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Soil management

Water management / rain-fed

Water management / irrigated

Nutrient management

Pesticide management / weed control

Pest management / IPM

Landscape management

# 1

## SOIL MANAGEMENT PRACTICES

Randall Reeder and Dale Westermann

- Soil management
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Soil management practices affect soil resources obviously, but those practices also affect water and air resources and the plants and animals that depend upon those resources. Good soil management builds soil quality, maintains or improves water and air quality, and supports plant, animal, and human life (NRCS, 1996a). Minimizing soil erosion, increasing water infiltration, and promoting biological activity through good management ultimately produces a soil with physical and chemical characteristics consistent with parent material, topography, and climate.

The spectrum of soil management practices ranges from crop residue management with conservation tillage systems to practices designed to keep plants growing on the land as much of the year as practical—cover crops, stripcropping, and conservation crop rotation. Vegetative buffers of various types for wind and water erosion control within fields or at the edge of fields also are included. Cropland conversion, which takes land out of crop production for several years or even permanently, is another in the spectrum of soil management practices, as is the related practice of bringing converted cropland, mainly Conservation Reserve Program (CRP) acres, back into crop production while maintaining the level of soil quality gained during the CRP years.

The primary environmental benefits of all soil management practices are, first and foremost, improvements in soil and water quality. In dryer regions of the nation, air quality is improved by reducing wind erosion, and water conservation is enhanced by practices that strive to keep each raindrop and snowflake on the land where each falls. In fact, keeping precipitation on the land where it falls is an important goal in any climate. Runoff carries sediment, nutrients, and other potential pollutants from farm fields, which often becomes a direct cost to the farmer and to citizens downstream. Building organic matter (soil carbon) also is good for the long-term health of soil, good for crop yields, and good for slowing global warming by sequestering carbon from the atmosphere.

## Some management principles

Several general principles define how soil management activities and practices affect environmental outcomes. Historically, mismanagement of soil, often through ignorance or misguided farming practices, has led to many environmental problems. Adopting improved farming practices, especially conservation tillage systems that leave crop residue on the field surface, can significantly reduce runoff and soil erosion by wind and water, increase water conservation in the soil,

improve water quality in streams and lakes, build soil organic matter, and result in cleaner air. In most cases no-till is the ideal tillage system for maintaining high levels of crop residue. Ridge-till, mulch-till, and deep tillage (subsoiling) often give adequate residue coverage for environmental benefits. Continuous no-till is needed to maximize the benefits for soil quality and erosion control (Reicosky, D.C., 2001; Reicosky and Wilts, 2004; Dan Towery, personal communication, 2005). In humid regions residue breakdown can be rapid. Even with continuous no-till, cover crops are advantageous, especially following primary crops, such as cotton or corn silage, that produce little residue.

Various cropping practices, including stripcropping, crop rotation, and cover crops, can reduce erosion and provide other environmental benefits by keeping more of the soil protected (and for more months of the year) by the growing plants and/or crop residue. From a purely environmental standpoint, soil covered or otherwise protected by plant material is good; soil that is bare and fallow is not good.

Buffers, a group of conservation practices that sometimes take a small percentage of a field out of production to reduce wind and water erosion, include vegetative barriers, windbreaks, and alley cropping. For water erosion, these practices work by increasing infiltration, slowing water runoff velocity, and shortening the slope length of exposed soil so sediment is deposited closer to the crop area. For wind erosion, buffers reduce wind speed, which reduces the amount of soil particles picked up and moved by the wind. These buffers cause soil particles to be deposited in or near the buffer, prevent downwind surface and crop abrasion, and may prevent entry of soil particles into bodies of water.

Optimal practice combinations vary by geographic region, soil type, slope, crops, and climate. For irrigated farming, conservation practices include those for water, crop, and soil management. Practices, such as polyacrylamide (PAM), and salinity and sodic problems affect soil management and apply mainly to irrigated land. Other management practices apply to both irrigated and rain-fed production systems, such as conservation cover, residue management, conservation tillage, and filter strips.

The success of conservation practices is determined by how well the practices keep soil in place, build soil quality, and maintain clean water and clean air downstream and downwind. (Soil quality includes soil organic matter and soil structure, which directly affect infiltration, aeration, and bulk density.) Practices aimed at managing soil also impact nutrient and pest management.



Conservation tillage, combined with terraces and other conservation measures, saves soil and improves water quality.



The residue cover under these systems can range from a minimum of 30 percent to 100 percent, depending upon the system and cropping practice.

Whole-field practices that take land out of production and establish a long-term cover include critical area planting and tree and shrub establishment. CRP was established in the 1985 farm bill. It was preceded by the "Soil Bank" program in the 1950s. CRP land planted to grass or similar species often is put back into crop production after the contract ends, and the tillage practices used with the successive crops determines, to a large extent, the long-term value of the CRP.

The 1985 farm bill was the first major legislative effort to tie eligibility for agricultural program payments directly to conservation performance. According to Uri and Lewis (1999), conservation practices implemented to satisfy the conservation provisions of this legislation reduced total soil erosion by 42 percent from 1982 to 1997, from 18 Mg ha<sup>-1</sup> (8.0 tons per acre) to 11.6 Mg ha<sup>-1</sup> (5.2 tons per acre). Wind erosion accounted for about 45 percent of the 3.1 billion Mg (3.4 billion tons) of erosion in 1982; and 50 percent of the 1.8 Mg (2.0 billion tons) in 1997. Erosion on the most highly erodible cropland improved from 13.6 Mg ha<sup>-1</sup> (15.1 tons per acre) to 8.4 Mg ha<sup>-1</sup> (9.3 tons per acre) per year over the same 15 years. Erosion on non-highly erodible cropland declined from 4.5 Mg ha<sup>-1</sup> (5.0 tons per acre) to 3.1 Mg ha<sup>-1</sup> (3.5 tons per acre) per year. The best estimate of the savings to society for the reductions in erosion was about \$2 billion annually in 1997. The remaining costs to society were still almost \$30 billion a year. In addition to erosion's effects on crop productivity, eroded sediment deposited in rivers, shipping channels, and lakes can impose an extra cost on navigation as high as \$5.50 per Mg (\$5 per ton) (Hansen et al., 2002). In some watersheds there is no effect on downstream shipping.

Government commodity support programs offset conservation gains by encouraging increased crop production. While the CRP reduced soil erosion rates to 0.9 Mg ha<sup>-1</sup> (1 ton per acre) between 1982 and 1992, Goodwin and Smith (2003) estimated that other government programs indirectly added cropland with erosion that offset half of this reduction. One analysis showed that for every 100 hectares (40 acres) enrolled in CRP an additional 20 hectares (8 acres) of new or retired land was brought into crop production (Wu, 2000). Increases in direct government payments, as a percentage of farm revenues, lead to more soil erosion. In contrast, federally subsidized crop insurance and disaster relief payments appear to have little effect on erosion. The adoption of conservation tillage is more likely for family farms than for farms classified as retirement farms, lifestyle farms, or limited-resource farms (Soule, 2000).

To facilitate this review, we grouped conservation practices into four major categories: residue management, soil amendments, conservation buffers (for water and wind erosion), and cropland conversion (Table 1). Other practices we discuss individually. Practices listed under conservation buffers and cropland conversion share the common effect of creating semi-permanent vegetated areas that remove (some) land from production and typically improve infiltration, nutrient cycling, and carbon sequestration.

## Soil management practices

### Residue management

**Definitions.** Residue management—conservation tillage—systems include no-till (practice code 329A), strip-till (practices code 329A), ridge-till (practice code 329C), mulch-till (practice code 329B), deep tillage (practice code 324), and seasonal residue management (practice code 344). These systems are designed to manage the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round. The goals of conservation tillage systems include minimizing sheet, rill, and wind erosion; maintaining or improving soil organic carbon; conserving soil moisture; and managing snow deposition to increase plant-available moisture. The residue cover under these systems can range from a minimum of 30 percent to 100 percent, depending upon the system and cropping practice.

No-till (including strip-till) involves growing crops planted in narrow slots or residue-free strips of soil previously untilled by full-width inversion implements.

Mulch-till involves tilling the entire field surface with an implement designed to leave at least 30 percent of the soil surface covered with crop residue.

Ridge-till involves growing row crops on preformed ridges alternating with furrows. A ridge-till cultivator reforms the ridges by pushing loose soil from the row middles up against the standing crop. After harvest the crop residue protects the soil surface from erosion. The planter removes and inch or two of soil from the top of the ridge before dropping the seed in a slot (similar to no-till). The loose soil and residue is deposited in the bottom of the furrows.

Deep tillage (subsoiling) loosens soil below the normal tillage depth to modify the physical or chemical properties of a soil. Its primary purpose is to fracture restrictive soil layers, typically from 30 to 50 cm (12 to 20 inches) deep. It is considered here because several subsoiler designs maintain a residue cover of at least 30 percent.

Seasonal residue management practices, which include burying residue by tillage just prior to planting (instead of after harvest) or partially removing residue by grazing or baling, are included here because the goals of these practices are to minimize soil erosion and provide other benefits by extending the time a soil is protected by resi-

due compared to conventional tillage.

Mulching (practice code 484) involves the application of plant residues, by-products, or other suitable materials produced off-site to the land surface. Mulching potentially can help conserve soil moisture, moderate soil temperatures, provide some erosion control, suppress weed growth,

**Table 1. Division of soil management conservation practices into review categories.**

Categories	Conservation practice	Practice code
Residue management	No-till & strip-till	329A
	Mulch tillage	329B
	Ridge tillage	329C
	Deep tillage	324
	Seasonal residue management	344
	Mulching	484
Crop sequencing	Conservation crop rotation	328
	Cover crop	340
Soil amendments	Anionic polyacrylamide (PAM)	450
	Salinity and sodic soil	610
<b>Conservation buffers</b>		
Water erosion reduction	Alley cropping	311
	Contour buffer strips	332
	Contour orchards	331
	Vegetative barrier	601
	Field border	386
	Contour farming	330
	Row arrangement	557
	Riparian forest buffer	391
Wind erosion reduction	Herbaceous wind barrier	603
	Windbreak/shelterbelt	380
	Windbreak/shelterbelt renovation	650
	Cross wind trap strip	589C
<b>Tillage orientation</b>		
Water erosion reduction	Contour farming	330
	Row arrangement	557
Wind erosion reduction	Cross wind ridges	589A
	Surface roughening	609
Cropland conversion	Conservation cover	327
	Critical area planting	342
	Tree & shrub establishment	612

**Residue management—primarily no-till and other reduced tillage systems—is the single most effective method of minimizing wind and water erosion on cropland.**

help establish vegetative cover, and improve the soil physical condition. Most mulching materials have an organic composition, although gravel, plastic, and fabric materials are sometimes used. This practice generally involves the complete coverage of the soil surface, although this may be impractical and unnecessary in some situations. Mulching has some similarities to stubble mulch tillage or conservation tillage, where plants grow on-site and their residue is partially incorporated by tillage. The type and kind of mulch used depends upon site conditions and availability of materials. The material used should be of sufficient composition and durability to achieve the intended purpose without detrimentally affecting the soil or plants via toxic ions or compounds, weed seeds, pathogenic effects, or allelopathic effects. The effectiveness of mulching generally lasts from only a few months to a year, primarily because of the nature of the mulching materials and their interaction with the soil and weather conditions.

**Background Information.** A great deal of research has been conducted on crop residue management practices. The results of many of these studies are reviewed in this chapter, including a few that may not appear to relate directly to our goals. Because the effects of soil management practices vary greatly by soil type, climate, crop choice, and other factors, we chose to present many results in this chapter, with enough detail that most readers will not need to search out the reference. Research often is identified by state so readers can identify information specifically important to their region. Some international research also is included because it demonstrates results important to American conservation policy and practice.

Agricultural soil is home to a diverse array of living organisms. Soil fauna include earthworms, nematodes, mites, and other insects. Microorganisms include bacteria, fungi, and others (Doran and Werner, 1990). Tillage and residue management practices significantly affect soil biotic activity. Earthworms, for example, prefer plant residue on the soil surface and no tillage. Frequent tilling favors organisms with short life cycles, rapid dispersal, and small body size.

Residue management—primarily no-till and other reduced tillage systems—is the single most effective method of minimizing wind and water erosion on cropland (Pappendick, 1996).

When Europeans arrived on the East Coast, they found soils covered with grass, trees, and plant residues. Organic matter was relatively high, and because many plants were legumes, nitrogen (N) was being added to the soil (Mold-

enhauer et al., 1995). Although Native Americans grew crops, there were few of them and their farming practices involved little tillage. In fact, Native Americans are sometimes referred to as the nation's first no-tillers.

Friendly Native Americans taught the Europeans to grow corn, and the Europeans introduced a heretofore unknown element into American agriculture, but one that continues to play a dominant role: iron (Moldenhauer et al., 1995). Iron hoes and mattocks made planting and weed management easier for those early pioneers. Later, an Illinois blacksmith named John Deere gave iron (steel) a bigger role in farming the prairie soils.

Today, from a soil management standpoint, we can look at iron as good or bad, depending upon how it is used. Iron in all the components that help a no-till planter work successfully through tight soil, crop residue, and cover crops is good. Iron in selected tools used for strip-tillage and deep-tillage shanks that leave the field surface generally undisturbed also is good. And if farmers did not have access to low-cost herbicides today, iron in the form of plows, disks, and cultivators would be considered good. But it is not good when iron is used to make tillage tools that invert soil and leave it vulnerable to water or wind erosion for long periods of time.

Conservation tillage continues to grow as a primary means of managing soil to reduce environmental damage. In 1990 conservation tillage was practiced on 26 percent [30 million hectares (73 million acres)] of U.S. cropland; no-till was used on 7 million hectares (17 million acres). By 2004 use of no-till had grown to 25 million hectares [62 million acres (23% of the total)], and conservation tillage was practiced on 45 million hectares (112 million acres), 40 percent of U.S. cropland (CTIC, 2004). Conservation tillage practices are sometimes coupled with other conservation practices, such as vegetative buffers in areas of concentrated flow. Much of the remaining 60 percent of cropland [67 million hectares (165 million acres)] is vulnerable to soil erosion. Crop selection and other conservation practices are needed on those acres to protect the environment.

Soybeans are the leading no-till crop with almost 12 million hectares (30 million acres), followed by corn [6.5 million hectares (16 million acres)], small grains [4.5 million hectares (11 million acres)], cotton [1 million hectares (2.4 million acres)], and grain sorghum [0.7 million hectares (1.7 million acres)]. Forages and other crops accounted for 0.9 million hectares (2.1 million acres) of no-till (CTIC, 2004). As a percentage, the leading no-till crops were as follows: soybeans (40%), grain sorghum (20%),



corn (19%), cotton (18%), small grains (15%), and forages and other crops (9%).

States with at least 4 million acres of no-till included Illinois, Indiana, Iowa, Kansas, Nebraska, Ohio, and South Dakota. States with at least 40 percent of their cropland acres in no-till included Alabama, Kentucky, North Carolina, Ohio, South Carolina, Tennessee, and Virginia.

The growth of crop residue management systems is fairly impressive, but it is worthwhile to put use of no-till into a global context. Adoption of no-till in the United States, especially continuous no-till, is low compared to the region leading the world in no-till—South America (Derpsch, 2002). In Brazil, Argentina, and Paraguay, farmers use no-till on 45 to 60 percent of all agricultural land. The United States remains far ahead of Europe, Asia, and Africa, where no-till collectively accounts for about 2 percent of all cropland.

Much of the native grassland converted to soybean production in South America went directly to no-till without plowing. No tillage meant essentially little or no loss of organic matter. With conventional tillage, organic matter dropped from 4 percent to 2 percent in 12 years on a soil in southern Brazil (Dijkstra, 2002). South America's experiences with no-till planting on native grassland provide valuable information for North American farmers taking land out of CRP. Technology today makes it feasible to convert land to crop production without destroying organic matter and other soil attributes.

In the early days of research and experimentation with no-till, success was limited by the availability of good chemicals for controlling weeds, disease, and insects and planters that could handle heavy residue and firm soil and achieve good seed germination. Triplett et al., (1964) applied 5.4 kilograms (12 pounds) of herbicides per acre to no-till plots on a well-drained Canfield silt loam at Wooster, Ohio. Corn was planted on May 18, 1960; the resulting yield was 8.9 Mg ha<sup>-1</sup> (132 bushels per acre), statistically equal to yields on plowed plots. That no-till yield was quite good at the time. Research on that site continues today.

Several years after research was initiated at the Wooster site, another research site was added in northwestern Ohio on a poorly drained Hoytville clay loam (VanDoren and Triplett, 1969). Averaging about 8 years of data, no-till on the sloping silt loam plots resulted in slightly higher yields than plowing; on the flat clay loam plots, no-till yields were 5 to 10 percent lower than on the plowed plots.

A pioneering ridge-till farmer, Ernie Behn (1982), experimented with till-plant, generally called ridge-till, in Boone County, Iowa, in an

attempt to control soil erosion on slopes and reduce ponding in low spots on level ground. He first installed terraces and found they filled with silt in 2 years and did nothing to solve the ponding problem. Determined to keep the soil (and rainfall) in place, he decided to try ridge-till on the contour. "A terrace every 76 centimeters (30 inches) instead of one every 90 meters (300 feet)" is the way he described it.

The first research on no-till soybeans grown in a silt loam soil in Tennessee began in 1979 at Jackson. In the 4-year experiment comparing no-till to five other tillage systems, no-till yields equaled or exceeded yields with conventional tillage systems in every year (Tyler et al., 1983).

Introduction of the John Deere 750 model no-till drill expanded acreage of no-till soybeans nationally, and adoption of no-till cotton in the southeast was accelerated by the introduction of Roundup Ready seed (Bradley, 2002).

In the southeastern United States, the warm, humid climate, combined with highly erodible soils and intense rainstorms during the growing season, makes soil erosion a major problem. Soybean and cotton production especially requires a cover crop, such as wheat or rye, to help manage soil erosion (Blevins et al., 1994). No-till drilling of soybeans as a double crop after wheat harvest effectively controls soil erosion. The climate also provides an environment in which crop residue decomposes rapidly. Runoff cannot always be eliminated by no-till because of the intense rainfall or subsurface horizons that limit deep percolation of precipitation (Edwards et al., 1993; Dabney et al., 2000). On clay pan soils in Missouri, no-till can even increase runoff, although soil erosion is greatly reduced (Ghidey and Alberts, 1998).

The northeastern region of the United States has only three percent of the nation's cropland, largely because the terrain is too steep for row-crop production. About 40 percent of the crops grown in the region are grown with conservation tillage (CTIC, 2004). Corn silage is a prominent crop, but it leaves almost no residue on a field surface, and the cold climate in the northern part of the region makes it difficult to establish a cover crop to protect the soil from erosion. Livestock manure is a significant "residue" in several northeastern states (Radke and Honeycutt, 1994).

Crop residue management practices often are part of a package of compatible practices that compliment each other and reduce soil erosion more than conservation tillage alone. Grassed waterways, terraces, and cover crops frequently are added to minimize soil losses and improve water quality and water conservation.

Crop yields are sometimes lower with con-

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servation tillage, especially during the first 1 to 3 years. Stubbs et al., (2004) identified several problems related to residue cover: poor crop establishment due to a lack of suitable no-till drills and planters, more disease, more weeds, and reduced nutrient availability for the crop. During the transition to no-till, soil physical, chemical, and biological characteristics must change. Several years may be required to reach a new equilibrium. Change in soil quality occurs most rapidly, particularly in the top 5 cm (2 inches); those changes include increased mineralization of carbon, more active microbial biomass, increased soil organic matter, and greater aggregate stability. There are varying levels of soil disturbance for different no-till planting implements that affect the transition time. Nearly all soil organisms are harmed by soil disturbance.

Improved equipment designs, better herbicides, and new management practices clearly have helped to raise crop yields for conservation tillage systems relative to conventional tillage. There no longer is an automatic yield lag for no-till. Research in recent years carries more value than similar research 20 or more years ago. If research from the 1970s or 1980s, for example, were repeated today, yields with conservation tillage might very well switch from the negative side to the positive side.

**Soil quality effects.** Soil quality has been defined as the "capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994). A properly managed soil that improves and conserves soil quality is good for crop productivity and the environment (Kennedy and Papendick, 1995). A good quality soil also helps to improve water and air quality.

Soil quality has physical, chemical, and biological components. Management practices that influence soil quality include tillage, residue management, crops grown, and compaction from machinery. A healthy soil, with a balanced population of active microorganisms, is essential for agriculture. Microbes help aggregate soil, which reduces soil erosion and increases infiltration and aeration. Soil microbes also affect the persistence of organic compounds on or in the soil. Among the negative effects of soil microorganisms are plant disease, loss of nutrients, and production of allelopathic compounds that suppress plant growth. Positive effects of microbes include the ability to control insects, pathogens, and weeds by lowering pest populations or reducing their impact.

Crop residue management practices significantly affect soil quality. Maintaining a protective

cover of growing plants or crop residue is the first line of defense against soil erosion. Keeping soil particles in place tends to keep nutrients and pesticides in place as well. The biomass from plant materials on and in the soil builds soil organic carbon. In contrast, farming practices that invert the soil and leave the surface bare and unprotected for months at a time deplete soil organic carbon. Soil quality benefits are highest when no-till and high-residue cropping systems are used in combination. Badly degraded soils show the greatest improvement in soil quality when conservation practices are applied.

Several research articles cited in this section provide examples of how soil organic matter declined over a period of 25 to 50 years or more as a result of conventional farming, and others show how crop residue management helped reverse the decline. Conservation tillage can sustain or increase soil organic matter (carbon) when combined with intensive cropping systems (Reeves, 1997). Soil organic carbon is a key indicator of soil quality. It provides a critical link to and is a controlling factor in other physical, chemical, and biological quality indicators (Franzluebbers, 2002a). Whereas conventional tillage causes a continuing decline in organic matter, conservation tillage systems that leave large amounts of residue on the field surface increase soil carbon.

Stratification of soil properties is a feature of most native environments. Stratification of soil properties also is a feature of cropland farmed with conservation tillage systems that leave most residues on the surface and do not invert the soil profile. (Stratification simply means that soil properties vary with depth; in contrast, soil that is plowed with a moldboard is homogenous to the depth of tillage.) Changes in soil properties occur most quickly at or near the soil surface (Stubbs et al, 2004). Franzluebbers (2002a) concluded that increased stratification will likely "1) improve water efficiency by reducing runoff and increasing retention in soil; 2) improve nutrient cycling by slowing mineralization and immobilizing nutrients in organic fractions; 3) resist degradative forces of erosion and compaction; 4) improve soil biological diversity; and 5) enhance long-term productivity of soils."

Building soil organic matter improves soil aggregation. More stable soil aggregates improve soil aeration, enhance soil drainage, reduce susceptibility to compaction, improve infiltration, increase resistance to soil dispersion, and improve plant emergence (Griffith et al., 1992).

Tillage systems combined with cropping choices that leave the soil surface nearly covered with residue offer many environmental benefits: accumulation of organic matter on or near the

soil surface, less soil crusting, improved soil quality, reduced erosion from water and wind, greater infiltration and water storage in the soil, and higher yields for crops at many locations. Research analyzed by Sojka et al., (1984) showed a typical 95 to 99 percent reduction in soil erosion with no-till compared to conventional tillage in the Southeast and Midwest. Lal et al., (2004) reported an impressive reduction in soil erosion on U.S. cropland since the early 1980s as a result of the adoption of conservation tillage systems and the conversion of highly erodible land to permanent cover. Total erosion on cropland declined 42 percent between 1982 and 1997 [to 1.8 billion Mg (1.9 billion tons) per year].

The universal soil loss equation (USLE) was developed to allow scientists to estimate soil erosion more accurately. Wischmeier and Smith (1965) developed the crop management or "C-factor" for the USLE. It is defined as the ratio of soil loss from land cropped under a specified condition relative to the loss from a clean-tilled, continuous fallow condition. For the latter condition, the C-factor was set at 1.0. Research studies cited by Sojka et al., (1984) reported C-factors in the range of 0.58 to 0.12 for continuous cotton, soybeans, or corn cropping under conventional tillage. In contrast, measurements for no-till on silt loam and fine loamy sand soils (mainly by McGregor, 1988) produced C-factors of 0.013 to 0.003 for various crops and rotations. The soil is most vulnerable to erosion from intense storms at planting time and soon thereafter because of the relatively low amounts of crop residue and little or no crop canopy.

Percentage of ground cover directly affects the C-factor (Table 2). For example, in Iowa research on no-till soybeans following corn, the C-factor improved from 0.12 with 50 percent ground cover to 0.05 with 80 percent ground cover (Moldenhauer et al., 1983). These researchers' measurements in Georgia produced similar results. For example, for no-till continuous grain sorghum,

the C-factor improved from 0.13 with 50 percent ground cover to 0.05 with 80 percent cover. (With 30 percent cover, C equaled 0.22.) In both states, spring plowing resulted in C-factors of 0.46 to 0.29 for continuous corn and continuous soybeans.

