).

Evaluation trials and research will need to include efforts focused not only on growth and survival, but also on the resilience of fruit/nut production to climate change impacts in plant materials. The information garnered from evaluations in locations with frequent environmental challenges provides insight into various species' long-term utility in agroforestry and urban landscapes.

## Seed Sourcing

Populations of trees and other plants can become adapted to local environmental conditions (Aitken et al. 2008, Hufford and Mazer 2003, Langlet 1971, Leimu and Fischer 2008, Linhart and Grant 1996). Some of these conditions are directly influenced by climate change; for example, water availability (Dudley 1996a, 1996b; Fenster 1997), winter temperature and length (Balduman et al. 1999), competitive regime (Leger 2008), and pests and pathogens (Thrall et al. 2002). On this basis, locally sourced seed is assumed to outperform nonlocal seed for restoration, revegetation, and forestry projects, especially over the longer term. The benefit of local seed, however, is predicated on an environment that is relatively constant, which, in this era of rapid climate change, will not be the case (Havens et al. 2015). Successful tree planting must balance adaptation to current and future climate conditions (Bower and Aitken 2008). Selection of plant materials for agroforestry can hopefully benefit from lessons learned and materials identified in ongoing, broad-based assisted migration studies for forests (Williams and Dumroese 2013) as well as that from the horticultural and landscaping sectors.

One strategy to account for climate change is to use seed from a different location where current conditions are similar to those expected locally under climate change. Seed transfer zones, within which seed can be transferred with little risk of maladaptation, have been developed for several tree species (Johnson et al. 2004, Kramer and Havens 2009). They can be derived experimentally through plant evaluation trials or more quickly estimated using combinations of mapped minimum winter temperature zones, aridity, and ecoregions (Bower et al. 2014, Erickson et al. 2004, Johnson et al. 2010, Omernik 1987). The estimation approach has been modified to account for climate change, such as warmer temperatures (Kramer and Havens 2009, Vitt et al. 2010, Ying and Yanchuk 2006), but this approach, like plant evaluation trials, likely will yield only approximate results because of uncertainty in both the prediction of future local climate conditions and the ability to find those conditions currently at a different location. Seed transfer zones that account for climate change have been under development for economically important tree species for more than two decades (Billington and Pelham 1991, O'Brien et al. 2007, Potter and Hargrove 2012, Rehfeldt 2004, Rehfeldt et al. 1999, Ying and Yanchuk 2006). These strategies might also be useful for identifying multiple species that have developed mutualisms through co-evolution and are suitable for transferring as a group (Gallagher et al. 2015).

Agroforestry tree species may be more tolerant and resilient than the herbaceous agricultural crops they protect, but they are not immune to the adverse impacts of climate change. New management practices will need to be developed and, in some cases, more resilient germplasm or new species altogether will need to be considered. Climate Envelope Modeling, if applied correctly, could be a valuable tool for determining which species will continue to be suitable for a specific region, identifying other regions that may possess hardier germplasm for seed sourcing, and identifying potential breeding opportunities that will yield climate change-adapted plant material for the future.

## Other Adaptation Issues and Strategies

Along with seed source and plant material considerations in developing resilient plantings, belowground aspects, especially those related to the mycorrhization of plants, need to be considered (Compant et al. 2010, Johnson et al. 2013). For instance, the ability of southern California oaks to form both vesicular-arbuscular and ecto-mycorrhizae provides added diversity to help buffer against adverse conditions (Allen 2015). Not taking into account the belowground conditions, like mycorrhizal diversity and suitability, may impair plant performance such as found by Kranabetter et al. (2015) in their assisted migration studies with Douglas-fir. Management activities, ranging from mycorrhizal inoculation to the use of tree shelters, application of hydrogels and organic amendments, and planting methods, can impact seedling establishment success under changing conditions (Piñeiro et al. 2013) and therefore provide additional strategies to establish and grow more resilient agroforestry plantings.

Given the complexity of factors affecting plant performance and persistence, additional research is needed to fully understand climate change impacts on agroforestry plant materials (Ayres and Lombardero 2000, Luedeling 2012). In the meantime, adaptation strategies for agroforestry can be pulled from existing information generated in other sectors, such as horticulture. Orchard production research has identified varieties of plant materials with lower dormancy requirements and has also provided information for in-field management options. One of the most effective adaptation strategies is simply increasing the plant diversity within a planting, which broadens the mix of genetic, phenological, and biophysical attributes (Altieri 1999, Lin 2011). Using a wide range of plant materials can reduce herbivory by pests (Jactel and Brockerhoff 2007, Aitken et al. 2008), decrease disease transmission (Lin 2011), minimize phenological mismatching between pollinators and plants (Polce et al. 2014), and decrease risk from extreme weather events (Altieri 1999, Lin 2011). Because agroforestry is a designed planting, it offers opportunity for using a variety of species and arrangements within a planting. More innovative practice designs, such as using resilient woody species to provide microclimate benefits to fruit/nut-producing species through a mixed-use windbreak or alley cropping system, can also offer a way forward while new plant materials and management guidance are being developed.

## Key Findings

- Agroforestry species currently used in a specific region may not tolerate stresses brought on by future climate conditions, thus jeopardizing long-term benefits of these practices.
- Successful agroforestry practices may require the introduction of new species and/or cultivars that are better adapted to both current and future climatic conditions.
- Models, field evaluation trials, and seed sourcing will likely be required to develop suitable species and cultivars.

## Key Information Needs

- Better understanding of the impact of future climate conditions and interrelated stressors on agroforestry species.
- Improved modeling for predicting species suitability under future climatic regimes.
- Refined plant species options for agroforestry practices in different regions of the United States under climate change.

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