More extensive research on residue cover led to figure 1 (from Foster, 2004), which highlights the benefits of greater residue cover immediately after planting. The vertical scale is the ratio of soil erosion with no-till compared to that with conventional tillage, expressed as a decimal; the horizontal scale is the percentage of the soil surface covered with crop residue. The scatter about the fitted line shows that even for 20 to 50 percent residue cover there are several data points where the C-factor was worse than 0.20. At 50 percent ground cover, the fitted value is 0.1, but the experimental values ranged from about 0.02 to 0.4. The C-factor was consistently better than 0.05 only when residue cover exceeded 60

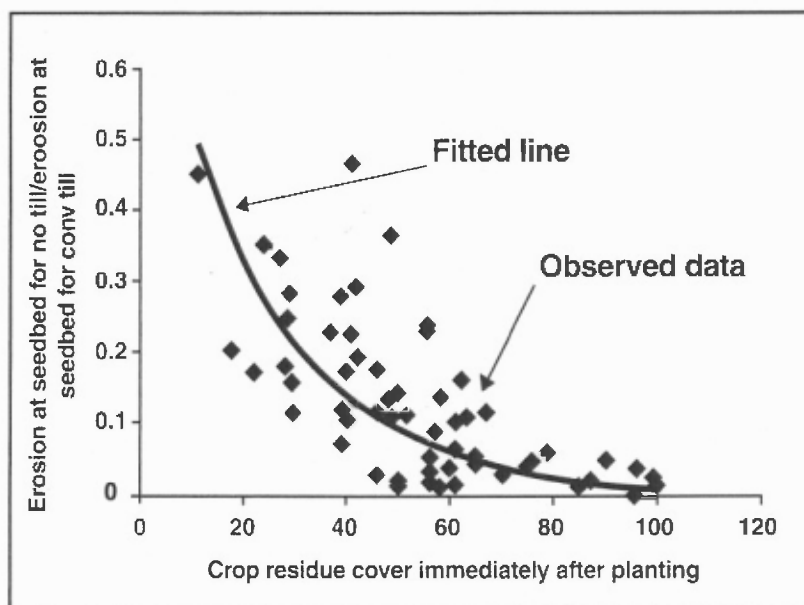


Figure 1. Relation of erosion with no-till cropping to erosion with conventional tillage for seedbed period (Foster, 2004).

**Table 2. Tillage effect on the C-factor in the universal soil loss equation (note: lower is better).**

System	C-factor	Crop/location/soil	Reference
Conventional tillage	0.58-0.12	Various crops	Sojka et al., 1984
No-till	0.013 - 0.003	Silt loam and fine loamy sand	McGregor, 1988
No-till	0.12 for 50% cover 0.05 for 80% cover	Soybeans after corn, Iowa	Moldenhauer et al., 1983
No-till	0.22 for 30% cover 0.13 for 50% cover 0.05 for 80% cover	Continuous grain sorghum, Georgia	Moldenhauer et al., 1983
Conventional tillage	0.46-0.29	Corn and soybeans, Iowa and Georgia	Moldenhauer et al., 1983

percent. This high level of cover after planting is typical only when the previous crop was permanent grass, a cover crop, or a crop producing large amounts of residue.

Residue cover that accumulates as biomass in the upper soil layer with continuous no-till increases water infiltration, which also reduces runoff and rill erosion (Foster, 2004). This extra erosion control benefit does not occur for the same percentage of residue cover with short-term no-till cropping or where mulch is applied to a bare soil (such as freshly tilled soil or a graded construction site).

An often-ignored or forgotten factor in dealing with soil erosion on field slopes is the downhill movement of soil caused directly by tillage implements. Tillage translocation and tillage erosion are major contributors to net soil movement on field slopes. Tillage translocation is the resulting movement of soil forward or laterally relative to the direction of tillage. While soil is not lost directly from the field by tillage translocation, the movement of soil from convex slopes and its deposition on lower concave slopes likely reduces total crop yield and soil productivity.

Pulling a moldboard plow across a slope throws a slice of soil downhill several inches with each pass of the implement; this obviously contributes to tillage erosion. Other tillage tools also loosen soil and move it forward slightly. Previous research showed that, for example, annual moldboard plowing on a convex slope in southwestern Minnesota could cause a soil loss of about 30 Mg ha<sup>-1</sup> (13 tons per acre) per year (Reicosky, 2004b). In southwestern Ontario, the estimated soil loss from the upper edge of a slope was 54 Mg ha<sup>-1</sup> (24 tons per acre) per year when tillage consisted of moldboard plowing, tandem disking, and cultivation with a C-tine (Lobb et al., 1995). Tillage erosion contributed about 70 percent of the total loss.

Tillage also causes dispersion of soil constituents, and both dispersion and translocation are greater on steeper slopes (Van Oost et al., 2000). In an experiment on a slope that varied from 5 to 13 degrees, moldboard plowing moved "tracers" a mean distance of 0.45 to 0.72 m (1.5 to 2.4 feet) when plowing downhill and 0.24 to 0.31 m (0.8 to 1.0 foot) when plowing uphill. In the Palouse region of the Pacific Northwest, soil banks up to 4 m (13 feet) thick have formed above field boundaries as a result of plowing downhill for many years (Papendick and Miller, 1977).

Translocation of soil by tillage on undulating landscapes also leads to changes in the chemical and physical properties of soil. In Minnesota, the combination of a hundred years of soil erosion by water and moldboard plowing on a field caused

large variability in topsoil depth, pH, organic matter, and soil carbonate (Papiernik et al., 2005). Wheat yields in the most eroded areas, measured over 3 years, were only half the field average.

Tillage erosion and translocation are covered in detail in a 1999 issue of *Soil & Tillage Research*, which includes several papers presented at the first international symposium on that topic in 1997 [see Govers et al., (1999)].

**Soil erosion reduction.** Conservation tillage is recognized as a primary means of reducing soil erosion on cropland. Table 3 summarizes extensive research on this topic.

Economic and environmental evaluations of a representative 490-ha (1,200-acre) southwestern Tennessee farm showed that soil erosion losses of 11,000 Mg (12,000 tons) could be reduced to less than 3,600 Mg (4,000 tons) by adopting no-till planting for cotton, soybeans, and sorghum, coupled with cover crops or a wheat-soybean double crop and farming on the contour (Bowling and English, 1994). That combination of practices reduced soil erosion by two-thirds. The economic analysis showed a drop in income of \$25,000 compared to conventional practices, which translates to an annual cost of about \$3 per Mg (\$3.50 per ton) of prevented erosion, or \$20 per hectare (\$50 per acre). (The authors did not define any changes in crop yield as a result of adopting the conservation practices. A likely increase in yield with long-term conservation tillage could result in a net increase in farm income, rather than a decrease.)

A simulation (using a computer model) of soil erosion in a typical Iowa watershed showed that, compared to conventional tillage, no-till reduced soil erosion 90 percent for continuous corn and 70 percent for a corn-soybean rotation (Lakshminarayan et al., 1994). Using an erosion benchmark of 10 Mg ha<sup>-1</sup> (5 tons per acre), nearly 80 percent of the soils in continuous corn were at risk with conventional tillage; 40 percent were at risk with reduced tillage; and 15 percent were at risk with no-till.

In a Virginia experiment with a rainfall simulator, no-till, compared to conventional tillage, reduced soil loss 97 to 99 percent on plots prepared with rye at residue levels of 0, 750 and 1,500 kg ha<sup>-1</sup> (0, 675, and 1,350 pounds per acre) (Mostaghimi et al., 1987). No-till reduced runoff volume 87 percent with zero residue cover and 99 percent for the highest level of residue cover. The rainfall pattern and intensity were representative of a storm with a 2- to 5-year return period in Virginia. Granular phosphorus (P) fertilizer at a rate of 46 kg ha<sup>-1</sup> (40 pounds per acre) of phosphorus was applied 24 to 48 hours before the



Conservation tillage and no-till in particular are among the most effective soil erosion control measures used on cropland. These practices also conserve water and improve soil, water, and air quality.



**Table 3. Effects of conservation tillage systems on soil erosion.**

<b>System<sup>a</sup></b>	<b>Impact</b>	<b>Location/soil, etc.</b>	<b>Reference</b>
NT	Reduce erosion 95-99%	Southeast, Midwest	Sojka, et. el., 1984
CT	Combined with converting highly erodible land to permanent cover, reduced erosion 42% in 15 years, 1982-1997	Continental U.S.	Lal et al., 2004
NT	Reduced erosion to zero, compared to 3.8 Mg/ha	Ohio and Mississippi	Rhoton et al, 2002
NT	Reduced erosion to 0.5 Mg/ha, compared to 5.7 Mg/ha, 7-13% slopes	Ohio	Edwards et al., 1993
Disk, field cultivate	Erosion up to 330 Mg/ha on 20% slope	Iowa and Nebraska, loess soil	Wittmuss, 1987
NT	80% cover compared to 30% cover, erosion reduced fourfold	Georgia	Moldenauer, et. el., 1983
NT	50% cover crop compared to 30%, erosion reduced 2.5-fold	Georgia and Iowa	Moldenauer, et. el., 1983
NT	>60% residue cover consistently reduces erosion 95% compared to bare soil		Foster, 2004
NT	Reduced erosion to 0.13 Mg/ha, compared to 26 Mg/ha with plow	Georgia	Sojka et al., 1984
NT + DT	With cover crop, reduced erosion 90-95% compared to conservation tillage, no cover	Alabama	Truman et al., 2002 Truman et al., 2003
NT + DT	Infiltration 96% compared to 42% for conventional tillage	Alabama	Truman et al., 2005
NT	0.3 Mg/ha erosion compared to 7.8 Mg/ha for conventional tillage	Mississippi	McGregor and Mutchler, 1992
RT	Reduced erosion 80% on contour, compared to up and down, 5% slope	Mississippi	Mutchler et al., 1994
NT	Erosion reduced threefold by 10 years of NT, residue removal doubled erosion	Mississippi, loess silt loam	Dabney et al., 2004
NT	Reduced erosion 75%	Eastern Tennessee, loam	Yoder et al., 2005
Cover crop	Reduced erosion 95%, 3% slope	Missouri, silt loam	Wendt and Burwell, 1985
Plow	For various portions of an undulating field, tillage erosion up to 53.8 Mg/ha, water erosion up to 156.8 Mg/ha	West central Minnesota	Papiernik et al. 2005
Conventional tillage	Average erosion rate 20 to 40 Mg/ha; as high as 450 Mg/ha	Palouse region of Idaho, Washington, and Oregon	Pappendick and McCool, 1994
NT	Vegetable production with cover crops and crop rotation, erosion reduced to zero from 31 Mg/ha	Pennsylvania	NRCS, 2002
NT	Erosion about 12 Mg/ha, compared to 27 Mg/ha for plow	Idaho	Prato and Shi, 1990
NT	Reduced erosion 70 to 90%	Mississippi, silt loam	Meyer et al., 1999

<sup>a</sup>NT is no-till; CT is conservation tillage; RT is ridge-till; DT is deep tillage (subsoiling).

**The erratic nature of severe storms is a major cause of wide variations in soil loss and runoff from year to year.**

rainfall simulation. Averaged across all residue treatments, no-till reduced phosphorus losses in all forms by more than 90 percent compared to conventional tillage.

In a rainfall simulation study [100 mm (4 inches) in 2 hours] on two Alabama soils, interrill erosion was 10 to 20 times less with no-till, paratill, and a rye cover crop compared to conventional tillage without deep tillage or a cover crop (Truman et al, 2002; Truman et al, 2003). Paratilling—about 40 cm (16 inches) deep—occurred in the fall, after cotton harvest, on the silt loam soil in northern Alabama and in the spring on the loamy sand in southern Alabama. The paratill reduced bulk density 10 to 12 percent. Maintaining a surface residue cover combined with non-inversion deep tillage is ideal for promoting infiltration and reducing runoff and soil loss. The combination of no-till with residue cover and paratilling produced the most infiltration (Truman et al, 2005). About 96 percent of the simulated rainfall infiltrated (providing the equivalent of almost 7 days of crop water needs); only 42 percent infiltrated on the conventional tillage without paratilling (less than 3 days of water needs). This conventional tillage situation—the most common practice used by farmers in Alabama—represented the worst-case scenario for runoff, sediment loss, and infiltration.

Poultry litter was studied as an aid for reducing soil erosion in cotton production on a Decatur silt loam in northern Alabama (Nyakatawa et al, 2001b). Tillage and cover crops also were considered variables. Conventional tillage, with or without a winter rye cover crop, resulted in an estimated soil erosion loss of about 20 Mg ha<sup>-1</sup> (9 tons per acre) per year, double the tolerable loss rate. When poultry litter was substituted for chemical fertilizer as an nitrogen source in a no-till system, at 200 kg ha<sup>-1</sup> of nitrogen (180 pounds of nitrogen per acre), soil erosion declined to about 6 Mg ha<sup>-1</sup> (2.7 tons per acre) per year. Cotton lint yields were highest with no-till. Poultry litter at the rate of 200 kg ha<sup>-1</sup> of nitrogen (180 pounds of nitrogen per acre) increased lint yield by more than 300 kg ha<sup>-1</sup> (270 pounds per acre)—about 25 percent—compared to 100 kg ha<sup>-1</sup> of nitrogen (90 pounds of nitrogen per acre) applied either as nitrate or litter. A winter rye cover crop increased the yield slightly compared to no cover. In areas where excess poultry litter is an environmental issue, using higher rates in combination with no-till and cover crops offers a solution to both soil erosion and manure disposal problems.

Continuous no-till produced the lowest soil loss in a comparison of six tillage systems for sorghum following cotton (with a wheat or

vetch cover crop) in Mississippi (McGregor and Mutchler, 1992). Continuous no-till resulted in only 0.3 Mg ha<sup>-1</sup> (0.13 ton per acre) of annual soil loss, compared to 7.8 Mg ha<sup>-1</sup> (3.5 tons per acre) with conventional tillage. Reduced tillage and ridge-till produced losses of 3.3 and 5.7 Mg ha<sup>-1</sup> (1.5 and 2.5 tons per acre), respectively. Plots were 22 m (72 feet) long, with a 5 percent slope. About half of all soil loss occurred in the month of June, a time when there is little or no residue or plant canopy to protect the soil. Soil loss with ridge-till was higher than expected. Crop residue that collected in the valley between ridges was insufficient to prevent sediment eroded from the ridges from leaving the slope. In a later project, ridges on the contour, compared to the up-and-down-slope ridges, reduced soil loss by 80 percent (Mutchler et al, 1994). Almost half the soil loss occurred in June.

High-value vegetable crops also can be grown with no-till. In eastern Tennessee, tomatoes and tobacco were transplanted on two deep, well-drained loamy soils in a 2-year research project (Yoder et al, 2005). The replicated large-plot studies with natural rainfall showed a 90 percent reduction in runoff and more than a 75 percent reduction in soil erosion compared to conventional tillage. Nitrogen movement off the plots in runoff declined by 80 percent.

Corn and soybeans dominate in the Midwest, and wheat is the primary crop in the Great Plains. No-till research in these regions started in the hills of eastern Ohio, and crop residue management practices have since spread westward to encompass poorly drained soils that depend upon subsurface drainage and on to the drier Plains states where moisture conservation is a primary concern.

The erratic nature of severe storms is a major cause of wide variations in soil loss and runoff from year to year. Other variables include antecedent soil moisture, surface residue, crop canopy, and even wind direction during storms (Edwards et al, 1993).

Runoff and soil erosion on cropland vary widely, but reductions in both with no-till can be dramatic. In research with rainfall simulators at U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) sites at Senatobia, Mississippi, and Coshocton, Ohio, runoff under conventional tillage and no-till was 28 and 16 mm (1.1 and 0.65 inches), respectively. Soil loss from the conventional tillage treatments averaged 3.9 Mg ha<sup>-1</sup> (1.7 tons per acre), compared to 0 from no-till treatments (Rhoton et al, 2002). The reduction in runoff and elimination of soil loss under no-till treatments was attributed to increased organic matter and treatment effects on

other properties that affect infiltration and surface crusting. That does not mean there is never any soil loss under no-till. In watershed studies at the North Appalachian Experimental Watershed, Coshocton, Ohio, a corn-soybean rotation was maintained for 6 years on six sloping watersheds, with three conservation tillage treatments: chisel plow, paraplow, and no-till (Edwards et al., 1993). A rye cover crop was established each winter following soybeans. The watersheds ranged from 0.6 to 0.8 ha (1.5 to 2 acres). Slopes were between 7 and 13 percent, with lengths of 105 to 130 m (340 to 435 feet). Erosion is largely the result of infrequent, severe storms. In 6 years there were only 15 events that caused more than 100 kg ha<sup>-1</sup> (90 pounds per acre) of soil loss on any of the watersheds. Two storms caused most of the erosion. A single 20-year-return storm, on June 21, 1989, accounted for 42 percent of the 6-year total. Average annual soil loss for the watersheds was only 525 kg ha<sup>-1</sup> (0.5 ton per acre), less than 10 percent of the allowable soil loss. In contrast, when the watersheds earlier had been in a 4-year rotation of corn-wheat-meadow-meadow, for 40 years, average annual soil loss with conventional tillage was 5,750 kg ha<sup>-1</sup> (2.6 tons per acre) during the 10 corn years.

On the same watersheds at Coshocton, nutrient concentrations were measured in surface runoff (Owens and Edwards, 1993). Nutrient losses were less than 5 percent of the applied nitrogen. Losses were greatest in the corn year, with 70 percent of the nitrate-nitrogen losses occurring during the growing season. Most losses occurred in June or July because those were usually the first runoff events following fertilizer application. Sediment-attached phosphorus losses also were small, and more phosphorus was lost with sediment than in water. Nitrogen concentrations were less with no-till than with paraplow. Of concern was the fact that 11 of the 17 annual nitrate-nitrogen concentrations were above 10 mg/L, the maximum level allowed for drinking water.

On two silt loam soils at other Ohio research stations, 28 years of continuous no-till gave a substantial increase in soil organic carbon, while moldboard-plow treatments reduced soil organic carbon (Mahboubi et al, 1993). Hydraulic conductivity was 12 times greater for no-till than either chisel plowing or moldboard plowing, largely the result of relatively large pores and visible earthworm activity in no-till. Aggregation and aggregate stability was significantly better in the no-till plots. Bulk density was relatively unaffected by tillage system. Bulk density in trafficked row middles averaged almost 10 percent higher than in the row zone. Traffic increased the cone penetrometer resistance 50 to 75 percent

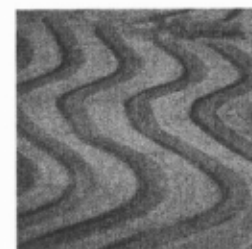
over resistance in the row zone. Chisel plowing and moldboard plowing produced similar resistance measurements, but no-till was about 60 percent higher than plowed plots in the row and 45 percent higher than plowed plots in the trafficked zones.

Economic analysis of conservation tillage and other options for Iowa farms included several ways to reduce soil erosion, including contouring, stripcropping, terracing, and rotations that included hay or pasture (Pope et al, 1983). After considering six scenarios for a range of soil types and slopes, conservation tillage in combination with contour planting was the most economical combination for reducing soil erosion. Specifically, ridge-till and no-till systems were highlighted as the most profitable ways on most Iowa soils to control erosion. In 2004 Iowa farmers used no-till on 18 percent of corn ground and 33 percent of soybean acreage. Ridge-till numbers were 0.5 percent and 0.7 percent, respectively (CTIC, 2004).

A combination of conservation practices kept soil erosion below the tolerable level of 10 Mg ha<sup>-1</sup> (5 tons per acre) per year on a Marshall soil with various slopes in the loess hills along the Missouri River in Nebraska and Iowa (Wittmuss, 1987). On a 183-m (600-foot), 6 percent slope, contour planting of corn and soybeans was sufficient to cut soil loss in half compared to up-and-downhill farming. On a 12 percent slope, terraces (and grassed waterways) were installed to reduce the slope length to 61 m (200 feet). Without these practices, soil loss was about eight times greater. On the 20 percent slope, terraces (and underground waterway) reduced the slope to 46 m (150 feet). With no conservation practices, erosion was 20 to 30 times greater—as high as 330 Mg ha<sup>-1</sup> (150 tons per acre) per year. The farming practices for all situations included disking and field cultivation in the corn year. A continuous no-till system was not included in the study.

The estimated value of lost annual income as soils become severely eroded ranged from about \$35 to \$44 per hectare (\$14 to \$18 per acre) in Iowa and Missouri (Speidel, 1994). This research indicated that no-till was a less costly method of soil erosion control than terraces alone.

A winter cover crop after corn silage harvest reduced runoff by half and soil erosion by 95 percent during a 6-year tillage study on Mexico silt loam with a 3 to 3.5 percent slope in Missouri (Wendt and Burwell, 1985). All rows were planted on the contour. Runoff from no-till silage with a cover crop was similar to runoff from corn for grain produced with no-till, reduced tillage, or conventional tillage. Soil loss from no-till silage with a cover crop was similar to no-till



Combinations of conservation practices, like the terraces and contouring on this Kansas field, can dramatically reduce soil erosion.



No-till systems are essential to control soil erosion on the steep, rolling hills in the Palouse region of the Pacific Northwest.

for grain, about half compared to reduced-till corn for grain, and a quarter of the soil loss for conventional tilled corn for grain. Yields were not significantly different in 4 of 6 years, and the overall averages were likewise similar.

The Palouse region of Washington, Idaho, and Oregon historically has had severe soil erosion problems (Papendick and McCool, 1994; Jennings et al, 1990). The steep topography and production of winter wheat with plow tillage leads to soil erosion rates averaging 20 to 40 Mg ha<sup>-1</sup> (9 to 18 tons per acre) per year, with extremes of up to 450 Mg ha<sup>-1</sup> (200 tons per acre) per year. Water erosion is the main problem, but wind erosion also can be severe. Before the native prairie was converted to grain production in the late 1800s, the soil organic matter content was 5 to 8 percent. By 1950 it had nearly been reduced in half. Burning crop residue was the main cause of the decline, along with tillage-intensive summer fallowing. In the mid-1970s only six models of conservation tillage drills were available for growers wanting to adopt conservation practices. By 1990, more than 60 models became commercially available. Crop residue management, achieved through crop rotation and no-till planting, is the main conservation practice because the steep, irregular terrain is not readily adaptable to other measures.

Reduced tillage and no-till systems provide a first line of defense against water and wind erosion in the Pacific Northwest, but conventional tillage typically has resulted in higher yields (Papendick, 1996). Cropping systems in the Northwest wheat region are determined mainly by precipitation that divides the region into three zones: high [greater than 430 mm (17 inches)], intermediate [330 to 430 mm (15 to 17 inches)], and low [220 to 330 mm (9 to 15 inches)]. In the low precipitation zone continuous spring cropping with no-till has allowed earlier planting, in February, and water conservation benefits that reduce the risk of crop failure. In the higher precipitation areas annual soil erosion has exceeded 350 Mg ha<sup>-1</sup> (150 tons per acre) on slopes, with field averages of 27 Mg ha<sup>-1</sup> (12 tons per acre). No-till has not been well accepted, but maintaining surface residue has proven to be effective against runoff-induced soil erosion. The erosion is caused mainly by runoff from melting snow or low-intensity rainstorms, usually associated with frozen or partially thawed soil.

A simulation of soil erosion and pollution control strategies for a watershed in northern Idaho with serious erosion and water quality problems compared no-till and minimum tillage to conventional tillage, each with conservation practice options of cross-slope, contour, or divided-slope

farming (Prato and Shi, 1990). A wheat-pea rotation was used. Most soil erosion in the area occurs in January-February from snowmelt and rain. The simulated erosion rate per year, based on the universal soil loss equation, was 28 to 30 Mg ha<sup>-1</sup> (12 to 13 tons per acre) for conventional tillage, regardless of the conservation practice. For minimum tillage the range was 17 to 20 Mg ha<sup>-1</sup> (7.5 to 9 tons per acre), and for no-till, 11 to 14 Mg ha<sup>-1</sup> (5 to 6 tons per acre). By comparison, permanent vegetation resulted in an estimated 2 Mg ha<sup>-1</sup> (1 ton per acre) of soil erosion. Clearly, the choice of tillage system was more important than other conservation practice options. At that time, research indicated a 15 percent yield reduction with no-till and a 3 percent reduction with minimum tillage. Given this yield assumption, the best economic choice was minimum tillage with permanent vegetative cover in riparian areas along streams.

In areas of low precipitation, such as the inland Pacific Northwest, farmers can maximize soil quality by following practices that minimize tillage, minimize the use of summer fallow, maintain adequate nitrogen, and maintain a cover of surface residue to control wind and water erosion (Kennedy et al., 2004). Soil microorganisms, which include bacteria, fungi, algae, and protozoa, affect nutrient and carbon cycling, plant growth, natural biological control, and changes in soil structure.

A diversified cropping system has been proposed for the Pacific Northwest. The system, designed for areas with adequate rainfall to support continuous cropping, includes no-till to maintain surface residue, paratill subsoiling to increase water infiltration, legume grass seed cropping (in rotation with wheat) to improve soil quality, grazing by sheep, and possibly biological weed control (Elliott and Chevalier, 1996). Annual cropping in low rainfall areas is important to reduce soil erosion and increase water use efficiency. Legumes fix nitrogen and improve soil quality.

Burning wheat residue was common practice in eastern Washington. A 3-year study of continuous winter wheat systems compared a "burn followed by low tillage" system with a conventionally managed system (McCool et al., 2000). Soil erosion under both systems was very low, about 1 percent of the erosion from winter wheat following summer fallow. Minimizing soil disturbance was more important than the amount of residue cover. Belowground stem material appeared to influence erosion rates if crop residue was removed, a result that indicates biomass harvest would not hurt soil quality if no-till seeding practices were followed.



In irrigated fields, straw or organic residues mechanically applied as mulch in the bottom of irrigation furrows will increase filtration and reduce soil erosion. Applications usually are after furrow formation and after the crop is planted. Erosion can be reduced 60 to 85 percent and infiltration can be increased 50 to 60 percent (Brown, 1985; Brown et al., 1998). On steeper land (greater than 4 percent slope) dry bean yields declined about 60 percent with fewer irrigations (Brown and Kemper, 1987). Jumbo and colossal-sized onions also were increased by straw in the furrows (Shock et al., 1999), and cumulative total nitrogen and phosphorus losses in runoff during the growing season declined 365 kg ha<sup>-1</sup> (325 pounds per acre) and 350 kg ha<sup>-1</sup> (310 pounds per acre), respectively (Shock et al., 1997). Straw in the furrow, combined with whey (Brown et al., 1998) or polyacrylamide (Lentz and Bjorneberg, 2003), proved more effective than straw alone. Soil organic matter increased after 3 years of applying straw to the bottom of the furrows (Miller and Aarstad, 1971), although soil organic matter may not change if the mulch itself is readily decomposed without adding any carbon to the system (Tian and Brussaard, 1997).

**Carbon and soil organic matter.** Crop residue management practices greatly influence changes in organic carbon levels in soil. Table 4 and the following discussion summarize the effect of tillage on soil carbon.

Moldboard plowing was the dominant tillage system prior to and including the 1960s. Conservation tillage was used on only 15 to 25 percent of U.S. cropland in 1980 (Allmaras et al., 2000). Largely because of conventional tillage, U.S. cropland prior to the 1980s contributed carbon to the atmosphere. Thereafter, the transition to no-till and other reduced tillage systems led to cropland becoming a carbon sink (Schomberg et al., 2002).

Reicosky (2002) argues that “residue” is not an appropriate term for something that is a valuable source of soil carbon. Until about 1990, the parts of plants remaining on a field after grain harvest were usually called “waste” or “trash.” Reicosky suggested going a step beyond “residue” and calling it “potential black gold.”

As yields of grain and crop biomass increase and farmers adopt less intensive tillage systems, the land should gradually become a long-lived carbon sink (Reicosky and Wilts, 2004). Soil carbon (soil organic matter) is so important that a person could make a case for calling this group of practices soil carbon management rather than crop residue management.

Farm soils typically contain 0.5 to 4 percent or-

ganic carbon on a mass basis (Reicosky, 2004b). This small amount of carbon is analogous to a catalyst: a small amount has a big impact on biological functions important to environmental enhancement. Removing carbon dioxide from the atmosphere is only one benefit of storing carbon in soil. The amount, diversity, and activity of soil fauna and microorganisms relate directly to the quantity and quality of organic matter (Reicosky, 2004a). Soil aggregation and stability of soil structure increase as organic carbon increases. Intensive tillage breaks up aggregates, resulting in a dense soil without natural channels, which makes it more difficult for plants to get nutrients and water.

No-till farming generally reduces soil loss by contributing to an increase in soil organic matter near the surface. Soil carbon, the primary indicator of soil quality, is considered by some to have a direct bearing on environmental quality (Reicosky, 2002). Because no single crop residue management system is superior in all situations, farmers must choose from a variety of practices in an attempt to optimize crop yield and environmental benefits.

Adding manure and chemical fertilizers to crops increases vegetative growth, which increases organic matter (NRCS, 1996b). Crops that produce little residue and farming systems that require intensive tillage result in greater losses of organic matter. Research shows it is practically impossible to increase organic matter when intensive tillage is used.

Measurements of carbon and phosphorus losses from crop residues show that tillage that buries residues causes faster and greater loss of carbon and phosphorus from the residues when compared to no-till (Buchanan and King, 1993). For corn, after 2 years, only 5 percent of the carbon remained in buried residue; 25 percent remained with no-till. A similar pattern existed in the case of wheat and soybean residue. This suggests that continuous no-till will lead to the accumulation of carbon and phosphorus in surface residues.

Crop residue management practices and their effects on organic matter and soil quality vary significantly by region and climate. Crops grown, rainfall amounts and patterns, and soil types all contribute to decisions regarding tillage practices and the resulting impacts on soils. In the South, for instance, higher temperatures mean that crop residue decomposes rapidly and throughout the year compared to northern areas. The opportunities for year-round plant growth allow farmers to use cover crops that provide additional carbon to increase soil organic matter. Cover crops also protect the soil from erosion during intense rainfall events. In the Midwest and Northern Plains

**Research shows it is practically impossible to increase organic matter when intensive tillage is used.**

- Soil management
- Water management / rain-fed
- Water management / irrigated
- Nutrient management
- Pest management / mitigation
- Pest management / IPM
- Landscape management

rainfall amounts decline from east to west. In the eastern Corn Belt, water erosion is the major concern, while in dryer areas wind erosion and water conservation are more important. In the northern areas rapid snowmelt can cause severe soil erosion. In the Northwest rainfall distribution is a big factor in soil erosion because most precipitation occurs in fall and winter. Low rainfall in many areas means that a crop only can be grown every

other year, leaving fallow fields susceptible to both wind and water erosion

Soil organic matter is an important determinant of soil physical, chemical, and biological characteristics (Reicosky and Wilts, 2004), and tillage is the primary factor affecting changes in soil organic matter levels. No-till leaves crop residue on the soil surface where it becomes a source of soil organic matter and nutrients for crops.

**Table 4. Effects of tillage systems on soil carbon.**

System*	Impact	Location/soil	Reference
NT	25% of C remained in residue compared to 5% for buried (after 2 yrs.)		Buchanan & King, 1993
CT	Increased C 39% in 3.5 yrs.	Alabama	Prieto, et al., 2002
NT	With cover crops, a corn-cotton rotation increased C storage 10% in top 30 cm in 30 months	Alabama, loamy sand	Terra et al., 2005
NT	Increased C 130% in top 2.5 cm in 12 yrs.; no difference for next 23 cm.	Alabama, silt loam	Feng et al, 2003
NT	Increased stratification rate for C and N much more in warm climate compared to colder climate	Texas, Georgia, and western Canada	Franzluebber, 2002b
NT	Twice as much C after 17 years compared to three other tillage systems	Coastal Plains, sandy loam	Motta et al., 2002
CT	Combined with rotations and cover crops with narrow-row cotton, increased C 46% in top 5 cm.	Alabama, loamy sand	Reeves & Delaney, 2002
NT	Substantial increase in C after 28 yrs.	Ohio	Mahboubi et al., 1993
Plow	C losses 13 times greater than no soil disturbance	Minnesota	Reicosky, 1997
CT	C losses averaged 4 times greater than no soil disturbance	Minnesota	Reicosky, 1997
NT	Soil C was 2.0% in top 2.5 cm compared to 1.6% for plowed ground	Texas, black clay	Potter and Chichester, 1993
NT, RT	Soil C was 58% greater in top 4 cm compared to plow after 9 yrs.	Texas, sandy clay loam	Zibilske et al, 2002
NT	16 yrs. of wheat-fallow reduced soil C 20%	Nebraska, native grassland	Follett and Schimel, 1989
Plow	16 yrs. of wheat-fallow reduced soil C 40%	Nebraska, native grassland	Follett and Schimel, 1989
NT	Organic matter increased to 6% from below 2% in 19 yrs., corn-soybean rotation	Illinois	NRCS, 1996a
NT	Soil organic C levels the same in top 5 cm as with chisel plow; slightly lower in next 10 cm.	Washington	Peterson et al., 2002
Plow	Wheat-fallow cropping, and burning the stubble, reduced organic matter from 2.4% in 1930 to 1.6% in 2000.	Oregon	Rickman et al., 2002
NT	25% higher organic C in top 10 cm compared to plow	Montana, clay loam and sandy loam	Bricklemeyer et al., 2005
NT	Vegetable production with cover crops and crop rotation increased organic matter to 4.9% from 2.7% in 10 yrs.	Pennsylvania	NRCS, 2002

\*NT is no-till; CT is conservation tillage; RT is ridge-till; plow is moldboard plow.

The cumulative effect of tillage and many crop rotations has been a 30 to 50 percent decline in soil carbon, which causes undesirable changes in soil physical, chemical, and biological properties. Tillage results in an immediate and significant gaseous loss of carbon, generally in proportion to the volume of soil disturbed (Reicosky, 2001). Conservation tillage tools that leave more residue on the soil surface result in the loss of only 31 percent as much carbon dioxide as the moldboard plow. The plow loses 13 times more carbon dioxide than untilled soil, while conservation tillage tools average about four times as much carbon dioxide loss (Reicosky, 1997).

Strip-till reduces carbon loss. In tillage comparisons on Hamerly clay loam at Morris, Minnesota, measurements of carbon dioxide losses were made over 19 days (Reicosky and Lindstrom, 1993). The cumulative flux from each tillage surface was as follows: 913, 475, 391, 366, and 183 g m<sup>-2</sup> for moldboard plow, moldboard plow + disk harrow twice, disk harrow once, chisel plow, and no-till. For all tillage situations, there was a large flush of carbon dioxide in the first hour or so, and the rate declined over time. These results suggest that the high initial flush of carbon dioxide related more to surface roughness and the volume of soil disturbed than to residue remaining on the surface. Farmers can enhance soil carbon by increasing the quantity and quality of crop residues and by reducing the intensity of tillage.

Crop residue management practices (including rotations and cover crops) in cotton production have improved over the last 20 years or so. The result has been a dramatic turn around in soil quality. Continuous no-till is sometimes defined broadly to include such operations as strip-till and deep tillage that leaves surface residue undisturbed. The goal does not change (keep residue on the surface to minimize soil erosion and provide other soil-related benefits), but the "precision tillage" creates the necessary soil environment for root growth and competitive yields. During hot, dry periods, surface residue helps retain enough moisture in the soil for the plant to keep growing instead of wilting. In one experiment, cotton yields under no-till outperformed yields under conventional tillage in each of the first 3 years (Werblow, 2005).

In the "Old Rotation" at Auburn, Alabama, the oldest continuous cotton experiment in the world, measurements of soil organic carbon 3.5 years after adoption of conservation tillage in 1996 showed a dramatic 39 percent increase in the top 20 cm (8 inches), averaged across six basic cropping systems (Prieto et al, 2002). Conservation tillage consisted of non-inversion tillage 45 cm (18 inches) deep with a paratill before no-till

planting into a killed cover crop or winter weed residue. The soil organic carbon in continuous cotton without a legume or nitrogen, 0.4 percent in 1994, increased to about 0.7 percent in 1999. In a 3-year rotation that included a legume plus nitrogen, soil organic carbon increased over the same period from 1.0 percent to 1.4 percent.

In a 12-year continuous cotton research project on Decatur silt loam in the Tennessee Valley at Belle Mina, Alabama, no-till increased soil organic carbon by 130 percent and nitrogen by 70 percent in the top 3 cm (1 inch) of soil compared to conventional tillage (Feng et al., 2003). There was no significant difference from 3 to 25 cm (1 to 10 inches) for either carbon or nitrogen. Soil pH was essentially equal in both tillage systems, ranging from 6.4 to 6.7 at all depths. The microbial community structure shifted with tillage. No-till soils featured increased infiltration and higher water-holding capacity, which means they are wetter, cooler, and fluctuate less in moisture and temperature. This stimulates the growth and activity of soil microorganisms.

On two similar loamy soils in Alabama, soil organic carbon was measured for different land use practices (Fesha et al, 2002). No-till resulted in a higher percentage of soil organic carbon in the top 5 cm (2 inches) than conventional tillage on both sites. On one site, loblolly pine did not improve soil quality relative to no-till cropland. On the other soil, a mixed forest woodland had more soil organic carbon than either cropland or pasture. Bermudagrass pasture at one site had higher soil organic carbon than no-till cropland, but at the other site, bahiagrass pasture had slightly less soil organic carbon than no-till.

A 4-year study involving various cotton rotations and tillage systems on Compass loamy sand in Alabama showed that ultra-narrow-row cotton grown in rotation with corn, wheat, and cover crops, and using conservation tillage, produced the highest net returns and increased soil organic carbon (Reeves and Delaney, 2002). Soil organic carbon increased 46 percent in the top 5 cm (2 inches) of soil compared to conventional tillage. These results suggest that on the drought-sensitive soils of the Southeast this combination improves soil productivity and enhances economic returns.

In another Alabama study, a field that had been in continuous cotton under conventional tillage for 30 years was converted to no-till cotton grown in rotation with corn and cover crops (Terra et al, 2004). Cotton yields increased immediately and for the first 3 years averaged about 15 percent more than plots in the field kept in the old system. The cover crops chosen provided up to 6.7 Mg ha<sup>-1</sup> (3 tons per acre) of residue. Benefits included

**Crop residue management practices (including rotations and cover crops) in cotton production have improved over the last 20 years or so.**



less soil crusting (improved crop emergence), increased organic matter in the surface layer, and greater water conservation in the topsoil. As an example of water conservation, 16 hours after a 36-mm (1.4-inch) rain in mid-season 2002, the no-till soil had 67 percent more water stored.

On two coastal plain soils, the 17-year influence of four tillage systems on soil quality showed that soil carbon accumulation in the top inch of no-till approximately doubled the levels in the other three systems. On Benndale fine sandy loam, the carbon measured  $27.6 \text{ g kg}^{-1}$  with no-till and 13.1, 12.7, and  $10.4 \text{ g kg}^{-1}$  with disk, chisel, and moldboard-plow systems, respectively. On Lucedale very fine sandy loam, the numbers were 16.7, 10.0, 9.8, and  $6.9 \text{ g kg}^{-1}$  for the respective treatments (Motta et al., 2002). The Lucedale soil had more soil organic carbon in the 7.5-cm (3-inch) depth in the no-till, chisel, and disk systems than in the moldboard-plow system.

On degraded soils in warm, humid climates, a high-residue-producing cropping system with no-till and cover crops sequesters carbon even during the first years after adoption (Terra et al., 2005). In research in central Alabama the conservation tillage system increased soil carbon by 10 percent in the top foot of soil in 30 months. When dairy manure was added, soil carbon increased 38 percent.

In northern Alabama, the combination of conservation tillage, application of poultry litter, and crop rotation, including wheat as a cover crop, was researched in the 1980s (Motta et al., 1999). Soil organic carbon approximately doubled in the top 24 cm (10 inches) of soil with conservation tillage compared to chisel plow and disk tillage. The increase was attributed to greater residue and/or carbon from the poultry manure retained with conservation tillage.

Measurements of carbon dioxide losses over a full summer's growing season after application of poultry litter, at  $100 \text{ kg ha}^{-1}$  of nitrogen (90 pounds of nitrogen per acre), showed that conventional tillage had 9 percent, 83 percent, and 307 percent higher efflux values than mulch-till, no-till, and bare fallow soils, respectively (Roberson et al., 2004). The accumulation of carbon and slightly higher levels of nitrogen in the soil had no adverse effects on soil pH over 5 years of research (Parker et al., 2002). Any extra nitrogen was in the top 5 cm (2 inches) where it would be accessible and available to the following crop.

On Norfolk loamy sand in central Alabama, research to measure the influence of tillage and wheel traffic showed no consistent effects on organic matter decomposition, nutrient mineralization, or bacterial and fungal biomass (Entry et al., 1996). In contrast to other research where differ-

ences were measured, this experiment was on a sandy soil (compared to clay), so compaction had less impact on porosity and other soil physical properties. Also, in warm, moist soil conditions, organic matter decomposes quite rapidly, regardless of tillage system used. When crop residue was buried 15 to 20 cm (6 to 8 inches) deep in decomposition bags, the rate of decomposition was greater than when the bags were placed on the surface. The weight of the tractor used to compact the soil on wheel-traffic treatments was quite low [ $4.6 \text{ Mg}$  (5 tons) total] in comparison to the 9 to 18 Mg (10 to 20 ton) per axle loads frequently used for compaction research elsewhere (Schuler et al., 2000).

In a 20-year continuous no-till, continuous corn study at Lexington, Kentucky, on Maury silt loam, soil organic carbon, nitrogen, and other chemical properties were significantly higher with no-till than with moldboard plowing, especially in the top 5 cm (2 inches) of soil (Ismail et al., 1994). The plots had been in bluegrass pasture for 50 years prior to the start of the tillage experiment, and carbon levels in no-till were restored to the level in the sod following a decline of 19 percent with plowing and 9 percent with no-till after the first 5 years of corn production, in 1975. About  $10 \text{ Mg ha}^{-1}$  (4.5 tons per acre) of carbon were lost in 5 years of plowing; about  $5 \text{ Mg ha}^{-1}$  (2.2 tons per acre) were lost with no-till. The increased organic carbon observed in 1989 accrued from corn residue, estimated at  $7.5 \text{ Mg ha}^{-1}$  (3.3 tons per acre) of dry matter per year, and a cover crop of rye, which added about  $3 \text{ Mg ha}^{-1}$  (1 ton per acre) per year.

More than 20 percent of U.S. cotton is grown in the Texas High Plains, usually as continuous cotton, with more than 90 percent conventional tillage. One study in the region (Acosta-Martinez et al., 2003) found that adopting no-till and using a rotation with peanuts, sorghum, or wheat resulted in significantly higher carbon content and other soil biochemistry benefits.

At Temple, Texas, long-term no-till permanent beds on a Houston black clay soil showed a significant increase in organic carbon, total nitrogen, and total phosphorus in the top 5 cm (2 inches) of soil compared to chisel plow and disk fields with annually formed beds (Potter and Chichester, 1993). Houston soil is a vertisol that self-mulches upon drying. After 10 years of no-till, the soil organic carbon in the top 2.5 cm (1 inch) was 2.02 percent; this declined to 1.58 percent in the layer between 7.5 and 10 cm (3 and 4 inches). In contrast, the field with annual tillage was consistently about 1.56 percent throughout the top 10 cm (4 inches). Total nitrogen and phosphorus were stratified in the top 10 cm (4 inches)



of no-till soil, indicating that little soil mixing was occurring, despite the self-mulching nature of the vertisol.

At Weslaco in southern Texas, 9 years of no-till and ridge-till on Hidalgo sandy clay loam increased organic carbon and nitrogen in the upper soil layers more than plow tillage (Zibilske et al., 2002). Soil organic carbon with no-till was 58 percent greater in the top 4 cm (1.5 inches) and 15 percent greater at 4 to 8 cm (1.5 to 3 inches); there were no differences among tillage systems in the 8- to 30-cm (3- to 12-inch) depth. Ridge-till treatments produced a similar soil organic carbon pattern to no-till. Both no-till and ridge-till resulted in significantly greater nitrogen concentrations in the top 8 cm (3 inches).

In western Nebraska, 16 years after native grassland had been converted to cropland (wheat-fallow) on a research farm near Sidney, measurements of organic matter showed how soil properties change (Follett and Schimel, 1989). The organic matter level in the top 5 cm (2 inches) of undisturbed sod was 53 g kg<sup>-1</sup> in comparison to 43, 37, and 30 g kg<sup>-1</sup> for no-till, stubble-mulch, and plow treatments, respectively. For the 5- to 10-cm (2- to 4-inch) depth, the corresponding values were 44, 33, 35, and 29 g kg<sup>-1</sup>, respectively. Total nitrogen concentration in the top 10 cm (4 inches) declined to 73, 68, and 50 percent of native sod for no-till, stubble-mulch, and plow treatments, respectively. The researchers found that as tillage intensity increased microbial biomass decreased. Respiration of carbon dioxide under controlled laboratory conditions was proportional to microbial biomass, while mineralization of nitrogen was not.

On a nearby site that had been in crested wheatgrass sod for 12 years after 27 years of conventional farming, organic matter appeared to be much lower at the beginning of the tillage experiment (Follett and Peterson, 1988). After 16 years of wheat-fallow cropping, organic matter in the top 5 cm (2 inches) was 27 g kg<sup>-1</sup> for no-till, compared to 24.5 g kg<sup>-1</sup> for stubble mulching, and 18 g kg<sup>-1</sup> for moldboard plowing. Organic matter from 5 to 20 cm (2 to 8 inches) did not vary with tillage.

Conservation tillage practices that fit local soil and climatic conditions can be among the best methods for improving soil quality by increasing soil biological activity and organic matter content. Carbon is an essential element for improving soil quality, regardless of the soil and crop management strategy (Karlen et al., 1992). Cover crops and crop rotations also help. Alley cropping may facilitate these effective agronomic practices that increase soil carbon.

Converting CRP or other grassland to crop

production using no-till practices will preserve the soil quality benefits of CRP, but conventional tillage "will destroy the benefits almost immediately" (Karlen et al., 1998).

Measurements on a private Illinois farm showed that 19 years of continuous no-till raised organic matter levels in the surface layer of soil from less than 2 percent to just over 6 percent (NRCS, 1996a). The farmer used strip-till for corn in rotation with soybeans.

On a Minnesota field, soil carbon concentrations varied widely as a result of erosion from tillage and water (Papiernik et al., 2005). A hundred years of cropping, including 40 years of annual moldboard plowing, on an undulating field led to areas with exposed subsoil and low areas with accumulated topsoil. Soil organic carbon levels averaged from 0.4 percent to 2.0 percent, with a mean of 1.0 percent.

Measurements of changes in soil quality over time in eastern Washington showed an increase in soil organic carbon with long-term no-till. Changes in microbial activity and other soil quality indicators take longer to occur in areas of low precipitation (Kennedy, 2002).

In an earlier study, Kennedy and Smith (1995) compared microbial diversity for two nearby sites, one with a history of plow tillage, the other undisturbed native prairie. Biomass carbon was significantly higher, by about 35 percent, in the native prairie. Inorganic nitrogen was slightly higher in the cultivated soil, and pH was the same. The plowed site had greater diversity of microbes, probably caused by mixing of the substrate. The microbe populations in the prairie soil were less diverse.

Measurements taken during the spring wheat-growing season showed little difference between no-till and chisel-plow systems for microbial properties (Peterson et al., 2002). Soil organic carbon in the top 5 cm (2 inches) was not significantly different (about 31 g kg<sup>-1</sup>). In the 5- to 15-cm (2- to 6-inch) depth, soil organic carbon was slightly lower in the no-till system (about 24 g kg<sup>-1</sup> compared to 29 g kg<sup>-1</sup>).

In other research on dryland wheat, not only was organic carbon higher in conservation tillage systems, compared to conventional tillage systems, but the conservation tillage systems resulted in a greater percentage of carbon in the larger aggregates, making the soil less susceptible to erosion (Hansen et al., 2004). Populations of microbial communities varied with tillage system and aggregate size.

A report on modeling the effect of tillage, crop rotation, and added organic amendments on carbon sequestration included a summary of a 70-year experiment at Pendleton, Oregon (Rickman,

**Conservation tillage practices that fit local soil and climatic conditions can be among the best methods for improving soil quality by increasing soil biological activity and organic matter content.**

et al, 2002). For a wheat-fallow cropping pattern, two treatments—burning of stubble or plowing and adding 225 kg ha<sup>-1</sup> (200 pounds per acre) of nitrogen before plowing—both resulted in soil organic matter levels that declined from 2.4 percent in 1930 to around 1.6 to 1.8 percent in 2000. In a third treatment, which involved adding 22 Mg ha<sup>-1</sup> (10 tons per acre) of wet straw manure and plowing, organic matter levels remained fairly steady at about 2.4 percent. Those measurements were in the top 30 cm (1 foot) of soil. The authors used the calibrated model to estimate changes in soil carbon for 11 tillage research sites across the country. With one exception (on a severely eroded site) the CQESTR model accurately predicted the organic matter levels within 0.33 percent. The Oregon research verified that Pacific Northwest soils lose carbon with any cropping system that includes a summer fallow unless large amounts of manure are added (which is not a reasonable practice on a wide-area basis). Soil organic matter can be maintained or improved if these soils are cropped every year and crop residues are preserved on the surface.

In northern Montana, soil organic carbon was measured at two sites on paired wheat fields to compare the effect of conventional tillage to long-term no-till (Bricklemyer et al., 2005). At both locations, no-till had at least 25 percent more carbon in the top 10 cm (4 inches): 18 Mg ha<sup>-1</sup> (8 tons per acre) compared to 14 Mg ha<sup>-1</sup> (6 tons per acre) on a clay loam and 9 Mg ha<sup>-1</sup> (4 tons per acre) compared to 7 Mg ha<sup>-1</sup> (3 tons per acre) on a sandy loam.

In southeastern Pennsylvania, a commercial vegetable grower has been using no-till, cover crops, and crop rotations for more than 10 years (NRCS, 2002; Steve Groff, personal communication, 2005). Steve Groff grows about 32 ha (80 acres) total of pumpkins, sweet corn, and processing tomatoes. He also has about 55 ha (135 acres) total of corn for livestock, soybeans, small grain, hay, and cover crops. Cover crops were added because vegetables provide little residue to protect the 3 to 17 percent slopes from soil erosion. Rye, hairy vetch, crimson clover, or a combination of these is used, depending upon the crop to follow. Soil organic matter has increased to an average of 4.9 percent from 2.7 percent before the farm switched to no-till. Soil erosion has declined from an estimated 31 Mg ha<sup>-1</sup> (14 tons per acre) to nearly zero. Earthworm populations are amazing in this no-till system. On a spring evening in 2005, with perfect weather conditions for worms to surface, Groff counted 17 earthworms in an area of about 0.74 square meters (8 square feet); he estimated that to be the average for the entire no-till field. In a neighbor's

field with conventional tillage, he walked over a third of an acre and saw only three worms. This observation is in line with research studies on earthworms and no-till.

In Quebec, Canada, measurements of microbial activity at various times during the year showed more variation by date than for different tillage systems (Spedding et al, 2004). The research was conducted on a very coarse-textured soil (sandy to sandy loam), which may have limited the impact of tillage on measurements of carbon. After 9 years of continuous corn, measurements of organic carbon showed the benefits of leaving residue on the surface. Where the researchers removed all residue before tillage, the organic carbon in the top 10 cm (4 inches) was about 18 g kg<sup>-1</sup> of soil for no-till, disk tillage, and moldboard plow. Where only the grain was removed, the increase in organic carbon for the three systems was 0.4, 1.5 and 4.3 g kg<sup>-1</sup> of soil, respectively. Amounts in the 10 to 20 cm (4 to 8 inch) depth were similar. Soil microbial biomass carbon did not vary much across the four sampling dates, from May 7 to September 29.

In Uruguay, soil organic carbon declined in a continuous cropping system, even with no-till (Terra and Prechac, 2002). The soil organic carbon reductions for conventional tillage, reduced tillage, and no-till were 24, 12, and 7.5 percent, respectively, over 4 years in the top 15 cm (6 inches) of soil. Removal of so much biomass through grazing of winter crops and hay harvest in summer contributed to the slight decline with no-till.

No-till and cover crops have proved to be an effective combination for increasing soil organic matter in subtropical climates. In southern Brazil, on a sandy clay loam after 12 years of no-till corn, including a cover crop, soil organic carbon increased 4.3 Mg ha<sup>-1</sup> (1.9 tons per acre), nearly 150 percent, compared to bare soil (Bayer et al, 2001). A rotation of oats, vetch, and cowpeas increased soil organic carbon by 2.1 Mg ha<sup>-1</sup> (1.0 ton per acre), almost 75 percent. Decomposition of soil organic matter in warm, wet subtropical soils is up to five times faster than in temperate conditions. No-till systems with cover crops can accumulate soil organic carbon as much as 1.0 Mg ha<sup>-1</sup> (0.5 ton per acre) per year.

**Stratification.** A high carbon:nitrogen stratification ratio, with depth, may be a better indicator of soil quality than total carbon or nitrogen in the soil profile (Franzluebbers, 2002b). Research on soils in two warm regions (Texas and Georgia) and a cold, dry climate (Alberta and British Columbia) showed a much higher stratification ratio with no-till in warmer soils (with inherently



A cover crop, like that in this California orchard, not only protects against soil erosion, but adds organic matter to the soil, which improves soil quality.

low organic matter) than with no-till in cold soils. The stratification ratio with no-till was not much different than with conventional tillage in the Canadian fields. The shallow tillage, 10 to 15 cm (4 to 6 inches) deep, coupled with the cold, dry climate probably did not allow crop residue to decompose more rapidly with tillage as it usually does in warmer, wetter climates.

Row spacing had no apparent effect on nutrient stratification in research at Florence, South Carolina, on Goldsboro loamy sand (Bauer et al., 2002b).

#### *Crop yields with residue management systems.*

If crop yields are not competitive, farmers cannot afford to use residue management systems and produce the environmental benefits those systems are capable of producing. In the southeastern coastal plain region, use of conservation tillage systems for corn production generally proved unsuccessful before the 1980s (Campbell et al., 1984). Research with autumn subsoiling increased corn yields in both conventional and conservation tillage systems on Norfolk loamy sand. Conservation tillage systems excelled only when soil moisture was limiting. A high-residue, no-till system with cover crops in Alabama increased yields about 15 percent for both corn and cotton in rotation (Terra et al., 2005).

Research was conducted at Florence, South Carolina, to determine if cotton, soybeans, and wheat grown on two different soil types would result in different yield responses to residue management systems (Bauer et al., 2002a). Both soils were loamy sand, but one extended to a depth of 1 m (40 inches), while the other changed to a sandy clay loam at about 0.4 m (16 inches). All three crops exhibited the same yield trend with conservation tillage on both soils; paratilling produced the lowest yield and paratilling plus crop rotation the highest. In contrast, disk harrow, S-tined harrow treatments produced variable yields. At this location, conservation tillage provided more consistent and predictable yields and, usually, the highest yield.

Blackland prairie clay and silty clay soils near Temple, Texas, produce good yields of corn, sorghum, and cotton with either no-till or shallow strip-till performed a day or so ahead of no-till planting (Morrison, 2002; Morrison and Sanabria, 2002). Keeping all soil disturbance confined to the top 5 cm (2 inches) is ideal on these poorly drained soils (Morrison et al., 2002). Tillage with a moldboard plow, chisel plow, or disk harrow creates sizable clods that require additional tillage to achieve successful seeding. Fertilizer application [phosphorus, potassium (K), or liquid nitrogen] also is done on the surface of

a shallow strip to avoid problems with the wet, sticky soil. Because crop residue keeps soil water nearer the field surface, the nutrients remain available to crop roots in the moist, shallow soil.

Residue affects soil temperature. Residue has a moderating effect on temperature extremes, both maximum and minimum. Even small differences in residue amounts and conditions (standing versus flat) have a major influence on temperatures (Unger, 1988).

Combining narrow rows with no-till and deep tillage with a paratill increased corn and soybean yields in research at Florence, South Carolina, on Goldsboro loamy sand (Bauer et al., 2002b).

Research on a deep loess soil in western Iowa showed that switching from disk tillage to no-till and changing from continuous corn to either a corn-soybean rotation or a 6-year rotation of corn, soybeans, and alfalfa did not negatively affect soil bulk densities or crop yields (Logsdon and Karlen, 2004). Although bulk densities increased in the first few years, the macropores allowed good root growth that overcame higher bulk densities. Bulk density is not a useful indicator of soil quality for these soils when changing to no-till or ridge-till. The measurements confirmed that farmers should not worry about increased compaction with no-till on these soils. Subsoiling these deep loess soils is not economical.

On a well-drained Port Byron silt loam soil in southeastern Minnesota, strip-till and deep tillage both provided competitive corn yields compared to conventional tillage, which consisted of fall chisel plowing and spring field cultivation (Vetsch and Randall, 2002). In the 4-year experiment involving corn following corn, yields for conventional tillage averaged 0.3 Mg ha<sup>-1</sup> (4 bushels per acre) higher than strip-till and deep tillage and 0.5 Mg ha<sup>-1</sup> (7 bushels per acre) higher than no-till. When corn followed soybeans, however, yields for all three conservation tillage systems were slightly but not significantly higher than conventional tillage. This research also showed that placing starter fertilizer in a band beside the row increased corn yields about 0.5 Mg ha<sup>-1</sup> (7 bushels per acre). The residue cover for all conservation tillage systems after planting was 55 percent or greater, compared to 26 percent for conventional tillage.

A large study at 13 sites in nine midwestern states compared tillage systems for a corn-soybean rotation over 5 years (Buman et al., 2004). Conventional tillage, no-till, and strip-till were evaluated, as were narrow-row and 30-inch-row soybeans. Yield differences within years were not significant, but profit for no-till and strip-till corn was highest in 4 of 5 years. For soybeans, the

5-year average profit for no-till with narrow rows was highest. Choosing those systems in the rotation resulted in about \$135 per hectare (\$55 per acre) more profit than the other practices.

Economic analysis of tillage options for a typical 2,300-acre nonirrigated wheat farm in Utah concluded that a combination tillage system would be the best choice under the constraints of the 1985 farm bill (Helms et al., 1987). No-till drills were expensive at the time, and that high cost relegated the practice to the third choice, despite yields being equal to conventional tillage. Government payments played an important role in the economic decision discouraging a switch to conservation tillage.

In northern New York, reduced tillage systems for corn performed well after rotation out of perennial alfalfa (Karunatilake et al., 2000). Yields the first year were significantly higher under plow tillage compared to no-till, but were similar in the second year. Ridge-till gained a slight but insignificant yield advantage in the next 6 years over fall plowing and no-till (no-till was converted to zone-till the last 5 years). All treatments involved controlled traffic.

Soybeans planted in wheat stubble performed best with low residue cover in tillage studies on

silty clay, clay loam, and loam soils in southwestern Ontario (Vyn et al., 1998). Zone tillage and disking treatments in the fall both left a residue cover of at least 35 percent, improved in-row seedbed conditions, and increased soybean yields 5 to 29 percent compared to no-till.

**Water quality effects.** Water quality is impaired when runoff from cropland includes sediment, pesticides, nutrients, and other contaminants. Reducing soil erosion usually improves surface water quality by reducing the suspended sediments in runoff. A strong linkage exists between water quality and soil quality, and it is impossible to completely separate the effects. Specific results (below and in Table 5) will be covered in two areas of water erosion: sedimentation and particulate pollutants.

The combination of higher grain yields and less tillage improves organic matter and water quality (Reicosky and Wilts, 2004). Crop biomass becomes the main food source for soil microorganisms, which nurtures nutrient cycling. Nitrogen sequestration in the additional organic matter with no-till is one reason nitrate concentrations in percolating water below no-till fields tend to be less than on plowed fields. The additional residue

**Table 5. Tillage effects on water quality.**

System <sup>a</sup>	Impact	Location/soil	Reference
NT	Reduced runoff 87% with zero residue, Reduced runoff 99% with 1.5 Mg/ha residue	Virginia	Mostaghimi et al., 1987
NT	Reduced P losses 90%	Virginia	Mostaghimi et al., 1987
NT	Reduced runoff 90%, reduced N losses 80%	Eastern Tennessee	Yoder et al., 2005
NT	Reduced runoff to 16 mm, from 28 mm	Ohio, Mississippi	Rhoton et al., 2002
NT	N losses were <5% of applied N, 11 of 17 annual nitrate-N concentrations >10mg/L	Ohio	Owens and Edwards, 1993
NT	Reduced erosion 90% for continuous corn, reduced erosion 70% for corn/soybeans	Iowa	Lakshminarayan et al., 1994
NT	Nitrate-N in leachate slightly higher	Iowa	Lakshminarayan et al., 1994
NT	Increased use of NT improves quality of streams and habitat in agroecosystems	Ontario, Canada	Yates et al., 2006
Residue cover	Reduced movement of pesticides bound to soil particles		Honeycutt and Jemison, 1995
Cover crop	Reduced runoff 50% on 3% slope	Missouri, silt loam	Wendt and Burwell, 1985
Cover crop	Vetch cover reduced runoff 5 to 10 cm/yr	Mississippi	Wilson et al., 2004
NT	Only 0.01% of applied dicamba was lost in runoff, compared to 0.08% for plow, 5 yrs.	Pennsylvania	Honeycutt and Jemison, 1995

<sup>a</sup>NT is no-till system.



may initially immobilize nitrogen, but over time, this condition favors nitrogen mineralization.

No-till farmers use about the same amount of herbicides per acre as conventional farmers (Moldenhauer et al, 1995). Survey results show that farmers recognize herbicides as a cost-effective way to manage weeds, even if row-crop cultivation is an option. Residue management systems are, therefore, not likely to add manufactured chemicals to the environment any differently than other systems.

The effectiveness of crop residue management systems varies somewhat by region. In drier regions, crop yields may be low, producing insufficient residue to protect the soil adequately from storms or snowmelt. In the Southeast and other warm climates, heat and humidity tend to deplete crop residue throughout the year, and frequent storms in early summer occur at the most vulnerable time of year for soil erosion from conservation tillage systems. Alternatively, cover crops and/or weeds will grow all year if allowed to.

**Water erosion: Sedimentation.** In a Georgia study, no-till reduced runoff to 8 percent, compared to 18 percent with conventional tillage; sediment loss declined to 0.14 Mg ha<sup>-1</sup> (0.06 ton per acre) with no-till, compared to 26 Mg ha<sup>-1</sup> (11.7 tons per acre) with conventional tillage (Sojka et al, 1984).

In northeastern Missouri, a 9-year project using a corn-soybean rotation and mulch tillage (disk plus one or two passes with a field cultivator) resulted in 4 years with soil erosion rates of about 6.7 Mg ha<sup>-1</sup> (3.0 tons per acre) (Lerch et al., 2005). Those years all were following soybeans, with less protective cover, and above average rainfall. In the other 5 years, soil erosion averaged 0.9 Mg ha<sup>-1</sup> (0.4 ton per acre).

In northern Mississippi, several conservation cropping systems were established on three watersheds and replicated plots (on a 4 percent slope) to measure runoff and soil loss over 6 years. Soils were primarily Grenada silt loam, previously in sod (Meyer et al., 1999). Conventionally tilled soybeans resulted in excessive soil erosion on both short plots and the 2-hectare (5-acre) watershed. Fescue buffer strips 5.5 m (18 feet) wide and grassed waterways proved inadequate to control soil loss. No-till systems for soybean, cotton, sorghum, corn, and wheat effectively controlled soil erosion, reducing soil losses 70 to 90 percent on the small plots, and even more on the watersheds, compared to conventional tillage.

On the northern Mississippi plots and watersheds, no-till, when combined with grassed waterways and grass hedges to control con-

centrated flow, provided adequate soil erosion control (Meyer et al, 1999). Conservation tillage systems, including a winter vetch cover crop, not only reduced winter and spring storm runoff, but also lowered sediment transport to waterways and channels. The vetch cover crop generally reduced runoff 50 to 100 mm (2 to 4 inches) per year.

Removing residue from no-till cropping systems in northern Mississippi resulted in runoff starting significantly sooner, even the following year (Wilson et al, 2004). Sediment concentrations doubled. Tilling previously no-tilled land resulted in significantly lower sediment losses compared to land previously in conventional tillage. This suggests no-till ground maintains soil quality when tilled, but these beneficial qualities are fully lost within 1 year of residue removal. Immediately returning to no-till can minimize the negative environmental impacts of tillage.

**Water erosion: Soluble and particulate pollutants.** Tillage is a well-known management technique to "mine organic nutrient reserves" to enhance crop yields (Martens, 2001). The result is the loss of soil nutrients (nitrogen, phosphorus, and potassium), a rapid reduction in organic matter, loss of soil structure, and increased soil erosion. When years of intensive tillage are reversed with the adoption of no-till, the soil tends to bank nutrients. Stratification of crop residue on and near the soil surface influences nutrient availability. Physical changes in a no-till soil result in greater nutrient content, but reduced nutrient availability. Competition exists for applied and mineralized soil nitrogen between nitrogen immobilization, nitrifiers, and plants, and competition increases because the residue is on the soil surface.

No-till soils pose less risk of losing nutrients associated with sediment than organically farmed and conventionally tilled soils (Green et al., 2005). In Maryland research on a Christiana-Matapeake-Keyport soil association, carbon, nitrogen and phosphorus concentrations were greater in macroaggregates than in small aggregates and microaggregates. No-till farming promotes the formation of macroaggregates more so than the other cropping systems, hence the lower risk of nutrient loss.

During a 9-year mulch tillage project in Missouri, almost a third of the precipitation ran off the surface in the 5 years with above-average rainfall (Lerch et al., 2005). Those years with high runoff tended to have higher levels of soil erosion and higher concentrations of herbicides (atrazine, alachlor, and metolachlor) and nutrients (nitrogen and phosphorus) in the runoff.

In Alabama research, no difference was noted

**No-till farming promotes the formation of macroaggregates more so than the other cropping systems, hence the lower risk of nutrient loss.**

**Pest management strategies often change with the adoption of conservation tillage systems.**

in the stratification of nutrients between conventional tillage (chisel plow plus disk) and no-till, except when manure was applied (Balkcom et al., 2005). Both systems also had non-inversion, in-row subsoiling. Nutrient concentrations generally were lower in the 15- to 30-cm (6- to 12-inch) depth than in the top 15 cm (6 inches). With two applications of dairy manure, the no-till plow system had a higher concentration of phosphorus in the surface 5 cm (2 inches). The chisel plow system mixed the manure into the top 15 cm (6 inches), but concentrations were still higher in the surface 5 cm (2 inches) than in the 5- to 15-cm (2- to 6-inch) depth.

Pest management strategies often change with the adoption of conservation tillage systems. Crop residues affect pest populations and methods of control either directly or through tillage (Forcella et al., 1994). Insects, disease organisms, and weed seeds respond differently and can require different means of control. Changes can be both good and bad; harmful insects that thrive in plant residue will increase with no-till, but predator populations also may increase. Weed species disseminated by wind (such as dandelion and foxtail) are more common in reduced tillage systems, but invader species (such as wild oats and millet) are more common in tilled systems because they require soil disturbance to germinate (Bailey and Goosen, 2002).

Diseases favored by cool, wet soils and those with pathogens that overwinter in crop residues may be more prevalent with no-till (Jardine et al., 2000). Pest problems associated with conservation tillage often can be addressed with complementary practices, such as crop rotation, subsoiling, controlled traffic, and better drainage (Reeder, 2004). Soil management practices that promote vigorous plant growth will lead to healthier crops that are more likely to tolerate pests.

Soil erosion and runoff directly affect the transport of pesticides, fertilizers, and other chemicals to streams, lakes, and other water bodies. Residue cover reduces the movement of pesticides, such as glyphosate and paraquat, because those pesticides are tightly bound to soil particles (Honeycutt and Jemison, 1995). The volume of pesticides carried in runoff from conservation tillage also is reduced. Although the concentration of atrazine, for example, in runoff from no-till was high, the total loss of the chemical from moldboard- or chisel-plow systems was greater because of a much higher volume of runoff. A 5-year study in Pennsylvania showed that 0.8 percent of applied dicamba was lost in runoff from conventional tillage compared to 0.1 percent from no-till. The effect of tillage on loss of nutrients, especially ni-

trates, to groundwater is mixed, with contrasting research results largely attributed to weather. No-till reduces surface runoff, but no-till fields have more macropores that can serve as flow channels for chemical movement through the soil.

In a 3-year study in Pennsylvania on a 14 percent slope, Hall et al. (1983) measured runoff of the herbicide cyanazine from no-tilled and conventionally tilled corn. At the 4.5 kg ha<sup>-1</sup> (4 pounds per acre) application rate, the no-till surface reduced losses of water, soil, and cyanazine each by 98 to 100 percent.

For a simulation of erosion from a typical Iowa watershed, Lakshminarayan et al. (1994) compared conventional tillage to no-till for continuous corn and a corn-soybean rotation. The nitrate-nitrogen concentration in runoff was less for no-till in both crop rotations. The nitrate-nitrogen concentration in the leachate was slightly higher for no-till in continuous corn. For the corn-soybean rotation, the concentration was about five times higher with no-till, but the authors concluded that the higher leaching could be corrected in the model if credit were given for the amount of nitrogen fixed by the soybeans. They did not discuss any potential benefits of a cover crop after soybeans to reduce soil erosion and nitrogen losses.

Subsurface drain tile can promote the loss of nitrate from farm fields. Eight Corn Belt states (Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Ohio, and Michigan) account for more than 20 million ha (50 million acres), or 37 percent of the total cropland drained in the United States (Fausey et al., 1995; Zucker and Brown, 1998). Research summarized by Randall and Goss (2001) showed that the choice of tillage system for row crops in this region does not affect the amount of nitrate lost in drainage. Nitrate concentrations are greatest for plow systems, and the drainage volume through the tile lines is often greatest with no-till, mainly because water tends to infiltrate with no-till rather than running off the field surface. Controlled drainage systems that manage water table depth can significantly reduce nitrate losses. Row crops (corn and soybeans) can have nitrate-nitrogen losses up to 50 times greater than from perennial crops, such as alfalfa or grass. Research in Europe indicates that winter cover crops can reduce nitrate losses.

## Mulches

Mulches (practice code 484) reportedly increase soil moisture (Edwards et al., 2000a; 2000b) and crop yields (Lal, 1998), reduce spring weeds (Russo et al., 1997), and reduce nutrient losses (Rees et al., 2002) (Table 6). There should be a subsequent increase in soil carbon when carbo-

naceous mulches are used repeatedly. Mulches at higher rates tend to reduce soil temperatures that may negatively affect early plant growth (van Wijk et al., 1959) and reduce evaporative demand (Gill et al., 1996). The benefit to soil-water relationships occurs because of reduced soil temperatures and greater infiltration. In a sprinkler irrigation study designed to identify ways to reduce runoff under application rates that exceeded the soil's infiltration rate, a mulch increased infiltration 50 percent (Oliveira et al., 1987). In an arid, water-short environment, corn production increased 100 percent and water-use efficiency increased 65 percent when mulch covered the furrow-plant area in a rainfall-harvesting study (Li et al., 2001). Because mulches increase infiltration, the offsite loading of pesticides in surface runoff is potentially reduced as well (Rice et al., 2001).

Mulches also increase soil aggregation (Rasse et al., 2000), increase copper tolerance by increasing soil pH and reducing free copper in the soil solution (Kikkilä et al., 2001), and increase

surface soil faunal activity and macroporosity (Franzen et al., 1994). In a hot, arid environment mulches were more beneficial for wheat production than in a hot, humid environment (Badaruddin et al., 1999), especially when soil moisture was limiting. Rapid decomposition can reduce the effectiveness of some organic mulches and also release nitrogen sooner than needed by the protected crop (Seneviratne et al., 1998). In a semiarid environment, a black polyethylene mulch mitigated the negative effects of water stress and increased nitrogen availability by keeping the soil moisture higher (Kirkak et al., 2003). Depending upon the effect of mulch on soil temperature, seedling emergence also can be enhanced or delayed (Chopra and Chaudhary, 1980).

Other potential effects of mulches on plant growth include radiation and energy balance and allelopathy. Mulches alter the surface properties of soils, affecting both shortwave albedo and longwave emissivity. These are linked to

**Table 6. Mulch study results.**

Mulch material	Effect	Conditions	Reference
Shredded cornstalks	40% erosion reduction	Rainfall simulation	Meyer & Mannering, 1963.
Wheat straw	30% erosion reduction	15% slope, rainfall simulation	Meyer et al., 1970.
Wheat straw	30-70% erosion reduction	6% slope, rainfall simulation	Kramer & Meyer, 1969.
Rice straw	20-80% erosion reduction, crop yield increase	Natural rainfall	Lal, 1998.
Barley straw	50% erosion reduction, increased soil water	Natural rainfall	Edwards et al., 2000a
Barley straw	50% erosion reduction	Rainfall simulation	Edwards et al., 2000b; Edwards et al., 1995
Hay mulch	24-40% erosion reduction, 10% yield increase	8-11% slopes, natural rainfall	Rees et al., 2002.
Straw or gravel	80-100% erosion reduction	4% slope, natural rainfall	Adams, 1966.
Prairie hay, wheat straw	20-80% erosion reduction	6% slope, natural rainfall	Swanson et al., 1965.
Wheat straw	30-100% erosion reduction	5% slope, rainfall simulation	Mannering & Meyer, 1963.
Gravel, emulsions, manure	10-90% erosion reduction	Wind and water erosion	Chepil et al., 1963; Armbrust, 1977.
Stones and wood chips	More effective than straw on slopes >20%	Construction sites	Meyer et al., 1972.
Oak leaves, oat straw, redwood litter	70% erosion reduction	Rainfall simulation	Singer & Blackard, 1978.
Wheat straw	Greater infiltration; 75% more stored water; 114% higher yields	Dryland farming, grain sorghum	Unger, 1978

the effect residues have on water evaporation and soil temperatures, which were reviewed by Horton et al. (1996). In addition, mulch or plant residue can affect the quality of light reflected to growing plants (Kasperbauer, 1971; Kasperbauer and Hunt, 1987). This change affects seedling morphology and stand establishment, negatively or positively (Kasperbauer, 1999). Some residues also have allelopathic effects that can interfere with several physiological processes of the receiving plants (Einhellig, 1996; Singh et al., 2001), reducing germination and crop yields (Hicks et al., 1989). Crops generally are more sensitive to allelopathic interference when moisture, temperature, nutrient, or general growing conditions are less than optimal.

Mulches are used for landscaping and horticultural purposes and to ameliorate problems associated with specific site conditions, such as road banks. Plastic and fabric mulches or covers are not reviewed in detail here. A major use of vegetative mulches is to control soil erosion. Table 6 lists several studies reporting mulch effects. In general, most studies reported positive results from an application of 2 to 4 Mg ha<sup>-1</sup> of mulch (1 to 2 tons of mulch per acre). Most but not all studies incorporated the materials before subjecting them to rainfall events. If residues are unanchored, they will not control water erosion beyond a critical length for a specific slope (Foster et al., 1982). In addition, preventing soil detachment by dissipating raindrop impact energy is a critical part of mulch's effect on erosion. In most studies, there was a proportionally larger reduction in sediment transport at low cover levels, confirming the effect of mulch on detachment, because sediment transport capacity was not appreciably affected. A review of the effect of a rock fragment cover on soil erosion showed that effectiveness in reducing rill and interill sediment losses depended upon the varying intensities of hydrological and erosion subprocesses (Poesen et al., 1994).

Only one study was found that evaluated mulches to control wind erosion. In that study the materials were gravel or a type of emulsion-covering material, such as asphalt.

There also is a critical surface coverage for slope, soil type, and rainfall intensity. In general, at least 30 percent of the surface should be covered with crop residue to be effective in conservation tillage systems (Allmaras and Dowdy, 1985). The portion of the soil surface covered by straw was 49, 71, and 92 percent at 1, 2, and 8 Mg ha<sup>-1</sup> (0.5, 1.0, and 4.0 tons per acre), respectively (Meyer et al., 1970). Approximately 50 percent cover by oat straw was required to reduce soil erosion and runoff significantly on a 9 percent slope (Singer and Blackard, 1978).

## Deep tillage, soil compaction, controlled traffic

Many different designs of subsoilers have been built, with widely varying degrees of soil and surface residue disturbance (Reeder et al., 1993; Raper and Sharma, 2004). At least five U.S. manufacturers promote the ability of their subsoilers to maintain surface residue coverage.

Subsoilers typically operate at depths of 30 to 45 cm (12 to 18 inches). They loosen the soil, which alleviates compaction and increases infiltration and aeration. In many no-till situations, deep tillage is never needed, but some soils compact "naturally," and subsoiling increases crop yields. In other no-till situations, especially with random traffic patterns, deep tillage partially alleviates soil compaction resulting from heavy machinery. For these situations, deep tillage increases yields, and if it leaves the surface residue in place, it's a valuable component in a crop residue management system.

Deep tillage can be conducted with a bentleg shank (paraplow or paratill) that leaves a maximum amount of crop residue on the field surface (Raper, 2004). Draft energy required is lowest for moist or dry conditions, compared to very dry, and more crop residue is buried in the very dry condition (Raper and Sharma, 2004). Subsoiling when the soil is too wet may result in additional compaction caused by the tractor, and subsoiling in extremely dry conditions causes more disruption of the soil surface and requires more fuel. The bentleg-shank design also had less draft than straight-leg shanks when tested on both a clay loam and sandy loam soil (Raper, 2005b).

Research verified that tilling only as deep as necessary to break through a Coastal Plains soil hardpan (site-specific subsoiling) can save draft energy while maintaining crop yields (Raper et al., 2004). Corn and cotton yields were similar whether the soil was tilled uniformly deep or tilled only to the depth of the compaction layer, and yields in both situations were higher than with a no-subsoiling treatment. For variable-depth subsoiling, a subsoiler with a straight-angled shank required less energy than one with a curved shank; the straight-angled shank also disturbed less soil (Raper, 2005a). This can be positive if a crop row is planted over the tilled area, and yields are the same as with more aggressive subsoiling.

In-row subsoiling (one type of strip-tillage) successfully removed the compaction effects of tire traffic on a sandy loam Coastal Plain soil (Raper et al., 1994). This tillage (in the row just ahead of planting), to a depth of 0.4 m (16 inches), reduced cone index, surface bulk density, and



energy use and increased water-holding capacity, which resulted in higher cotton lint yields in a 5-year research project. Traffic in the row middles did not affect soil condition beneath the row. When subsoiling removes a hard pan in this soil, traffic must be controlled or compaction can reoccur. If a hard pan does not exist, traffic will create one. If a hard pan already exists, traffic will compact the soil above it, and the pan will move closer to the surface.

Traffic can quickly eliminate the benefits of subsoiling. Raper and Reeves (1994) found that a plot that was completely disrupted by subsoiling 5 years earlier had compacted once again into a soil condition nearly identical to a plot that had never been subsoiled. A 2001 survey of central Alabama cotton fields found that two-thirds had hard pans within 0.3 m (1 foot) of the surface, including many that had been subsoiled the previous fall. Apparently, the benefits of subsoiling had been lost in less than a year (Balkcom et al., 2003). Low organic matter probably helped make the soil more susceptible to compaction. Seventy-five percent of the fields had less than 0.8 percent soil organic matter; half were below 0.4 percent. A new study, begun in 2004, showed that, although there was no difference in yields among four tillage systems, cover crops were better than none, and using a roller-crimper to flatten the cover crop before planting cotton provided a residue cover that helped conserve soil moisture (Kip Balkcom, personal conversation, 2005).

Deep tillage and controlled traffic also can affect fertilizer movement in the soil and recovery of nitrogen by a subsequent crop (Torbert and Reeves, 1995). For wheat double-cropped immediately after cotton harvest, plots that had been deep-tilled or strip-tilled prior to cotton planting had lower levels of nitrogen remaining in the soil after wheat harvest. On plots with no traffic, total fertilizer nitrogen recovery increased 15 percent in the 2-year experiment.

Controlled traffic is a good practice to improve soil quality. Most farmers who have adopted a permanent controlled-traffic system use ridge-till. In southeastern Nebraska, on Sharpsburg silty clay loam, Liebig et al. (1993) measured differences in soil properties after 11 years between row areas (which never get driven on) and trafficked row middles. The main compacting vehicle used in this 6-row system was a tractor with a rear axle load of 4 Mg (4.4 tons). Soil strength (as measured with a cone penetrometer) in the trafficked row middles was double the measurement in the rows. Saturated hydraulic conductivity was four times greater in non-trafficked areas. Controlled traffic systems create distinctly different zones in a field. Permanent traffic lanes

improve traction and floatation during machinery passes. Reeder and Smith (2000) identified other benefits, including timely planting and harvest and overall greater water infiltration and water-holding capacity for a field, which often translates to higher crop yields.

Cumulative rainfall also can cause deep-tilled soils to re-compact (Busscher et al., 2002). In South Carolina research on Goldsboro loamy sand, cone penetrometer measurements taken from a week to 6 years after paratilling showed that compaction increased with time and cumulative rainfall accounted for 70 to 90 percent of the re-compaction. Water filtering through this structureless sandy soil apparently caused the re-compaction. Even with controlled traffic, this research indicated that deep tillage may be necessary on these soils every year to maintain crop yields if rainfall totals 40 or more inches a year.

In an experiment to measure runoff and soil erosion from subsoiled treatments on a silty clay loam in southeastern Nebraska, subsoiling reduced the rate of runoff, but did not reduce soil erosion after equilibrium was reached between water application and runoff rates (Jasa and Dickey, 1991). Equilibrium was reached after a 95-mm (3.7-inch) water application. This experiment with a rainfall simulator also included tilled and no-till treatments and contoured versus up-and-down-hill treatments. The erosion rate, after equilibrium, was four times greater for the tilled treatment compared to the untilled treatment, mainly because of soil residue cover (40 percent versus 4 percent). Contour farming on the 5 percent slopes reduced runoff 56 percent and soil erosion 65 percent compared to the up-and-down-hill treatment, also after equilibrium. Subsoiling with either an in-row Ro-Till implement just before planting or between rows after planting, using a narrow-point shank, reduced runoff for the first runoff event after tillage.

In a 5-year research project on Cecil sandy loam at Watkinsville, Georgia, annual in-row subsoiling 23 cm (9 inches) deep at planting resulted in the highest cotton lint yield and the best economic return, compared to fall paratill, disk tillage, and shallow-sweep tillage (Schomberg et al., 2003). The most likely explanation for lower paratill yields was reconsolidation of the soil in the months before planting. The frequency (once every 1, 2, or 3 years) of paratilling and sweep tillage was not a factor in yields. The researchers attempted to maintain controlled traffic patterns throughout the study.

Soil strength with four tillage systems on three soils was measured in Indiana. Compaction in the wheel tracks of no-till and ridge-till was greatest, which is where it is most valuable for traction

**Traffic can quickly eliminate the benefits of subsoiling.**

**Controlled traffic is a good practice to improve soil quality.**

(Larney and Kladvik, 1989). Ridge-till also had high soil strength in non-trafficked positions, indicating that the scraping action of the row cleaner at planting and the cultivator sweep during ridge reforming might result in some compaction. The greatest soil strength (compaction) occurred deepest in moldboard-plowed ground. Next in order of depth was chisel plowing, then no-till; the shallowest compaction "layer" occurred with ridge-till.

On a Charity clay in the Saginaw Valley of Michigan, subsoiling followed by controlled traffic prior to planting produced the most favorable soil condition for root growth, based on improved internal drainage and soil aeration (Johnson et al., 1989). Benefits of subsoiling generally persisted through only 1 year because wheel traffic associated with conventional spring tillage re-compacted the loosened soil.

In the Palouse region of the Pacific Northwest, fall subsoiling 0.4 m (16 inches) deep with a paratill significantly increased water infiltration on Larkin silt loam (Mizuba and Hammel, 2001). The result was less soil erosion and greater water conservation on fall-planted wheat fields with slopes of 5 to 20 percent. The deep loosening of soil, combined with maintenance of surface residue, offers benefits in this region where 70 percent of annual precipitation occurs between November and April.

**Water conservation effects.** By reducing runoff and evaporation and trapping more snow, residue management increases the water entering a soil profile. No-tilled soil with good structure offers the maximum storage capacity. Although tilling the soil increases soil porosity temporarily, it is a short-term benefit with negative long-term consequences. Tillage reduces soil structural stability, surface residue, and soil organic carbon in the surface layer, all of which are critical factors for water infiltration and storage in the soil (Franzuebbers, 2002c).

Dryland crop production in the Great Plains depends upon storing sufficient water in the soil. (Unger, 1994) Research started after the first Dust Bowl years of the early 1930s confirmed the importance of crop residue on a field surface for controlling soil erosion and increasing infiltration. In 1939, J. C. Russel reported the effects of various levels of straw cover on water storage and runoff on field plots at Lincoln, Nebraska. Plots with straw cover of 18 Mg ha<sup>-1</sup> (8 tons per acre) and no tillage stored 140 mm (5.5 inches) [with total precipitation of 320 mm (12.5 inches) for the period]; straw cover of 2 Mg ha<sup>-1</sup> (1 ton per acre) and normal sub-tillage stored 30 mm (1.2 inches); and bare ground with disk tillage stored

7 mm (0.3 inches). Crop production with significant residue levels was not practical at the time, but later development of herbicides and stubble-mulch tillage implements that undercut the soil surface 7 to 10 cm (3 to 4 inches) led to practical farming practices that reduced soil erosion by wind and water and increased crop yields.

In the northern Great Plains, snow accounts for a major portion of annual precipitation (Unger, 1994). No-till, which leaves standing wheat stubble to trap snow, greatly increases the amount of water in the soil that is available for subsequent crop growth. Taller stubble traps more snow.

Wheat is the major dryland crop in the southern High Plains of Texas and Oklahoma, but sorghum seems better suited to the region's typical pattern of late spring-summer rainfall (Jones and Popham, 1997). In a 10-year project on Pullman clay loam at Bushland, Texas, comparing no-till and stubble-mulch tillage, continuous sorghum produced 92 percent more grain than a wheat-sorghum-fallow rotation, 240 percent more grain than continuous wheat, and 320 percent more grain than a wheat-fallow rotation. No-till stored slightly more water in the soil than stubble mulch, but the amount was insignificant relative to seasonal evapotranspiration.

As a follow-up to the same experiment using the 3-year rotation, wheat-sorghum-fallow (which included two 11-month fallow periods), a comparison of no-till and stubble mulch, with and without subsoiling [Paratill, 35 cm (14 in) deep, once every 3 years after sorghum harvest] showed that deep tillage led to soil drying (Baumhardt and Jones, 2002b; Baumhardt and Jones, 2002a). There was no benefit to crop yield or water use efficiency attributed to subsoil tillage. Residue management that reduced evaporation was much more important to dryland grain production than deep tillage. The infiltration rate of rainfall did not appear to benefit from paratilling. Measurements taken 9 months after the subsoiling indicated that even with about a 35 percent residue cover in the no-till treatments the soil quickly crusted and sealed. With systems that used several passes of a sweep plow at the 10-cm (4-inch) depth to control weeds during fallow, the tillage action formed a compacted layer that kept rainfall from infiltrating deeper, canceling any benefits of deep tillage.

Previous commodity programs (1985 farm bill) generally discouraged use of no-till for grain sorghum and wheat in the central Great Plains (Williams et al., 1990a). Farmers who were risk-averse with regard to income preferred conventionally tilled wheat-fallow or wheat-sorghum-fallow rotations. In northeastern Kansas, however, the government commodity program



Use of wind erosion control measures in the Great Plains not only controls soil loss, but conserves moisture needed for crop production through increased infiltration.

tended to favor a no-till corn-soybean rotation (Williams et al., 1990b). This system produced the highest corn yields and net returns.

In the Palouse region, Kennedy and Schillinger (2004) found that over-winter water storage and ponded water infiltration rates were similar for no-till and conventional tillage if the fields had undisturbed standing wheat stubble. On research plots and watersheds in northern Mississippi, conservation tillage systems that included a vetch cover crop in winter reduced runoff 50 to 100 mm (2 to 4 inches) (Meyer et al., 1999).

In laboratory experiments using undisturbed soil cores from two Georgia fields with a 25-year history of conventional tillage and no-till, the infiltration rate in no-till soil was more than three times greater than for conventional tillage (Franzluebbers, 2002c). The difference related directly to the stratification ratio of soil organic carbon. [Stratification ratio is the soil organic carbon level in a top layer of soil compared to a deeper layer. Franzluebbers (2002c) used the top 3 cm (1.2 inches) compared to the 6- to 12-cm (2.4- to 4.7-inch) layer.] The ratio for no-till averaged 5.3, for conventional tillage, 1.4. Sieving and mixing samples, to simulate tillage, showed that even though no-till samples had double the soil organic carbon the infiltration rate was not much better than for the conventionally tilled soil. Location of soil organic carbon (stratification with soil depth) is important to infiltration and water storage.

Water use efficiency represents the amount of crop produced per unit of water used by the crop (Hatfield et al., 2001). In semiarid regions, water use efficiency is an important factor in comparing practices, but in areas with generally adequate rainfall, such as the Corn Belt, it is seldom considered. Water use efficiency varies greatly, even in the same field. It is possible to increase water use efficiency 25 to 40 percent by changing tillage and crop residue management. Nutrient management can increase water-use efficiency 15 to 25 percent. Freshly tilled ground has a higher water-holding capacity, but if the soil seals after the first rainfall, efficiency declines rapidly compared to no-till with residue cover. Reducing tillage showed a trend to higher water use efficiency. In one experiment on the southern High Plains, the water use efficiency for irrigated wheat was double the water use efficiency for dryland wheat. Good management can increase water use efficiency, which, in turn, can increase crop yields.

**Air quality effects.** Crop residue management offers immediate benefits for air quality. Residue standing or laying on a field surface protects the soil from high winds and subsequent dust storms.

Elimination of tillage, or use of a tillage system that leaves the surface generally intact, such as paratilling, greatly reduces dust generated during tillage and planting operations. Residue from a previous crop or cover crop also reduces dust from traffic during spraying or fertilizer application.

Increased levels of soil organic matter, usually the result of maintaining crop residue, ultimately aid air quality because dust, allergens, and pathogens in the air decline (Reicosky, 2005). Continuous no-till systems result in increased organic matter levels after 2 to 3 years (Reicosky, 2002).

For irrigated corn in eastern Colorado, no-till significantly reduced emissions of nitrous oxide ( $N_2O$ ), compared to conventional tillage, without an apparent change in nitric oxide (NO) emissions (Liu et al., 2005). During the growing season, about twice as much nitrous oxide was emitted from conventionally tilled plots than from no-till plots. In the fallow months, from harvest to planting, the conventionally tilled soil emitted about 15 times as much nitrous oxide.

**Factors driving environmental outcomes.** The main factor limiting widespread adoption of conservation tillage systems is lower crop yields. Often, this occurs only in the first 1 to 3 years of no-till, and research is continuing to identify practices that help eliminate yield reductions. Strip tillage for corn is one example. Controlled traffic to minimize compaction is another.

The downhill movement of soil resulting directly from tillage has not been fully recognized as an erosion factor. Decades of tillage with plows and disks have caused topsoil to be moved generally from summit and convex-slope positions to concave slopes and depressions. Adoption of no-till systems or use of subsoilers designed to minimize disturbance of surface soil (such as Paratill), instead of conventional tillage implements, would eliminate this particular cause of soil-particle movement.

Use of effective conservation practices is key to achieving environmental outcomes, as is the widespread adoption of those best practices on land most in need of protection. Following are specific examples of the problems encountered in getting crop residue managements systems adopted where they can improve water, soil, and air quality the most.

Targeting conservation practices to the most critical areas is essential to achieving desired environmental outcomes. Conservation tillage systems provide the most benefits by reducing soil erosion and nutrient loss on sloping soils. In southern Minnesota, analysis of adoption patterns showed that farmers in the Lower Minnesota River watershed apparently used conservation

**Targeting conservation practices to the most critical areas is essential to achieving desired environmental outcomes.**

tillage for reasons unrelated to soil conservation (Gowda et al., 2003). There was no significant targeting of conservation tillage to steeper slopes. Among six sub-watersheds, the steepest one recorded the second lowest rate of adoption. As slopes increased from 1 percent to 5 percent, use of conservation tillage trended upward only slightly. Slopes greater than 5 percent had less conservation tillage than slopes in the 4 to 5 percent class. In five of the six sub-watersheds, the adoption rate for conservation tillage on slopes exceeding 5 percent was essentially the same or less than on slopes less than 1 percent. Clearly, the steepest land had a less-than-desired rate of adoption. Conservation tillage often is practiced with little or no consideration for the impact of topography on soil erosion.

Adoption of conservation tillage generally has been unaffected by the soil erosion potential of the land, ranging from 58 percent of land with a low 0 to 22 Mg ha<sup>-1</sup> yr<sup>-1</sup> (0 to 10 tons per acre per year) soil loss potential receiving at least one conservation practice to 47 percent of the land with a soil erosion potential of 80 Mg ha<sup>-1</sup> (40 tons per acre) to more than 330 Mg ha<sup>-1</sup> yr<sup>-1</sup> (150 tons per acre per year) (Pierce, 1987).

A 1991 study in southern Wisconsin (reported by Griffith and Wollenhaupt, 1994) showed that, while 60 percent of farmers were using a chisel plow as their main tillage tool for corn following corn, 40 percent of those farmers were not meeting the residue management goals in their conservation compliance plans, although most assumed they were practicing conservation tillage.

Data collected from more than 1,000 farmers in three watersheds in Minnesota, Iowa, and Ohio showed that although farmers adopt many conservation practices they ignore others that could help reduce soil and water degradation (Napier, 2001). The study revealed that factors considered important to adoption of conservation practices, including economic subsidies, access to educational training, and technical assistance, did not motivate farmers to use conservation farming practices.

Farmers who consider adopting conservation tillage systems want to maintain or increase productivity and profits. Factors that tend to lower yields in high-residue systems include cool soil, allelopathy, and poor seed placement. Soil drainage, soil texture, surface cover, latitude, and crop rotation influence the problems of delayed germination, slower crop growth, and reduced plant population.

Nowak and Griswold (1987) found that farmers in west central Wisconsin were not good at recognizing soil erosion problems on their farms and were largely ignorant of conservation econom-

ics. They identified four social conditions that should influence the design and implementation of conservation systems: a farmer's knowledge of resource degradation, compatibility of the conservation system with the production system, designing a conservation system consistent with the managerial capabilities of the landowner, and a farmer's level of comprehension and access to existing assistance programs. Their survey indicated that a quarter of farmers did not recognize soil erosion problems even when soil was degraded. There was no relationship between the perception of soil erosion problems and actual erosion rates. Farmers who had not adopted any conservation practices greatly exaggerated the anticipated costs of such practices.

Dan Towery (personal communication, 2005) reported that a farmer in a focus group discussing causes of water erosion stated that a 13-cm (5-inch) rainstorm essentially washed away the entire plow layer on a sloping field on his farm. Even though the field was recently moldboard plowed, the farmer termed the erosion "an act of God." The farmer had no concept that his moldboard plow was responsible for the severe soil erosion.

Economics is a driving force. Cotton production in the Southeast has switched dramatically to no-till. Nationally, the United States had 13.5 million acres of cotton in 2004, about the same as in 1994 (CTIC, 2004). No-till acreage increased from 3 percent to 18 percent in that 10-year period, a shift of almost 2.0 million acres to no-till. Six states in the Southeast (North Carolina, South Carolina, Georgia, Alabama, Mississippi, and Tennessee) have 33 percent of the total cotton acreage, but 71 percent of the no-till cotton. Alabama leads with 51 percent; Mississippi has 24 percent. Research in those states with no-till (including in-row and paratilling), crop rotations, and cover crops has shown farmers in the region how to improve cotton profits. In contrast to the success in the Southeast with conservation tillage, no-till has proved unsuccessful in Texas, Arizona, and California. Texas has 44 percent of the U.S. cotton acreage, and only 5.5 percent is no-tilled; California and Arizona account for 6.5 percent of cotton acreage, and none is no-tilled. More research is necessary if no-till cotton is to succeed in low rainfall areas, with or without irrigation.

An economic factor in the near future is the value of crop residue as feedstock for biofuels. Generally, the potential to convert crop residue to fuel results in too little energy to make a dent in fossil fuel consumption, representing at most about 6 percent of U.S. total energy demand and 11 percent of the world energy demand. But removal of crop residue from the land can seriously



Measuring crop residue levels is important to determine if conservation tillage standards are being met.



jeopardize soil quality and related environmental qualities. Crop residue is not a waste. At the same time, biomass for fuel production can be grown on land specifically identified for that purpose. The additional land needed to produce 10 percent of biofuel energy needs would be 40 to 60 million ha (100 million to 150 million acres) in the United States and 250 million ha (620 million acres) worldwide (Lal, 2004).

The purchase, transport, and application costs of mulch materials negates using mulching as a general practice, except for use in high-value vegetable production or to address a specific natural resource problem. It is usually done on a smaller portion of a producing field where a problem exists, rather than on a whole field. Both inorganic and organic materials can be used, depending upon their costs, purpose and ease of use, and availability. In general, there will be few if any direct effects of mulching on soil physical and chemical properties, except through temperature and moisture changes in the microenvironment, and on soil erosion control processes. Use of mulches is partially replaced by crop residue management practices, which tend to leave residues on the soil surface. These primarily include a reduction in tillage or even conversion to no-till production systems and an increase in cropping intensity. Effects of different mulches on a soil's biological activity and diversity are largely unknown.

**Adequacy of scientific documentation.** The value of no-till for soil quality improvement is unquestioned. Machinery design for conservation tillage systems has advanced greatly over the past 20 years or so. Earlier research on no-till often was hampered by a lack of good planters and drills, which tended to result in lower yields. Improved herbicides also have greatly increased the economic benefits of no-till.

Many unknowns still remain regarding no-till. For example, the relationship between the rate of change in soil organic matter and the rate of change in porosity when soils are converted to no-till is not well documented (Kay and VandenBygaart, 2002). Many studies report changes in soil porosity as a result of switching to no-till, but most measurements were taken just once. There are few follow-up measurements to show long-term trends. More studies are needed of pore-size distribution and accumulation of organic matter to be able to predict the effects of no-till on soil quality and productivity and the ability of various soils to sequester carbon.

The impact of tillage erosion and tillage translocation often is underestimated on slopes. More studies are needed to understand the interactions of tillage erosion with wind and water erosion

(Schumacher et al., 2005). A better knowledge of spatial patterns of previous erosion will allow farmers to use global-positioning-system-based management zones in the application of conservation practices where they are needed most in a field, such as cover crops and no-till on highly erodible slopes (Dosskey et al., 2005).

Early season crop growth often is inhibited by a lack of available nitrogen under no-till. More understanding of how to overcome the competition for nitrogen is needed so no-till crops, corn, for example, can avoid the problem of slow early growth (Martens, 2001).

Much research on no-till, subsoiling, and cover crops has been completed in the Southeast, with excellent results and a reasonable rate of adoption by farmers. More research is needed in northern climates, especially on using a precise amount of tillage to get corn off to an early start.

### Conservation crop rotation

Conservation crop rotation (practice code 328) is the process of growing crops in a recurring sequence on the same field over time. It does not apply to land occasionally tilled to renovate or re-establish perennial vegetation. The practice is applied as part of a conservation management system to reduce soil erosion, improve soil organic matter content, improve and/or balance plant nutrients, improve water use efficiency, manage saline seeps, manage plant pests, and provide food for domestic livestock and/or wildlife. Crops must be adapted to the climatic region and selected to provide sufficient biomass at the appropriate time to keep soil erosion within acceptable limits. Additional criteria may be imposed within a conservation plan's objectives and purposes. Operational specifics must include the sequence of crops to be grown, the length of time each crop will be grown, and the total length of the rotation. The practice usually is applied in combination with other practices in a producer's conservation plan for a field, farm, or production unit.

**Water quality and soil quality effects.** Tables 7, 8, and 9 summarize the effects of conservation crop rotations on nitrate leaching, air quality, soil erosion, soil fertility, soil properties, soil water, and soil carbon content and sequestration. Conservation crop rotations generally increase soil carbon content because greater amounts of crop residue are incorporated into the soil system. Tillage operations must be reduced in a production system, however, for residue to have an effect on soil carbon (Campbell et al., 1996; Halvin et al., 1990; Halvorson et al., 2002a; Jarecki and Lal, 2003). In nearly all examples,

**Table 7. Effect of crop rotations on soil carbon and carbon sequestration.**

<b>Soil carbon impact</b>	<b>Reference</b>
No effect of three crop rotations in tropical-subtropical climate on soil carbon	Balota et al., 2004
Increases in organic carbon in 0-15 cm (0-6 inches) largest with annual cropping with fertilizer inputs followed by rotations with rye winter cover crop	Campbell et al., 1996
Continuous wheat increased organic carbon in 0-7.5 cm (0-3 inches) 1.25% in two years	Curtin et al., 2000
66% increase in organic carbon with irrigated, intensified cropping	Entry et al., 2002
Rotations had 16% to 46% more organic carbon than monocultures after 35 years	Gregorich et al., 2001
Intensified cropping increased 0-15 cm (0-6 inches) organic carbon and reduced soil erosion potential	Halvorson et al., 2002a; 2002b
Continuous corn increased organic carbon 1.25% compared with soybean/corn rotation	Havlin et al., 1990
High residue crops had more effect on 0-30 cm (0-12 inches) organic carbon than low residue crops; rotations 25% > monoculture soybeans	Kelley et al., 2003
No significant effect of crop sequence on soil organic carbon and nitrogen	Hao et al., 2001
Continuous corn > corn/soybean > corn/oat/meadow effect on organic carbon	Lal et al., 1994
No measurable effect of crop rotation on soil carbon in northern Alberta	Lupwayi et al., 1999
Winter legume doubled 0-20 cm (0-8 inches) organic carbon compared with continuous cotton in long-term rotation	Mitchell and Entry, 1998
Continuous cropping increased organic carbon 0.63% in top 20 cm compared with stubble mulch tillage	Potter et al., 1997
<b>Soil carbon sequestration impact</b>	
Continuous no-till increased organic carbon 250 kg ha <sup>-1</sup> yr <sup>-1</sup> (223 lbs A-1 yr <sup>-1</sup> ) in Great Plains; Smaller change in Canadian prairies.	Campbell et al., 2005
23% potential increase in carbon sequestered with improved agricultural management (increased intense rotations) in Australian cereal belt.	Dalal and Chan, 2001.
Monoculture to continuous cropping increases organic carbon 200±120 kg ha <sup>-1</sup> yr <sup>-1</sup> (178±107 lbs A-1 yr <sup>-1</sup> ) (World database of 67 experiments)	Jarecki and Lal, 2003.
Enhancing rotation complexity increases carbon 20 ±12 g m <sup>-2</sup> yr <sup>-1</sup>	West and Post, 2002

increasing soil carbon also increases soil organic nitrogen because soil organic matter has a nearly constant carbon:nitrogen ratio. Different crop rotations can have little or no effect on soil carbon contents in subtropic (Balota et al., 2004) or cold northern climates (Lupwayi et al., 1998). In the subtropics this is because soil respiration rates are high enough to prevent carbon from accumulating; in colder climates it is because of the higher amounts of labile carbon produced. An additional factor is the relatively short duration of these studies (5 years); 25 to 50 years may be required to reach a new equilibrium (Jarecki and Lal, 2003). The northern study also suggests that labile forms of soil organic carbon may be more sensitive indicators of changes because microbial biomass carbon, basal respiration, and the ratio of microbial biomass carbon to soil organic carbon

is rotational-crop dependent. Campbell et al. (2001) showed that total soil carbon and nitrogen, microbial biomass carbon, light fraction organic carbon and nitrogen, mineralizable nitrogen, and wet aggregate stability in the 0- to 15-cm (0- to 6-inch) range was higher with rotations that included a legume green manure or legume hay crop.

Water-soluble organic carbon, another measure of labile carbon, also was more sensitive to crop rotations than total soil carbon and nitrogen and microbial biomass carbon (Jin-Zhi et al., 2004), but not as much as the light fraction organic carbon (Wu et al., 2003b). Liang et al. (2003) also reported that the light fraction organic carbon, a key attribute of soil quality, was more affected by crop rotation and tillage. Gregorich et al. (2001) concluded that residue quality had a key role to play in the retention of soil carbon in agroecosystems

**Table 8. Effect of crop rotation on selected soil properties.**

Category	Impact	Reference
Soil erosion & air quality	Wind erosion reduction by converting to annual cropping from wheat/fallow on Columbia Plateau	Thorne et al., 2003
	Three-year rotation reduced water erosion 87% compared with monoculture	Miller, 1936; Amir, 1996
	One-half less topsoil loss with six-year rotation vs. monoculture	Gantzer et al., 1991
	Irrigation soil erosion reduced 47% to 100% by selected cropping sequences and tillage	Carter and Berg, 1991
	Crop rotations including wheat and barley gave high soil cover in northern plains (98% to 62%); cover was only 48% to 35% after 2 to 4 years of low-residue producing crops	Merrill et al., 2006
	Dust enzymatic activities was dependent upon crop rotation for three soil textures	Acosta-Martínez and Zobeck, 2004
	Increasing cropping intensity/ground cover reduces potential wind erosion	Halvorson et al., 2002b; Fryrear, 1985
	Plant area index and canopy cover of specific crops inversely related to wind erosion	Armbrust and Bibro, 1997.
Soil fertility	Non-vesicular-arbuscular mycorrhizae crops or fallow reduced zinc availability to following crop	Hamilton et al., 1993
	Soil phosphorus availabilities increased in continuous cropping compared with wheat/fallow	Bowman and Halvorson, 1997
	Phosphorus, calcium, magnesium, manganese and zinc availabilities affected by crop rotations through organic matter and pH changes	Edwards et al., 1992
	Nitrous oxide emissions continuous corn>soybean/corn >soybean/corn/alfalfa	MacKenzie et al., 1997
	Higher nitrogen mineralization in rotations with legume green manures reduced fertilizer requirement	Soon and Clayton, 2003
	Continuous cropping may not increase fertilizer requirements because efficiency increases and leaching is reduced	Schlegel et al., 2005; Yamoah et al., 1998
	Crop rotation had little effect on nitrogen availability in lowland rice because of sensitivity to soil aeration	Witt et al., 1998.
	Soil organic nitrogen increased by continuous cropping compared with fallow rotation without increasing nitrogen availability	Liang et al., 2004
Soil properties	Decreased penetration resistance and increased earthworms by soybean-wheat/clover-corn rotation	Katsvairo et al., 2002
	Microbial diversity higher with legume in rotation with wheat	Lupwayi et al., 1998
	Soil strength was lowest in continuous cotton compared with cotton/wheat/fallow rotation	Hulugalle et al., 1997
	Soil organic light-fraction increased by green manure crop in rotation with potatoes	Grandy et al., 2002
	Vesicular-arbuscular mycorrhizae infections higher in rotation than in continuous sorghum	Alvey et al., 2001
	Arthropods affected by vegetative crop rotations	Hummel et al., 2002
Soil water	Precipitation storage efficiency and water use efficiency increased by increasing cropping intensity	Nielsen et al., 2005; Farahani et al., 1998
	Increased crop diversity and synergism increased precipitation use efficiency from 42% to 65%	Tanaka et al., 2005
	Salinization reduced by increased crop diversification and cropping intensity in recharge areas	Conner, 2004; Brown et al., 1982
	Infiltration was greater in continuous corn than in soybean-corn rotation	Eisenhauer, 1993



**Table 9. Effect of conservation crop rotation on selected parameters.**

Parameter	Impact	Reference
Nitrate leaching	Continuous corn>soybean-corn rotation; most leaching during winter months	Ritter et al., 1997
	Continuous corn>soybean-corn>soybean-corn-wheat; rotation considered in context of production system	Power et al., 2001
	Nitrate in soil wheat-fallow>wheat-corn-fallow >wheat-corn-millet-fallow dryland cropping systems	Westfall et al., 1996
	Potential rotational leaching of wheat-fallow>continuous wheat>wheat-pea	Soon and Clayton, 2003
	Subsurface drain nitrate concentrations were 37-fold and 35-fold higher in continuous corn and corn/soybean systems than alfalfa and CPP systems	Randall et al., 1997
	After alfalfa, a dry bean-dry bean sequence had more nitrate leaching losses than a corn-winter wheat	Meek et al., 1995; Carter and Berg, 1991
Weed populations	Two cool-season crops followed by two warm-season crops reduced weed populations 6- to 12-fold	Anderson, 2004
	Long rotations with phenologically diverse crops reduced seed-bank populations and important annual broadleaf weed species in organic production	Teasdale et al., 2004
	Continuous wheat facilitated downy brome infestation, while stinkweed and Canada thistle increased in wheat-canola rotation	Blackshaw et al., 2001
	Weed seedbank density and diversity increases were lowest with sweet corn rotation and highest in rye rotation	Bellinder et al., 2004
	The sequence of crops rather than number of different crops is the important rotation effect	Mertens et al., 2002
	Continued use of glyphosate increases population of weeds tolerant to herbicide regardless of rotation	Puricelli and Tiesca, 2005

and that soils under legume-based rotations tended to be more 'preservative' of residue carbon inputs, particularly from roots, than from monoculture.

Crop simulation models illustrate potential soil and plant responses to alternative cropping systems. This information can be used to design field experiments that achieve research goals at minimum cost. To be effective, these models must estimate crop yields and soil carbon and nitrogen dynamics. Simulation models are sometimes used as substitutes for field studies (Dogliotti et al., 2003; Jones et al., 2003; Staggenborg and Vanderlip, 2005), and alternatively, long-term studies are useful for development of simulation models (Amir, 1996).

In a CERES simulation of wheat or sorghum with fallow in a dry environment, wheat yields were overestimated by 16 percent and sorghum yields were underestimated by 27 percent in a 19-year simulation (Staggenborg and Vanderlip, 2005). Even with these errors, final conclusions

were similar to those obtained from field studies. The DSSAT cropping system model, in use for more than 15 years, recently was redesigned and programmed to facilitate more efficient incorporation of new scientific advances, applications, documentation, and maintenance (Jones et al., 2003). More than 40 different applications by researchers on five continents were simulated using the DSSAT crop model, with a reasonable measure of success.

Another model that predicts the magnitude of soil organic matter changes from current or planned practices is CQESTR (Rickman et al., 2002). It uses thermal time as the primary driver of residue and organic matter decomposition. This model provided estimates of 0.55 percent soil organic matter for a 95 percent confidence interval in a validation study across 11 independent sites.

**Water conservation effects.** As shown in Table 8, conservation crop rotations can increase water-



use efficiency. This is accomplished by reducing runoff and thereby capturing more precipitation or by increasing cropping intensity. Some crops also help avoid salinization by removing soil water in recharge areas.

**Air quality effects.** Air quality improvements occur primarily because of the soil cover provided by crop residue or growing plants during potential wind erosion periods.

#### **Factors driving environmental outcomes.**

Conservation crop rotations offer numerous advantages for sustainable production systems. As stated earlier, most rotations are designed to solve specific problems or gain advantages that are specific to crops or different crop sequences. For example, highest soil carbon gains usually occurred from continuous cropping of crops that produce large amounts of residue, with reduced tillage operations, but these were not always the most profitable or the most environmentally positive. Incentives for carbon sequestration may offset some of the extra cost associated with a production system. Accumulated carbon credits may be rapidly lost if the producer increases tillage intensity later on. Disease and other pests also can become significant problems in a monoculture and require additional pesticides.

Increasing the cropping intensity with winter or off-season cover crops and/or annual cropping offers distinct advantages to producers. As well as protecting soil and water resources, these practices often improve soil physical and chemical properties (soil quality) and increase soil productivity and the sustainability of production systems. A disadvantage is the additional cost of implementation, unless they are used for forage or the gains in nitrogen at least equal the cost of establishing the cover crop.

Economic considerations also influence the adoption of a conservation crop rotation in most cropping systems. In a comparison of cropping rotations in the central Great Plains, economic returns depended upon crop yields. Rotations with greater frequency of sorghum in the 4-year rotation produced the highest net returns, compared with continuous wheat (Schlegel et al., 2002). Growers who substituted a soybean-corn rotation for continuous corn under low chemical management showed the greatest net returns in both chisel-plow and moldboard-plow tillage systems (Katsvairo and Cox, 2000). Growers who used ridge-tillage systems also may substitute rotations for continuous corn without lowering net returns while gaining the advantages rotations offer. In a comparison of a potato-barley-forage rotation with a barley-soybean rotation under dif-

ferent tillage systems, the barley-soybean rotation generally was more profitable because of fewer tillage operations (Sijtsma et al., 1998). With yield penalties or differences in other variable input costs applied, this advantage might disappear with some tillage systems.

**Adequacy of scientific documentation.** Conservation crop rotations usually are designed for a specific production system. Tillage practices are a major variable in the system. Other practices include fertilization, cover crops, irrigation, forage or cash crops, and livestock production. If soil carbon retention is a goal, then more information is needed on the effect of residue chemical characteristics because legume-based rotations tend to be more "preservative" of residue carbon inputs, particularly from roots, than from monoculture (Gregorich et al., 2001). Climate also is a variable, but not a controllable variable, except for irrigation water applications. There also is the potential for variables to interact in positive or negative ways, especially tillage practices and rotations.

Crop rotation studies are expensive and require a long-term commitment to obtain meaningful data (Jenkinson, 1991; Mitchell et al., 1991). Long-term studies provide information on cropping systems, tillage, manuring and fertilization effects on crop yields, and soil chemical and physical properties. Continued use of conservation crop rotations will require their evaluation as a complete agroecosystem. Further use and development of improved cropping system models will link water quality and mixed cropping-livestock systems into comprehensive agricultural production analyses.

#### **Cover crops**

Cover crops (practice code 340) are defined as close-growing crops grown primarily for the purpose of protecting and improving soil between periods of regular crop production or between trees and vines in orchards and vineyards. When incorporated into the soil, they often are referred to as green manure crops (Anon., 1997).

This conservation practice establishes grasses, legumes, forbs, or other herbaceous plants for seasonal cover and other conservation purposes. It applies to all land requiring vegetative cover for natural resource protection. Species should be consistent with approved local criteria and site conditions, compatible with other conservation plans, and not interfere with subsequent crops. Any residue produced should be returned to the soil or sufficient amounts left on the soil surface for resource protection. Cover crops are

Soil management

Water management / rain-fed

Water management / irrigated

Nutrient management

Post management / mitigation

Pest management / IPM

Landscape management

**Continued  
use of  
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as a  
complete  
agro-  
ecosystem.**

used to reduce soil erosion from wind and water; sequester carbon and increase soil organic matter; capture and recycle nutrients in the soil profile; promote biological nitrogen fixation; increase biodiversity, including soil fauna; suppress weeds; provide supplemental forage; manage soil moisture; and reduce particulate emissions (dust) into the atmosphere. Cover crops can be used for any duration so long as their intended purpose is accomplished. They are frequently grown in rotation between cash crops as a ground cover for a green manure crop to be incorporated or left on the soil surface as mulch.

Cover cropping is not a new idea; legumes were used for soil improvement in early Mediterranean civilizations (Semple, 1928). The practice also was known in American colonial times, but not

Sacramento, California, on cover crops, soil quality, and ecosystems were subsequently published in a special issue of the *Journal of Soil and Water Conservation*. In addition, Hargrove (1991) edited the proceedings of an international conference on use of cover crops for clean water that contained 61 papers, 11 of which were review papers. Power (1993), Masiunas (1998), Sarrantoni and Gallandt (2003), and Lu et al. (2000) published shorter reviews. The Sustainable Agricultural Network (Bowman et al., 1998) also published a comprehensive overview of cover crops that is used as a reference by farmers and agricultural professionals. Other related reviews cover legume winter cover crops (Smith et al., 1987), green manure effects on nutrient transformations in soils (Singh et al., 1992), winter cover crops in

**Table 10. Advantages and disadvantages of using cover crops (Dabney et al., 2001; Reeves, 1994) and their effect on soil (S), fertility (F), pest (P), or other (O) sustainable property (Lal et al., 1991).**

Advantages	Effect	Disadvantages	Effect
Reduces soil erosion	S/F	Scheduling and labor conflicts to implement	O
Increases residue cover	S/F	Additional costs	O
Increases water infiltration into soil	S	Reduces soil moisture	S/F
Increase soil organic carbon	S/F	May increase pest populations	P
Improves soil physical properties	S/F	May increase risks of diseases	P
Recycle nutrients	F	Difficult to incorporate residue with tillage	S
Legumes fix nitrogen	F	Allelopathy effects on following crop	P/O
Weed suppression	P	Production system change required	O
Increases populations of beneficial insects	P	Specific species may be required	O
Reduces some diseases	P	Competition with cash crop	O/P
Increases mycorrhizal infection of crops	P/F	Nutrient immobilization	F
Increases biodiversity and biological activity	S/F/P		
Manage soil moisture	S/F/P		
Reduces nutrients in runoff	O		
Reduces particulate emissions	O		
Supplemental forage production	O		
Improves landscape aesthetics	O		

commonly used as an agriculture practice (Pieters and McKee, 1929). During the last 20 years, interest in cover crops has increased because of four factors: increasing costs of fossil fuels and fertilizers; increasing concern about soil erosion on agricultural land; agriculture's impacts on environmental quality, including soil physical and chemical properties; and the adoption of conservation tillage production systems.

The literature on cover crops is voluminous. Kristensen et al. (2003) reviewed the use of catch crops and green manures as biological tools in the temperate climatic zone. The abstracts of 18 papers and 25 posters from a 1998 conference in

horticultural systems (Sainju and Singh, 1997), and cover crops in rotations (Reeves, 1994).

A cover crop should be easy to establish, produce a sufficient amount of above-ground dry matter, be disease resistant, not act as a host for diseases of the subsequent crop, die back at the appropriate time or be easy to kill, and be economically viable (Reeves et al., 1995). Dabney et al., (2001) in their review listed 14 potential advantages and seven potential disadvantages of using cover crops. Additional advantages and disadvantages were added from other sources (e.g., Reeves, 1994) and shown in Table 10. Cover crops also should facilitate the sustainabili-

ty of an agricultural production system (Lal et al., 1991) by enhancing soil physical and chemical properties, improving soil fertility or plant nutrition, and/or facilitating pest management. The advantages listed in Table 10 are divided according to different categories (Lal et al., 1991). Many affect more than one of the sustainable properties.

**Water quality effects.** Cover crops reduce soil erosion and increase nutrient-use efficiency, which help prevent sediment and nutrients from reaching off-site water bodies. Cover crops reduce total nitrogen and phosphorus transported in surface runoff, although the bioavailable portion (soluble phosphorus plus the bioavailable portion of particulate phosphorus) may increase if runoff water has contact with dead and exposed cover crop residue (Sharpley and Smith, 1991). Sufficient soluble phosphorus usually remains for potential eutrophication of receiving freshwater bodies even if particulate phosphorus is completely removed because of the very low concentrations required for eutrophication (USEPA 1996). The simultaneous corn and cover crop system developed for dairy farms in the northeastern United States had no effect on dissolved reactive phosphorus concentrations, but reduced total phosphorus loads 75 percent in runoff on plots without manure applications (Kleinman et al., 2005). In this last example, the cover crop was actively growing when the study was conducted.

Nitrogen taken up by cover crops is not subject to leaching and denitrification. Leaching losses of nitrogen as nitrate-nitrogen is most severe when a crop is not actively growing in a soil. The cover crop also can effectively capture unused nitrogen from the main crop, as well as that mineralized from crop residue and soil organic matter. Nitrate leaching following no-till corn production declined approximately 80 percent with the use of rye cover crops planted immediately after grain harvest (Staver and Brinsfield, 1998). Rye also effectively kept residual nitrogen from being lost to ground water in Virginia (Ditsch et al., 1993).

Research on Pullman clay loam in Texas showed alfalfa's ability to remove nitrate-nitrogen (Mathers et al., 1975). Removal of 300 kg ha<sup>-1</sup> (270 pounds per acre) proved feasible with good alfalfa yields. Alfalfa also was evaluated for removing nitrates from sprinkler-irrigated effluent from municipal waste at Dodge City, Kansas, and from beef processing waste in Texas (Vocasek and Zupanic, 1995). Alfalfa reduced the nitrogen accumulated in 3 m (10 feet) of soil by 90 percent in the first 4 to 5 years of growth. Nitrogen removal was progressive over time and depth.

A clover cover crop improved water quality by providing the equivalent of 70 percent of the ni-

trogen removed by a following sorghum crop in a Georgia study (Harper et al., 1995). Two cuttings of sorghum removed 450 kg ha<sup>-1</sup> of nitrogen (400 pounds per acre of nitrogen), and total nitrogen in the clover at dessication was 325 kg ha<sup>-1</sup> (290 pounds per acre).

Grasses and brassicas scavenge nitrogen two to three times more effectively than legumes, according to Meisinger et al. (1991). Nitrate concentrations in ground water declined more than 60 percent in field-scale watersheds during a 9-year study as a result of using rye cover crops. A variety of cover crops, the researchers reported, reduced nitrate leaching between 20 and 80 percent. The researchers also used the EPIC (Erosion-Productivity Impact Calculator) model to evaluate a series of different production scenarios on a national scale. Results showed that cover crops had the greatest impact in the humid Southeast and irrigated areas of the South and Southwest, although reductions occurred in all areas. The model also predicted higher leaching reductions on soils higher in organic matter because nitrogen mineralization is higher and not controllable.

In the winter vegetable production area of Florida, a legume cover crop reduced nitrogen leaching more than 90 percent, which was subsequently used by a following crop (Wang et al., 2005). Over a 3-year period, subsurface tile drainage declined 11 percent and nitrate-nitrogen discharge dropped 13 percent for a corn-soybean rotation with a rye cover crop following corn in Minnesota (Strock et al., 2004). The magnitude of the reduction depended upon the amount of annual precipitation. The cover crop may depress the yield and nitrogen uptake of the subsequent crop if nitrogen is limiting and the mature cover crop has a high carbon:nitrogen ratio (Francis et al., 1998). Also, by increasing soil organic matter and potential nitrogen mineralization, the nitrate concentration of leachate may increase if the nitrate is not captured by a cover crop (Garwood et al., 1999). Winter cover crops represent a good strategy for reducing soil erosion and absorbing free nitrate in the root zone, thereby keeping it from getting into ground or surface water (Bellinder and Gaffney, 1995; Sojka et al., 1984).

**Soil quality effects.** A principal benefit of cover crops is to help prevent wind and water erosion by providing surface cover that offers resistance to soil-particle detachment and transport (Langdale et al., 1991) and protection of aggregates from breakdown by raindrop impact. Indirect benefits also occur from increased soil organic matter that helps prevent surface sealing and increases water storage capacity and soil mac-

**Nitrogen taken up by cover crops is not subject to leaching and denitrification.**

**The cover crop also can effectively capture unused nitrogen from the main crop, as well as that mineralized from crop residue and soil organic matter.**

## Cover crops can reduce the use of chemical fertilizers and other soil amendments.

porosity (Dabney, 1998). Wischmeier (1960) reported that cool-season cover crops in a corn rotation reduced soil losses 62 percent on runoff plots in the southeastern United States. Also, chickweed (*Stellaria media*), Canada bluegrass (*Poa compressa* L.), and downy brome (*Bromus tectorum* L.) reduced mean annual soil losses 87, 95, and 96 percent, respectively, compared to no cover crop (Zhu et al., 1989). A Mississippi study showed that use of vetch and winter wheat cover crops in conservation-tilled cotton reduced soil erosion 47 percent, but both cover crops proved unacceptable in conventionally tilled cotton (Mutchler and McDowell, 1990) because the residue was incorporated. Data presented by Langdale et al. (1991) also suggest that more agronomic cover crops are best adapted to conservation tillage systems on Ultisols and Alfisols, while a meadow vegetative cover functions best on Mollisols, primarily because of climatic differences.

Planting a cover crop between rows of trees in a short-rotation woody crop (sweetgum) reduced soil erosion during a 2-year experiment in northern Alabama. (Malik et al., 2000). The erosion rate for four cover crops on the Decatur silty clay loam with slopes from 2 to 6 percent ranged from 2.6 to 4.5 Mg ha<sup>-1</sup> (1.2 to 2 tons per acre) per year, which is far below the rate for cropland with conventional tillage. Those results indicate that ryegrass, crimson clover, lespedeza, and tall fescue reduced erosion about 64, 61, 51, and 37 percent, respectively, compared to bare soil. Fescue was considered a poor choice, since nitrogen was not added to the soil.

No-till cotton systems, especially with cover crops and poultry litter, can rapidly increase surface soil organic matter and provide other soil chemical benefits (Nyakatawa et al., 2001a). In 2 years on Decatur silt loam, with either no-till or mulch-till and a winter rye cover crop, soil organic matter in the top 15 cm (6 inches) increased to 2.2 percent from 1.5 percent. Plots that received 200 kg ha<sup>-1</sup> (180 pounds per acre) of nitrogen in the form of poultry litter had 55 percent more soil organic matter than plots that received the same amount of nitrogen as ammonium nitrate fertilizer. The winter cover crop also provided a temporary safe haven for nitrogen. The winter rye scavenged residual nitrate after cotton harvest, reducing the amount available for leaching. In April, the level of ammonium was higher with a cover crop than with no cover, which is probably the result of mineralization of winter rye residues and increased soil organic matter, which holds ammonium against leaching.

Sunn hemp is a good cover crop in warm climates (NRCS, 1999). In Hawaii, compared to fallow, soil loss from plots with a Sunn hemp

(*Crotalaria juncea* L.) cover crop during the corn-growing season declined 68, 43, and 39 percent for no-till, chisel-plow, and moldboard-plow treatments, respectively (Fahrney et al., 1987). Sunn hemp also increased corn yield 18 percent.

The best germplasm for successful cover crops is not always available for the climates of different agroecosystems (Sims and Slinkard, 1991). Bowman et al. (1998) described the general suitability of selected cover crops in U.S. growing regions. Snapp et al. (2005) discussed cover crops for four spatial and temporal niches in the United States. Warm-season C4 grasses were best for summer niches, while rye was the most promising for winter niches. Brassica proved best for pest control. Benefits of cover crops in irrigated cropping systems are specific to the production system.

Maintenance of soil organic matter is key to improved soil physical properties because soil carbon is associated with better soil aggregation, water infiltration, and other soil properties that yield a more productive soil (Morachan et al., 1972; Mullen et al., 1998; Wienhold and Halvorson, 1998). In general, soil carbon increases when cropping strategies produce carbon with less tillage. Cover crops increase the carbon inputs to agricultural systems that subsequently may increase soil carbon content (Bruce et al., 1991; Lal et al., 1998; Larson et al., 1972; Reicosky and Forcella, 1998; Sainju and Singh, 1997; Waggoner et al., 1998). When relatively small amounts of biomass are produced, long-term changes in soil organic carbon with winter cover crops often are small or nonexistent (Lal et al., 1991). A key factor in achieving a soil carbon increase is the reduction or elimination of soil tillage that stimulates the oxidation and dilution of the decomposition products and disrupts soil faunal activities (Boquet et al., 2004; Reicosky and Forcella, 1998). Yields of succeeding crops often benefit from cover crops (Sainju and Singh, 1997).

Lack of residue cover affects soil quality. In North Carolina, an analysis of a no-till cropping system with two silage crops a year, compared with systems using cover crops and/or a grain crop in rotation with silage, showed the disadvantages of removing all above-ground crop material (Franzluebbers, 2005). With no crop residue, soil compaction was greater and soil porosity and soil organic carbon declined. Crop residue on the soil surface is necessary to improve soil quality and increase productivity.

Cover crops can reduce the use of chemical fertilizers and other soil amendments. The effect depends upon soil and weather conditions during the development and decomposition of the cover crop, the time the cover crop is present and actively growing, the quantity of biomass produced,



and the cover crop species. As Lal et al. (1991) reported, the impact of the first three factors largely depends upon climate and location. Cover crops in northern climates, grown in rotations with full-season cash crops, generally have little time for growth and development, while cover crops in southern climates often have greater opportunity for impact. Overseeding cover crops into established main crops before harvest may provide sufficient ground cover for resource protection without reducing yields in northern climates (Johnson et al., 1998). There also is evidence to suggest that the longer growing period provides more nitrogen from mineralization if the overseeded crop is a legume (Jones et al., 1998).

Most emphasis regarding cover crops on soil fertility and plant nutrition has been directed to subsequent nitrogen availabilities (Doran and Smith, 1991; Kristensen et al., 2003; Herbek et al., 1987; Ditsch et al., 1993; Smith et al., 1987; Singh et al., 1992; Wagger et al., 1998). The quantity of nitrogen available to the subsequent crop from a cover crop can be quite variable. In addition to climate and biomass effects, the time of incorporation, the carbon:nitrogen ratio, and the concentrations of lignin and other structural carbohydrates influence the kinetics of residue decomposition and nutrient release (Wagger et al., 1998; Vyn et al., 2000).

Moreover, there must be a high degree of synchrony between release of nitrogen from cover crop residues and the timing of nitrogen requirements of the subsequent crop to use this nitrogen source efficiently. Early desiccation of a vetch cover crop supplied sufficient nitrogen to a corn crop, compared to desiccation immediately prior to planting in Virginia (Vaughan and Evanylo, 1998). Also, a 2-week-later killing of a vetch cover crop in central Georgia increased nitrogen uptake and yields of a subsequent corn crop in no-till, but not in chisel plowing or moldboard plowing (Sainju and Singh, 2001). Part of the desiccation effect is related to plant maturity. Doran and Smith (1991) and Reeves (1994) reported fertilizer nitrogen equivalencies between 0 and 200 kg ha<sup>-1</sup> (0 and 180 pounds per acre) of nitrogen from cover crops in corn and sorghum rotations. Average recoveries ranged between 56 and 100 kg ha<sup>-1</sup> (50 and 90 pounds per acre) of nitrogen. Usually, the nitrogen available from a legume cover crop is greater than that from a non-legume crop (Kristensen et al., 2003; Smith et al., 1987). The apparent recovery amount is sometimes greater than that found in the cover crop. The apparent higher recoveries may be in part from improved water-use efficiency and other beneficial soil physical characteristics related to the cover crop. The average recovery of

isotopic-labeled nitrogen residues was about 32 percent with conventional tillage and 20 percent with no-till (Varco et al., 1989). A similar 2-year study showed that corn recovered 14 to 21 percent of the labeled nitrogen from crimson clover and only 4 percent from rye (Ranells and Wagger, 1997). Soil tillage also affects nitrogen mineralization and availability (Levin et al., 1987; Doran and Smith, 1991) as it breaks up the crop residue and roots. Nitrogen from a green manure clover cover crop was only available to sorghum after some tillage (Lemon et al., 1990). Some success predicting the nitrogen release dynamics from different cover crops has been achieved with models (Delgado, 1998; Quemada and Cabrera, 1997).

Cover crops also affect other nutrients. Phosphorus mineralization from residues is somewhat analogous to nitrogen transformations, except that the phosphorus concentration of the cover crop appears to be a controlling factor regulating phosphorus mineralization (Singh et al., 1992). There also is some tendency for cover crops to reduce the available soil test phosphorus concentrations near the soil surface from apparent uptake by the cover crop (Hargrove, 1986; Eckert, 1991). Indirect effects also occur from changes in soil pH, activity of other nutrients, and interactions with decomposition products. Changes in potassium, calcium, and magnesium availabilities are largely from increased cycling from the residue. Sulfur is analogous to nitrogen transformation because nitrogen and sulfur are both integral components of proteins and subject to biological transformations (Kristensen et al., 2003), except sulfur usually is not subject to volatilization losses. Cover crops and green manure crops generally are not important sources of micronutrients (iron, manganese, copper, and zinc), except for the transformations caused by oxidation-reduction reactions and chelation via decomposition products (Hinsinger, 1998). There may be indirect effects of cover crops on specific biological organisms (vesicular-arbuscular mycorrhizae) that affect availabilities of nutrients (Galvez et al., 1995; Hamilton et al., 1993). These fungi also produce glomalin, a glycoprotein important for soil aggregate stability (Wright et al., 1999). Part of the cover crop effect also may be "rotational" from increased microbial diversity and numbers and enzyme activities (Mullen et al., 1998). Soil moisture conditions causing anoxic conditions during decomposition can affect the physiochemical properties and biological activities of soil and, thus, some nutrient availability.

**Water conservation effects.** The effect of cover crops on water use from fall through early

**The quantity of nitrogen available to the subsequent crop from a cover crop can be quite variable.**



This clover cover crop protects against soil erosion and suppresses weed growth, which may reduce pesticide use.

spring months is not well defined. In central Kentucky, hairy vetch and big-flower vetch provided benefits to no-till corn by increasing soil water content throughout the growing season and adding soil organic matter in the top 7.5 cm (3 inches) after 2 years (Utomo et al., 1987). On conventional tillage plots, there was no increase in soil water or soil organic matter from the cover crops. Corn grain yield was significantly higher with hairy vetch than any other treatment. In dry years and in arid and semiarid regions, this extra water use may seriously affect growth of the main crop (Munawar et al., 1990; Unger and Vigil, 1998). A factor limiting use of cover crops in arid and semiarid areas is their use of stored soil water (Unger and Vigil, 1998), unless irrigated. Low-biomass cover crops may use less water and have a role in some limited-precipitation climates (Zhu et al., 1989).

Cover crops are known to increase the residue on the soil surface, which decreases soil temperature, water evaporation, and runoff and increases infiltration. Evaporation during the dormant or nongrowing season was found to be considerable and an important part of the yearly hydrologic water balance (Prueger et al., 1998; Wright, 1993). Climate, snow, residue cover, and available energy drive the energy balance at the surface over grass, rye, oats, and bare soil during this period. Evaporation totals ranged from 12 to 20 cm (5 to 8 inches) over a 3-year period in Iowa (Prueger et al., 1998) and averaged 24 cm (9.4 inches) over 6 years in Idaho (Wright, 1993). In Idaho, this amount exceeded the precipitation normally received during this period, and cover crops in this environment would not be feasible without supplemental irrigation.

**Other environmental effects.** Cover crops offer the potential to reduce pesticide applications for weed and insect control (Lal et al., 1991; Dabney et al., 2001; Kristensen et al., 2003; Worsham, 1991). Cover crops also control weeds through competition, allelopathy, and/or physical effects (Creamer et al., 1996; Liebman and Davis, 2000). Weed control by cover crops can be highly variable, however (Al-Khatib et al., 1997; Moore et al., 1994; Liebl et al., 1992; Hoffman et al., 1993). The suppression of weeds generally is better with no-till systems and living mulches than with dead mulches. Some mulches, both living and dead, provide nearly complete weed control without herbicides or tillage (Illicki and Enache, 1992). A rye (*Secale cereale* L.) cover crop suppressed the most weeds among several small grains, while subterranean clover (*Trifolium subterraneum* L.) and crimson clover (*Trifolium incarnatum* L.) were the most suppressive le-

gumes (Nagabhushana et al., 2001). Some cover crops potentially can be used as a smother crop for weed control (Buhler et al., 1998; Buhler et al., 2001). They must be competitive with native vegetation, however, and easy to control in the subsequent crop. If the cover crop is difficult to control, additional herbicides may be required. Cover crops can promote weed infestations by hindering chemical or mechanical control measures. Phytotoxic or allelopathic substances generated by and/or from cover crops for weed control also may detrimentally affect main crop growth. While legume cover crops may increase disease risk among subsequent crops (Rickerl et al., 1988; Dabney et al., 1996), specific cover crops reduce nematodes in potatoes (Al-Rehiyani and Hafez, 1998) and root diseases in cotton (Rothrock and Kendig, 1991). Volunteer winter weeds managed as cover crops, with other off-field conservation practices, can cost-effectively reduce sediment losses (Zhu et al., 1989; Yuan et al., 2002). Cover crops also can reduce cotton seedling stress and damage from wind (Zak et al., 1998).

Cover crops can harbor both harmful and beneficial arthropods (Bugg, 1991; Masiunas, 1998). Arthropods are invertebrate animals of the phylum (family) Arthropoda, which includes insects, crustaceans, arachnids, and myriapods. Cover crops also can serve as a host for alternative prey for beneficial arthropods, provide a favorable habitat for arthropod predators, interfere with host-finding abilities of the pest species, and serve as a trap crop for pests of the primary crop. Improvements in managing biological controls will become more critical as opportunities to use insecticides and acaricides decline and concerns increase about their contamination of surface and ground water resources.

#### **Factors driving environmental outcomes.**

Cover crops are attractive for a number of environmental reasons, but economic factors, at least in part, are likely to drive producers' acceptance of the practice. Complicating any economic analysis is the cost assigned to soil erosion and other forms of environmental degradation and the value placed on long-term crop productivity benefits. The cost of establishing and managing a cover crop can be substantial. Economic returns depend upon the indirect benefits derived from a higher yield from the following crop, which may include the sequestration of nutrients, moisture conservation, and weed suppression. Use of cover crops only as a replacement for nitrogen fertilizer showed a slight economic advantage of vetch over rye for the production of no-till silage corn (Flannery, 1981). Fyre et al. (1985) showed that

the general cost of establishing a legume cover crop was about the same as the cost of nitrogen fertilizer replacement. A 10-year comparison of vetch, clover, and winter wheat as cover crops for no-till corn in Tennessee showed that the highest net revenue was with vetch, followed by no cover, although the cost of cover-crop establishment generally exceeded the cost of nitrogen fertilizer replacement (Roberts et al., 1998). Another evaluation by Larson et al. (1998) showed that average net revenue was maximized when vetch was used without a reduction in N fertilizer use. Using a non-legume as a cover crop resulted in little economic incentive. A corn-soybean rotation that included a rye cover crop showed that use of rye as a cover crop was profitable when weed populations were low, but not when weed populations were high (De Bruin et al., 2005). Combining no-till and cover crops in a 6-year irrigated-cotton experiment protected the soil and environmental quality and increased potential farm productivity (Boquet et al., 2004). The cropping system with the lowest risk in a mid-Atlantic states study was no-till with cover crops (Lu et al., 2000). In a Missouri study, winter cover crops in a no-till soybean system significantly reduced runoff and losses of soil and nutrients (Zhu et al., 1989).

Using crop prices for the 1995-2000 period, a fall rye cover crop with minimum tillage produced economic returns similar to those with no cover crop and either minimum tillage or no tillage in a semiarid, fallow-crop environment (Smith et al., 2001). Treatments using spring-seeded rye were the least profitable. Sweet clover sowed as a companion crop with mustard provided soil erosion protection during the fallow period and high net economic returns if it was harvested as hay in early June (prior to seeding spring wheat). When underseeded with field pea or flax, however, yields declined about 50 percent, making the practice uneconomical, even though subsequent wheat yields increased about 50 percent.

The value of legume cover crops as a source of nitrogen may be questionable when the price of chemical nitrogen is relatively low. Prior to 2000, changes in the price of nitrogen fertilizer had marginal effects on the profitability of legumes either as a cover crop or in rotation (Allison and Ott, 1987). Even with 2005 price increases, nitrogen fertilizer is relatively low cost, and the higher cost has little effect on recommended application rates after legume cover crops (Bob Hoelt, personal communication, 2005).

Producers generally do not adopt cover crops because they lack the equipment or time to

incorporate cover crop residues and are uncertain when nitrogen will be released relative to inorganic fertilizers (Snapp et al., 2005). An accurate prediction of nitrogen release from cover crop residues in each production system is needed to synchronize that release with nitrogen demand on the part of summer or main crops. Cover crops have a major role to play in the restoration and maintenance of soil productivity and soil quality over a wide range of climates and crop species; they do so by increasing organic matter and providing good habitat for soil macrofauna, such as earthworms. A current need is description of the biological stimulation consequences of decomposing surface mulches and roots on soil and plant physical and chemical properties.

Expansion of managerial objectives from only maximizing or minimizing economic risk to broader soil and environmental quality concerns likely will be required before producers readily adopt the use of winter cover crops. There are important tradeoffs between increased profitability, less soil erosion, and reduced nutrient and pesticide hazards to surface and ground water supplies. If these tradeoffs benefit the general public, the additional costs associated with using cover crops could be shared. The costs of establishing and managing cover crops can be substantial. Economic returns depend upon the indirect benefits derived from a higher yield of the following crop, which usually results from short-term sequestration of nutrients, moisture conservation, and weed suppression by the cover crop. Over the long term, crop yields will increase because of improved soil quality, credited to cover crops. A cover crop perhaps could be harvested in part as biomass for energy production, leaving enough of the crop to protect the soil until the main crop is growing.

**Adequacy of scientific documentation.** The considerable research on cover crops indicates potential for substantial environmental enhancement and cropping system health benefits. Some benefits will not be identified in short-term studies, but require longer term studies of crops, soils, and production systems. Pieters and McKee (1929) discussed 18 research needs. Many solutions they cited are specific to a region, soil type, cash crop, and whether the cover crop is a summer or winter legume. Many of their research needs remain valid today, including (1) development and selection of adapted plant species, (2) development of management practices, (3) characterization of effects on soil moisture, (4) knowledge of effects on soil chemical and physical properties, (5) determination of effects on soil erosion and leaching, (6) quantification of nitro-

**Cover crops are attractive for a number of environmental reasons, but economic factors, at least in part, are likely to drive producers' acceptance of the practice.**



**A soil's susceptibility to erosion depends upon aggregate stability, which is determined by the strength of the bonds between primary soil particles.**

gen and other nutrient cycling, and (7) determination of influences on diseases, pests, and other soil microorganisms. The effectiveness of using cover crops to manage runoff within watersheds also can be moderated by subsurface hydrological characteristics (Dabney, 1998). Additional studies are needed to evaluate the impact of cover crops at the watershed scale.

Cover crops are considered by many to be the backbone of any sustainable annual cropping system. That is because of the multitude of effects that cover crops have on agricultural production systems. Expansion of cover crop use will require development of information and management techniques pertaining to preferred combinations of tillage, crop species, equipment, and biological, water, and human resources. Most cover crop research is being conducted in humid regions of the United States. More research is needed on use of cover crops in arid, semiarid, and northern climates, especially for use after crops that leave little protective residue on the soil surface. Many of these areas also are subject to severe soil erosion, off-season nitrate leaching losses, and low soil organic matter levels.

In northern regions, where soil typically is frozen and snow-covered in winter, cover crops offer protection for soil from spring snowmelt and rains, but in colder climates it is difficult to establish a cover crop after late-harvested crops, including corn silage. In milder northern climates, with frequent changes in soil condition (freeze/thaw), a good cover protects the soil even more days of the year, but the lack of success with currently available cover crops appears to have halted most interest in use of the practice. This appears to be an opportunity for success, perhaps with different means of "applying" the seed, or developing a seed or seed coating that can result in rapid establishment just prior to or immediately after crop harvest. Research is more extensive in southern climates where the value of cover crops has been proven in many situations.

#### **Anionic polyacrylamide erosion control**

Conservation practice standard 450 describes the application of water-soluble anionic polyacrylamide (PAM) to control soil erosion. The practice is designed to minimize or control irrigation-induced soil erosion and reduce wind and/or precipitation erosion. It applies to both surface and overhead irrigation systems, although the specific recommendation varies with system. The standard does not apply to flowing, non-irrigation waters, such as intermittent or perennial streams. Additional details can be found in the standard itself.

A soil's susceptibility to erosion depends upon aggregate stability, which is determined by the strength of the bonds between primary soil particles. Bond strength varies with soil texture (especially clay content), organic matter content, compaction, and adsorbed ions, along with the chemical composition of the water, time and water content since last disruption, water content before wetting, and wetting rate. Crop cover and surface or incorporated residues can also shield the soil surface or aggregates from erosive forces.

Soil erosion mechanics involve three components: detachment, transport, and deposition. Water droplets, flowing water, and wind detach soil particles. Depending upon energy dynamics, some particles may be deposited within a few meters after being detached; other particles will be transported off the field. Chepil et al. (1963) and Nearing et al. (1989) provided additional details on wind- and water-related soil erosion processes.

Differences exist between soil erosion from rain and surface irrigation. These include the lack of water droplets impacting the soil surface during a surface irrigation, the tendency for runoff volume from rainfall to increase downstream as additional water from sheet and rill flow join together, the generally shorter duration of a rainfall event compared with irrigation runoff, and the potential for the chemical properties of irrigation water to vary within and between irrigated fields (Bjorneberg et al., 2000a). Erosion mechanics and processes associated with overhead or sprinkler irrigation can be similar to rainfall, except for potential water quality differences.

Soil conditioners were primarily used for soil structure stabilization in horticultural, agronomic, and construction applications from the early 1950s through the 1970s. Those uses generally require high application rates for the complete stabilization of soil plow layers or soil volumes, such as plant containers. The creation of new polymers, for example, high-molecular-weight anionic and cationic PAMs, offer possibilities for additional uses. These are now employed for solid-liquid separations in clarification of potable and waste waters, dewatering of sludges, mining separations, food processing, paper making, petroleum recovery, textile additives, friction reduction, personal care products, and cosmetics (Barvenik, 1994). An additional use is the potential to stabilize soil aggregates at the soil surface to reduce erosion, a serious problem with irrigation that potentially impacts off-site water quality.

**Water quality and soil quality effects.** Most early PAM studies used rainfall simulators in the laboratory or on small field plots to simulate drop



impact conditions under sprinklers or rainfall. In these studies, 20 to 67 kg ha<sup>-1</sup> (18 to 60 pounds per acre) PAM produced a 10 to 100 percent increase in infiltration and a reduction in soil loss of 6 to 100 percent, although most reductions were between 30 and 85 percent (Wallace and Wallace, 1986; Levy et al., 1991; Agassi and Ben-Hur, 1992; Norton, 1992). The first report of a soil loss reduction in PAM-pretreated furrows was by Paganyas (1975), although the polymer properties were not clearly identified. Mitchell (1986) reported that 6.6 to 32.2 kg ha<sup>-1</sup> (5.9 to 28.8 pounds per acre) PAM stabilized the surface soil against dispersion and slaking and promoted formation of a more porous depositional seal when anionic PAM was applied in furrow irrigation water. Infiltration rates later in the irrigation event were similar to the control treatment. In a furrow-irrigated field study, Lentz et al. (1992) was the first to report that small amounts of PAM [0.5 to 1.2 kg ha<sup>-1</sup> (0.4 to 1.1 pounds per acre)] added in the first few minutes of inflow reduced soil loss 44 to 99 percent and increased infiltration 10 to 40 percent on a calcareous silt loam soil. In the next irrigation after treatment, the residual PAM effect was half the first treatment. Later, Lentz and Sojka (1994; 1996) and Sojka et al. (2000) reported that PAM at 0.7 to 1.3 kg ha<sup>-1</sup> (0.6 to 1.2 pounds per acre) reduced sediment loss in irrigation furrows by 94 percent and increased net infiltration 15 percent. The most effective treatment was the application of 10 g

m<sup>-3</sup> (10 ppm) of PAM in irrigation water inflows during the furrow water advance time.

It is for this latter use that the conservation practice standard 450 was initially developed. A "dry or patch" treatment in the first 0.9 to 1.5 m (3 to 4.5 feet) of furrow bottom was later developed to facilitate field applications. Table 11 shows a selection of relevant literature for this standard.

Relatively small amounts of PAM [1 to 5 kg ha<sup>-1</sup> (0.9 to 4.5 pounds per acre)] achieved significant soil erosion control in most irrigation studies, with slightly larger amounts required for the overhead or sprinkler irrigation studies. Larger amounts of PAM [20 to 80 kg ha<sup>-1</sup> (18 to 71 pounds per acre)] were used in the natural or simulated rainfall studies, primarily because of steeper soil slopes or higher water application intensities. Erosion usually declined in surface-irrigated furrows for one to two irrigations after an application, but PAM must be reapplied if the furrow soil is disturbed by cultivation. If PAM is applied according to the NRCS standard, irrigation-induced furrow erosion is reduced by more than 90 percent. An uncertainty factor of 10 percent was assigned (Annon, 2000) to account for field variabilities and application anomalies under irrigation.

PAM also can effectively reduce soil erosion under rainfall conditions, but higher application rates are required, and the material must be applied prior to the rainfall event, usually as a spray

**Table 11. Effectiveness of polyacrylamide on soil erosion by wind or water.**

System	PAM method	Soil erosion reduction	Infiltration change	Reference
Furrow	Solution	44-99%	10-40%	Lentz et al., (1992)
Furrow	Solution	80-99%	(-8)-57%	Lentz & Sojka (1994)
Furrow	Solution	80-99%	15-50%	Sojka et al., (2000)
Furrow	Dry	84%	22%	Lentz & Sojka (1996)
Furrow	Solution	70-93%	3-13%	King et al., (1996)
Furrow	Solution	70%	30%	Trout et al., (1995)
Sprinkler	Solution	40-70%	30-50%	Bjorneberg et al., (2000b)
Sprinkler	Pre-irrigation	30-84%	31-50%	Ben-Hur (1994)
Sprinkler	Solution	10-90%	58-70%	Levy et al., (1992)
Sprinkler	Solution	27-39%	25%	Santos et al., (2003)
Sprinkler	Solution	60-77%	66-88%	Bjorneberg et al., (2003)
Natural rainfall	Solution	40-54%	--	Flanagan et al., (2002b)
Simulated rainfall	Solution	48-66%	50-283%	Zang & Miller (1996)
Simulated rainfall	Dry	30%	--	Yu et al., (2003)
Simulated rainfall	Solution	83-91%	40-52%	Flanagan et al., (2002a)
Simulated rainfall	Solution	83%	40%	Flanagan et al., (2003)
Wind	Solution	70%	--	Armbrust (1999)

**Erosion usually declined in surface-irrigated furrows for one to two irrigations after an application, but PAM must be reapplied if the furrow soil is disturbed by cultivation.**

to cover the entire surface. Similarly, PAM is effective on construction sites (Soupir et al., 2004; Hayes et al., 2005), disturbed land (Vacher et al., 2003), and steep road banks (Flanagan et al., 2000a; 2003). Effective application rates may be higher than recommended on moderate to steep slopes (Hayes et al., 2005).

Wind erosion control using PAM is no better than natural rainfall (Armbrust, 1999), provided the treated area is protected from incoming saltation particles.

Use of PAM in furrow-irrigated fields also reportedly reduces phosphorus (Lentz et al., 1998), microorganisms (Sojka and Entry, 2000), weed seeds (Sojka et al., 2003), and pesticide transport (Singh et al., 1996) off an irrigated field.

Several criteria must be met if PAM is to reduce soil erosion in irrigated systems. The polyacrylamide must be the anionic type, have a charge density of 10 to 55 percent by weight, and a molecular weight of 6 to 24 Mg mole<sup>-1</sup>. The PAM material itself also should contain less than 0.05 percent residual acrylamide monomer by weight because this compound represents a potential environmental threat. Divalent cations, for example, calcium and magnesium, should be present in the water to facilitate bridging between soil particles and PAM molecules. It also is important that no untreated water wet the soil ahead of the PAM-treated flow. Untreated water will destroy the soil structure before PAM can stabilize it. A higher than normal inflow rate in furrows should be used when applying PAM to compensate for the increased infiltration caused by the use of PAM and to improve infiltration uniformity across an irrigated field. Infiltration can be adversely affected and the potential for PAM losses in runoff increases when high PAM rates are used. At recommended application rates and methods, PAM concentrations in field runoff are not a big concern because PAM is rapidly and irreversibly bound to soil particles. Articles by Barvenik (1994) and Seybold (1994) provide additional information on PAM fate and transport.

**Water conservation effects.** Increased infiltration with PAM mandates that surface irrigation practices accommodate larger water inflows initially to move water across a field rapidly, then flows can be reduced. When higher initial inflow rates are not used, greater leaching losses can occur in the upper portion of the field because contact time is significantly increased from a slower advance time. When surface irrigation is managed correctly, a PAM application should increase water application uniformity, thereby improving irrigation and water use efficiencies. This was demonstrated in a furrow-irrigated field

study that combined PAM and a higher inflow rate to increase field-average infiltration 17 percent and Russet Burbank potato tuber quality (Sojka et al., 1998).

**Air quality effects.** There are no known air quality benefits from PAM use. Polyacrylamide mixes can be used with other compounds to stabilize soil surfaces to reduce fugitive dust emissions.

**Factors driving environmental outcomes.** Use of PAM was among the first nonintrusive practices available for landowners to control irrigation-induced soil erosion. Substantial reductions in sediment and other runoff components were documented when PAM was used as recommended. To date, there have been no adverse effects from its use. Neither are there any known long-lasting, direct effects on soil physical and chemical properties. This practice is a major advance in helping to reduce the environmental impacts of surface irrigation on offsite water bodies.

There is some concern that PAM either contains or decomposes into a monomer, acrylamide, that might enter the food chain (Smith et al., 1997; Friedman, 2003; Dybing et al., 2005). The monomer is a known nerve toxin in humans and affects male reproduction. It also can cause birth defects and cancer in animals. Acrylamide absorbed by field crops is largely degraded after 18 hours, although the degradation mechanism in the plant is unknown (Bologna et al., 1999).

#### **Adequacy of scientific documentation.**

Research is needed to develop more effective application technologies before PAM can be used effectively in overhead irrigation systems and to better define its impacts on water quality. Other beneficial uses of PAM are being developed for irrigated agriculture. Changes in crop yields have not been fully documented, but yield increases related to improved infiltration have been verified.

#### **Salinity and sodic soil management**

Salinity and sodic soil management (practice code 610) is a practice designed to manage land, water, and plants in ways that minimize accumulations of salts and/or sodium on the soil surface and in the crop rooting zone. The practice applies to all land uses where salts limit the growth of desirable plants or where excess sodium causes soil crusting or permeability problems. It also includes the management of non-irrigated saline seeps and their recharge areas. A variety of land, water, and crop management practices potentially are components of this conservation practice.

They include soil amendments, water quality and quantity management, soil tillage, soil drainage, crop selection, land shaping, and crop residue.

Voluminous historic data and reports exist on this topic. Readers are referred to recent book chapters by Hoffman and Durnford (1999), Rhoades and Loveday (1990), Maas and Grattan (1999); books by Bresler et al. (1982), Hillel (2000), Sumner and Naidner (1998), Tanji (1990), and Handbook No. 60 (Richards, 1954); and a saline and sodic soils bibliography (Carter, 1966) for additional information. Reviews also have been written by Allison (1964), Grattan and Oster (2003), Sumner (1993), Qadir et al. (2000, 2001), Ghafoor et al. (1989), and Jayawardane and Chan (1994).

Salinity and sodic soil management is targeted to three general categories of problems that affect the sustainability of production agriculture. High dissolved salts in irrigation water and/or antecedent high salt concentrations in soil can cause general salinization of the plant root zone. Poor drainage exacerbates this problem by allowing soluble salts to accumulate in the root zone and eventually at the soil's surface. This can be a serious problem in semiarid and arid regions where adequate drainage is lacking.

The second general problem is associated with the accumulation of specific ions that become toxic or cause nutritional imbalances. Those include sodium, chloride, boron, selenium, or other trace elements. The ions usually limit crop production, but also may have offsite toxicological effects on other organisms when drainage effluents are discharged (Page et al., 1990).

The third general problem is associated with adverse soil physical conditions, usually caused by sodium accumulation. Except for the crops most sensitive to sodium, plant growth is affected by surface crusting, reduced permeability to water and air, and increased resistance to root penetration.

For purposes of this discussion, we will discuss saline and sodic soil management together. Soil quality aspects of these conservation practices are presented first because the initial impacts are soil-related.

**Soil quality effects.** Direct sodium toxicity usually is limited to perennial woody species. Sodium tends to accumulate in the roots and lower portions of woody plants; over time it is translocated to shoots and leaves, causing leaf burn (Maas, 1986). Sodium generally is not translocated to the shoots of most nonwoody plants in appreciable amounts. In nonsaline-sodic soils the sodium effect can be expressed as a calcium or magnesium deficiency because

the high pH and bicarbonate ion suppresses the solubilities and concentrations of these two elements. Amelioration of saline-sodic or sodic soils tends to increase calcium concentrations above the adequacy for most plants, but detrimental osmotic effects will dominate until excess salts are removed by leaching. Plant growth in sodic soils also can be affected by low water and oxygen supplies, which are usually corrected by successful amelioration.

Most nonwoody crops are not specifically sensitive to chloride toxicity because those plants restrict the transport of chloride to shoots. Many woody plants are susceptible to chloride toxicity because they allow the transport of chloride to plant tops. For some plants, translocation is determined by rootstock properties. Among those plants are avocado, orange, grapefruit, grapes, and some stone fruits. Chloride's major detrimental effect in the plant cell is its contribution to the osmotic level when concentrations are above nutritional requirements. Leaching chloride out of the root zone generally corrects the toxicity.

Boron also is an essential nutrient element, but it can become toxic when soil-solution concentrations exceed those required for optimum plant growth. A wide tolerance to boron exists among plant species, ranging from very sensitive to very tolerant (Maas and Grattan, 1999; Bresler et al., 1982). A very narrow boron concentration range in soil solution exists between deficiency and toxicity, so an understanding of the dynamics between the boron concentration in irrigation water, the soil solution, and the soil-solid phases is important. Leaching can remove excess boron in the soil solution (Keren, 1990), but about two times more leachate is required than for normal salt removal (Oster et al., 1999).

Molybdenum and selenium are two elements that can become toxic (Page et al., 1990). Pratt and Suarez (1990) recommended the maximum concentrations for 15 trace elements in irrigation waters thought to be sustainable for plants and animals. There is growing concern about the potential toxicological effects of these elements when drainage effluents are discharged into offsite water bodies. Elements in effluents used for irrigation also can accumulate sufficiently in soils and plants to become toxic for plants or consumers of plant parts. Concentrations also can become toxic as they move up the food chain. As well as being in the irrigation water, the soil can be a major source of these elements, as can irrigation water and irrigation effluent.

**Saline soil reclamation.** Saline soils generally contain excessive amounts of soluble salts that detrimentally affect the normal production of



Salt build-up in this soil is the result of salt-laden water percolating to the soil surface, then evaporating.

most agricultural crops. These detrimental effects are expressed by a loss of plant stand, reduced rates of plant growth, reduced yields, and crop failure in severe cases. Leaching and natural or artificial drainage must be adequate for salinity control in irrigated agriculture to ensure a net downward flux in soluble salts. If sufficient leaching does not occur naturally, the soil must be leached with water to remove excess salts. This process requires that the soil be permeable and that the applied water have lower salinity properties than the soil. Removal of soluble salts by the applied water is referred to as reclamation.

The most appropriate reclamation method depends upon the nature of the ionic chemistry affecting the soil. Traditionally, potential reclamation areas are divided into three broad categories, depending upon whether soils are saline, sodic, or both (Richards, 1954). The categories are based on electrical conductivity (EC) of a saturation paste, the exchangeable sodium percentage (ESP), and pH, as defined in table 12. Definitions are slightly different for Australian soils because a sodium adsorption ratio (SAR) is used, rather than the exchangeable sodium percentage (Naidu and Rengasamy, 1993), to adjust for the electrolyte's effect on the dispersive action of sodium (Rengasamy and Olsson, 1991; 1993). The quality of water used to define the hydraulic properties also affects the exchangeable sodium percentage at which conductivity declines (Sumner, 1993).

Method of water application and soil type are the primary variables affecting the amount of water required to reclaim saline soils. About 60 percent or more of the salts initially present will be leached by a depth of water equal to the depth of soil under continuously ponded conditions. Hoffman (1986) proposed the following relationship between the fraction of initial salt concentration remaining in the profile ( $C/C_0$ ) and the depth of water infiltrated ( $D_w$ ) through a given soil depth ( $D_s$ ), where  $K$  differs with soil type.

$$(C/C_0)(D_w/D_s) = K \quad [1]$$

Values of 0.45, 0.3, and 0.1 for  $K$  are given for peat, clay loam, and sandy loam soils, respectively (Hoffman, 1986).  $D_w$  does not include evaporation losses, and by definition equation 1 only is valid when  $(D_w/D_s)$  exceeds  $K$ . Differences

in  $K$  reflect differences in saturated volumetric water content and leaching efficiency among soils. A  $K$  value of 0.6 is used to calculate the amount of water necessary for boron leaching. Several studies were used to develop the relationship in equation 1 (Oster et al., 1972; Prichard et al., 1985; Reeve et al., 1948; Reeve et al., 1955; Hulsbos and Boumans, 1960; Khosla et al., 1979; Leffelaar and Sharma, 1977; Hoffman and Jobes, 1983; Jobes et al., 1981; Hoffman et al., 1979; Hoffman et al., 1983).

When intermittent applications of ponded water are used, the constant,  $K$ , can be reduced to 0.1 for silty clay, loam, and sandy loam soils (Oster et al., 1972; Hoffman, 1986; Talsma, 1967; Oster et al., 1999). Reclamation by sprinklers is possible if water application rates are controlled so ponding does not occur to circumvent the problems caused by bypass flow under saturated conditions. Leaching only occurs within the depth of soil wetted by sprinkler irrigation. In general, leaching efficiency is in the order of intermittent ponding greater than sprinkler greater than continuous ponding (Oster et al., 1972, 1999). A visual examination of the data presented by Hoffman (1986) and Oster et al. (1999) in the leaching fraction versus fraction of salt remaining relationship suggests that there is about a 10 percent uncertainty in the depth of applied water to achieve a given salt removal level.

**Sodic soil reclamation.** Sodic soils have their cation exchange complex saturated with sodium. To reclaim these soils successfully, the sodium on the exchange complex must be replaced with calcium or magnesium and then leached. Potassium-saturated soils can behave somewhat similarly (Robbins, 1984).

Saline-sodic soils that contain gypsum usually are reclaimed successfully by leaching without any additional amendment, provided there is sufficient gypsum to replace the exchangeable sodium. During this process, the salt content of the leaching water should be sufficient to avoid the adverse effects of the exchangeable sodium on the soil's hydraulic properties. In general, the electrical conductivity of the water should exceed  $20 \text{ dSm}^{-1}$ , and the ratio of the divalent cation concentration ( $\text{mmol L}^{-1}$ ) to total cation concentration should be greater than 0.3. Gypsum can be added to increase the ratio if necessary (Keisling

**Table 12. Definition of saline and sodic soils (Richards, 1954).**

Category	Saturated paste EC	Soil ESP	Soil pH
Saline	>4 dSm <sup>-1</sup>	<15	<8.5
Saline-sodic	>4 dSm <sup>-1</sup>	>15	<8.5
Sodic	>4 dSm <sup>-1</sup>	>15	>8.5



et al., 1978). Where the sodium-affected soil is underlain by soil containing significant amounts of gypsum, deep plowing is effective in breaking up and mixing the soil layers. Plowing depth can be from 0.5 to 1.0 m (20 to 40 inches). A procedure is available to predict the optimum plowing depth to maintain permeability during the reclamation process (Rasmussen and McNeal, 1973).

Gypsum can be added to sodic soils to supply calcium to replace the exchangeable sodium. The gypsum requirement (Richards, 1954) to provide sufficient soluble calcium is calculated as follows:

$$\text{kg gypsum ha}^{-1} = (8.5)d\rho_b E_c (R_{\text{Nat}} - R_{\text{Naf}}) \quad [2]$$

where  $d$  is the depth of soil to be reclaimed in meters,  $\rho_b$  is the soil bulk density in megagrams per cubic meter,  $E_c$  is cation exchange capacity in millimoles of charge per kilogram soil, and  $R_{\text{Nat}}$  and  $R_{\text{Naf}}$  are initial and final sodium adsorption ratios, respectively. The amount calculated by equation 2 must be multiplied by an appropriate factor to compensate for inefficiencies in the exchange process. A factor of 1.25 is often used (Richards, 1954). The actual amount of gypsum to accomplish reclamation may differ substantially from the calculated amount (e.g., Bresler et al., 1982; Dutt et al., 1972; Hira et al., 1981; Manin et al. 1982). Because of this discrepancy, the application rates in practice are most often determined by local experience and financial considerations (Rhoades and Loveday, 1990). Generally, gypsum applications are spread over several years to reduce 1-year costs and allow for gypsum dissolution.

There also is an effort to determine the gypsum requirement based on the quantitative calculation of exchange efficiency, calcite dissolution, and the calcium contribution of irrigation water using numerical models that appears promising (Simunek and Suarez, 1997).

When lime or calcite ( $\text{CaCO}_3$ ) is present, an acid or acid-forming amendment can be used to produce the required soluble calcium. The solubility of lime by itself, at the pH of sodic soils, is not sufficient to provide enough calcium to replace the exchangeable sodium. Materials used include sulfuric acid, elemental sulfur, pyrite, and iron or aluminum sulfates. Sulfuric acid can be more effective than gypsum because of an induced calcium supersaturation and bicarbonate ion production (Mace et al., 1999). Field experiments also demonstrate that acid is more effective on sodic soils (Overstreet et al., 1951; Miyamoto and Stroehlein, 1986). Combining some form of bioremediation with a gypsum application tends

to reduce the leaching or gypsum requirement (Suarez, 2001). The organic matter additions or increased plant growth facilitate increases in soil carbon dioxide concentration during growth or decomposition, which tends to lower soil pH, increasing calcium solubility (Qadir and Oster, 2003; Qadir et al., 2003). This assumes that drainage is adequate and that leaching does occur.

A field study by Suarez (2001) showed that predicted changes in sodium adsorption ratios, compared with average field sodium adsorption ratios down to a 1.2 m (47 inches) soil depth, generally were within the 95 percent confidence intervals of the measured mean, although individual comparisons varied by more than 100 percent. A wide degree of saline and saline-sodic spatial variability in fields is an opportunity for the application of site-specific remediation management practices (Corwin and Lesch, 2005; Horney et al., 2005).

**Water quality effects.** All irrigation projects require drainage to be sustainable over time. Without drainage, soils will salinize. To avoid salination, a downward flux of water must be maintained over time. Drainage can be accomplished with open or closed drains. Physical design approaches are several, but approved design criteria can be found in the National Engineering Handbook (USDA-NRCS, 2001). The amount of drainage is referred to as the leaching requirement. This is the amount of water that must move through the soil profile to maintain the salt balance for a specific crop. The leaching requirement is in addition to the amount of water required for evapotranspiration and to compensate for irrigation efficiency. It can be estimated by dividing the electrical conductivity of the irrigation water by the electrical conductivity of the soil solution leaving the root zone that a specific crop can tolerate (Hoffman and Durnford, 1999). The latter conductivity sometimes is multiplied by two for crops with intermediate and high salt tolerance. The actual leaching requirement can vary by 100 percent or more between sites because the amount of drainage required depends upon the salt content of the irrigation water, soil and ground water, the salt tolerance of the crop, climate, and soil and water management.

Saline seeps result when dryland farming practices accelerate a salinization process. It is the intermittent or continuous discharge of water containing salts at or near the soil surface downslope from a recharge area(s) under dryland cropping that reduces or eliminates crop growth in the affected area (Brown et al., 1982; Halvorson, 1990). To reclaim a seep area, the water recharge area must be identified and ground water flow to



Irrigated soils will salinize unless drainage remains adequate.

**In theory, the reclamation of sodic and saline soils is straightforward. In practice, the science remains inexact.**

the seep area reduced or eliminated. The recharge area can then be planted to alfalfa, grasses, or an annual crop to use the percolating water before it moves below the rooting zone. Interceptor drains installed immediately upslope from the seepage area also can be successful, but disposal of the saline drainage water may be an environmental problem. A relatively high water table in a saline seep area also must be lowered before remediation is possible. Remediation occurs in 3 to 4 years unless the recharge area reverts back to the causative cropping practices.

**Water conservation effects.** Salt accumulation and uptake by plants increases the osmotic tension within plant cells. Plants will initially compensate for this by taking up extra water, if available. Successful management of saline soils requires extra water supplies for leaching of soluble salts, especially if the water used contains appreciable amounts of soluble salts. As discussed under drainage, the leaching requirement increases as the salt concentration increases.

**Air quality effects.** Land with a salt accumulation on the surface is subject to wind-generated suspension of salt particles. This frequently occurs when land becomes saline and agricultural production ceases, or when all other plant growth that could protect the soil surface ceases.

**Factors driving environmental outcomes.** Management of salinity on agricultural land generally requires specific management practices. These may include (a) additional leaching, (b) planting salt-tolerant crops, (c) placement of seeds to avoid salt accumulation, (d) change in irrigation system, (e) chemical and/or mechanical modification of the soil profile, (f) improved surface and subsurface drainage, and (g) improved water quality. Most management practices prove successful when properly designed and applied. In addition, most saline or sodic problems are spatially dependent under field conditions. Additional technologies will be needed to identify and ameliorate saline or sodic problems successfully on a site-specific basis, rather than treatment of whole fields.

Saline or sodic reclamation processes can have serious environmental consequences because additional water, drainage, and a place for disposal of the removed salt are required (van Schilf-gaarde, 1994). Reviews of irrigated agriculture's impacts on ground water quality in the United States were done by Bouwer (1987), Helwig (1989) and Ritter et al. (1989). The magnitude of this problem depends upon the availability of additional water, the amount of salt removed, and

whether or not that salt contains ions or compounds that have potential deleterious biological effects. What can be done to minimize the volume of drainage water and should the disposal of unusable drainage water be localized to sub-regions where these waters are generated are key issues in the reclamation of saline or sodic soils. One proposed strategy is to improve irrigation management so that excess water is not applied over that needed for evapotranspiration and leaching (Wichelns, 2002). Another is to reuse drainage waters for irrigation of appropriate salt-tolerant crops (Rhoades, 1999). A related strategy is to use vegetative bioremediation or grow plant species that can tolerate higher salinity or sodic levels (Qadir and Oster, 2004). These and other potential strategies are key to future agricultural and economic growth and social wealth in regions where irrigation is practiced and where drainage waters are generated.

**Adequacy of scientific documentation.** Numerous conferences have been held and proceedings published that address the problem and reclamation of saline and sodic soils. In addition, comprehensive scholarly books have been written on the subject. Field research continues to be conducted in many developing countries that should apply to U.S. conditions.

In theory, the reclamation of sodic and saline soils is straightforward. In practice, the science remains inexact. Most projects consequently are over-designed to compensate for the uncertainties. Though significant progress has occurred, there remains considerable uncertainty about predicting the exact requirements and outcomes of salt management, especially in irrigated systems. Both reclamation processes require large volumes of water. More information is needed about when a pulse-water application procedure is more appropriate than ponding. Bioremediation with specific plants is another alternative that needs additional study. Plants should be selected or genetically developed to remove excess salts or to change the soil surrounding the root from chemical exudates.

## Conservation buffers

Conservation buffers are small areas or strips of land in annual or permanent vegetation designed to perform a variety of environmental management functions. Buffers include contour buffer strips, grassed waterways, vegetative barriers, field borders, filter strips, riparian forest buffers, constructed wetlands, windbreaks and shelterbelts, cross-wind trap strips, alley cropping, and herbaceous wind barriers. Vegetation in other ar-

eas also can serve a buffer function, for example, ditch banks, fencerows, and so forth. Not all types of buffers are discussed here.

Edge-of-field and within-field buffers are closely related practices with distinct definitions, yet practitioners often use some terms interchangeably, such as buffer, strip, and barrier. From a research standpoint, location in a field or direction of placement may be the only differences among practices that have similar environmental functions and benefits.

Contour buffer strips (practice code 332) are narrow strips [at least 4.6 m (15 feet) wide] of grass and/or legume sod established across a slope and alternated with parallel, wider cropped strips. The main purposes of contour buffer strips are to reduce sheet erosion, rill erosion, and sediment transport.

Field borders (practice code 386) are strips of permanent vegetation established at the edge of or around the perimeter of a field. The practice, which primarily applies to cropland, acts as a connection between the field and off-site areas. It may be part of the original field. Field borders are used to reduce wind and water erosion; protect soil, air, and water quality; manage insect populations; provide wildlife food and cover; provide a turning area for farm equipment; and increase and/or sequester carbon biomass on the soil surface and in the soil. Species planted can include grasses, legumes, and/or shrubs. The width of a field border depends upon the purpose for installing the practice.

Field borders are similar to filter strips (practice code 393), which generally are designed to treat surface runoff from cropland. Filter strips are relatively narrow areas or strips of permanent vegetation designed to intercept pollutants and manage other environmental concerns.

Vegetative barriers (practice code 601) are permanent strips of stiff, dense vegetation along the general contour of slopes or across concentrated flow areas. The barriers can be as narrow as 1 m (3 feet). Their primary purposes include reduction of sheet, rill, or ephemeral gully erosion and trapping of sediment.

Stripcropping (practice code 585) is the practice of growing crops in a systematic arrangement of equally wide strips across a field. The purposes of this practice include reducing soil erosion by wind and water and protecting crops from wind-borne soil particles. No two adjacent strips can be in an erosion-susceptible condition at the same time. On slopes where water erosion is a concern, the strips often are planted on the contour, effectively becoming contour stripcropping. If wind erosion is the concern, then the vegetative strips are planted perpendicular to the prevailing wind direction.

These are referred to as cross-wind trap strips.

Alley cropping (practice code 311) involves planting trees or shrubs in rows, with agronomic, horticultural, or forages crops produced in the alleys between rows. Typically, the crop in the alleys provides an annual income while the trees grow to maturity, or a legume shrub is grown in the rows to provide nutrients for the crop. Alley cropping reduces surface runoff and soil erosion and improves use and recycling of nutrients.

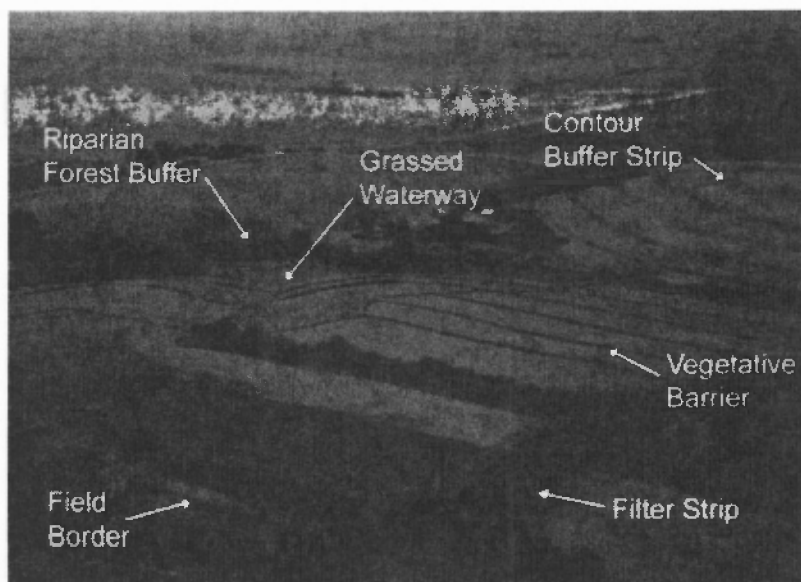
Riparian forest buffers (practice code 391) are areas of predominantly trees and/or shrubs located adjacent to and upgradient from water bodies. The practice applies to areas adjacent to permanent or intermittent streams, lakes, ponds, wetlands, and areas with ground water recharge that are capable of supporting woody vegetation.

**Water quality effects.** Strategically placed buffer strips in the agricultural landscape can effectively mitigate the movement of sediment, nutrients, and pesticides within farm fields and from farm fields. When coupled with appropriate field treatments, including crop residue management, winter cover crops, nutrient management, and integrated pest management, buffer strips should enable farmers to achieve a measure of economic and environmental sustainability in their operations, and enhance wildlife habitat and protect biodiversity. Use of conservation corridors on a watershed scale also can improve wildlife habitats and species diversity (Henry et al., 1999). Table 13 summarizes the impacts of various buffer practices.

In-field practices, such as conservation tillage, keep soil and nutrients in the crop field where they are resources rather than pollutants. On the other hand, when sediment and nutrients leave cropland and get trapped downslope in a vegeta-



Figure 2. Schematic illustration of several in-field and edge-of-field buffer types



tive filter strip, they are removed from the productive portion of the field and become unavailable to a crop (Dillaha and Hayes, 1992).

Some pesticides require incorporation by tillage to be effective, and the incorporation often reduces pesticide concentrations in runoff (Dabney et al., 2005). Soluble nitrogen and phosphorus often increase in runoff after passing through or across no-till fields, and vegetative buffers help remove those nutrients, keeping them out of streams.

For a vegetative filter strip to be effective, the flow into and through the filter must be shallow and uniformly distributed. Concentrated flow tends to inundate the vegetation and bend it over (Dillaha et al., 1986). Use of filter strips should be limited to topographic situations in fields with fairly uniform slopes and no preexisting drainage

patterns that concentrate flow. The grass must be erect and not submerged. Grass that is laid flat is vulnerable to inundation by sediment (Hayes and Hairston, 1983).

Vegetative filter strips perform differently than grassed waterways. A waterway is designed to remove water quickly in a channel without excessive soil erosion. A vegetative filter strip is designed to convey flowing water at a slow velocity so sediment and pollutants will deposit in the strip (Hayes and Dillaha, 1992). Most sediment is trapped by deposition rather than filtration (Dabney et al., 1994). Vegetation can slow concentrated flow, causing it to be temporarily ponded upslope and allowing time for sediment and other suspended pollutants to settle. Over time, vegetation will regrow after siltation; this tends to level

**Table 13. Conservation buffer effects on sediment transport.**

Type	Description	Impact	Location/soil	Reference
Filter strip	Bromegrass, 7% and 12% slopes, 18 m long	First 3 m removed 70% of sediment on 7% slope; 80% on 12% slope; First 9 m removed 85% of sediment	Iowa; silt loam	Robinson et al., 1996
Filter strip	Bluegrass sod, 0.6 to 4.5 m (2 to 15 feet) long	Each width reduced sediment by at least 90%	Indiana; silt loam	Neibling and Alberts, 1979
Filter strip	Simulated, CREAMS model, 2.4% slope	Sediment reduced 26 to 33%	Oklahoma	Williams and Nicks, 1988
Filter strip	Simulated, CREAMS model	Sediment reduced 10 to 80%; clay soils require a longer filter strip than sandy soils	29 states, 200 fields	Nicks et al., 1991
Filter strip	Simulated; along streams	Sediment reduced 41%	Iowa	Tim and Jolly, 1994
Contour buffer strips	Simulated, in field	Sediment reduced 47%	Iowa	Tim and Jolly, 1994
Filter strip and contour buffer	Simulated	Together, they reduced sediment by 71%	Iowa	Tim and Jolly, 1994
Riparian forest buffer	Vegetated riparian buffer between cultivated field and a stream	In 20 years, only 10 to 15% of sediment got through the buffer	North Carolina	Cooper et al., 1987
Filter strips	Pine, chaparral, and other tree species	Removed 95 to 99.5% of sediment	Arizona; mountains	Heede, 1990
Filter strips	Orchardgrass	Removed 60 to 80% of sediment	Virginia	Dillaha et al., 1989
Filter strips	Various slopes	Ineffective in hilly areas where concentrated flow resulted from natural drainageways	Virginia, 18 farms	Dillaha et al., 1989
Filter strips	Ky-31 fescue	Strips 4.5 m and 9 m long effectively removed sediment, not N or P	Maryland	Magette et al., 1989
Filter strips	Fescue on 1% and 15% slopes	Removed at least half of sediment	North Carolina	Parsons et al., 1994
Riparian forest buffer	Forest on 1% and 15% slopes	Effective on 1% slope; less effective on 15% slope because of channelization	North Carolina	Parsons et al., 1994
Filter strips	Smooth brome and Kentucky bluegrass	4.5-m strip removed 72% of sediment; 9-m strip removed 76%	Iowa	Mickelson and Baker, 1993



the topography, which will further improve the performance of the grass filter. Selection of appropriate vegetation for a filter strip is critical.

Vegetation helps control soil erosion by dissipating the energy in rainfall or runoff and by making the soil more stable (Dabney, 2003). When used in buffers on slopes, vegetation slows the flow of water running off cropland upslope and reduces or delays the development of rills and gullies, causing sediment to deposit within the vegetation. Tillage above a vegetative strip likely will create a small berm or terrace because the net effect of any tillage operation is soil movement downhill (Dabney, 2002). If this berm is off the contour, it may create a channel and greatly change runoff flow patterns by diverting water from parts or most of the vegetative strip.

The impact of buffer width on direction of flow is covered in several research reports cited below. Typically, the first foot of buffer provides much more benefit than the last foot. Several reports show that buffers less than 1 m (3 feet) wide can trap a great deal of sediment (Abujamin et al., 1985; Van Dijk et al., 1996; Rafaele et al., 1997; McGregor et al., 1999; Blanco-Canqui et al., 2004) because most of the sediment deposits upslope of the buffer itself (Dabney et al., 1995). Upslope trapping is enhanced if crop residues are washed up against the buffer (Jin et al., 2002). This backwater effect causes the first increment of a buffer to have a much larger impact than any subsequent increment; hence, narrow buffers can significantly improve water quality.

Vegetative filter strips were tested on Fayette silt loam soils in northeastern Iowa for removal of sediment from runoff on tilled soil with 7 and 12 percent slopes (Robinson et al., 1996). The source area was 18 m (60 feet), managed as continuous fallow; the brome grass filter strip was set up to collect samples at roughly 3 m (10 foot) intervals in the 18 m (60 foot) strip. The first 3 m (10 feet) of the strip removed more than 70 percent of the sediment on the 7 percent slope and 80 percent on the 12 percent slope; more than 85 percent of the sediment was removed in the first 9 m (30 feet) on both slopes. There was no change in effectiveness of sediment removal during the season, which featured 11 storms.

In Indiana, a study of vegetative filter strips was conducted on an eroded Miami silt loam (Neibling and Alberts, 1979). Sod strips of varying widths from 0.6 to 5 m (2 to 16 feet) each reduced total sediment by more than a factor of 10. The source area was 6 m (20 feet), freshly tilled before the test, which was conducted with a rainfall simulator applying 125 mm (5 inches) of rainfall over a 2-day period. The vegetative filter was commercially available bluegrass sod.

An Oklahoma field was used to simulate filter strip effectiveness. The CREAMS model predicted a 15 m (50 foot) filter strip would reduce soil loss 26 to 33 percent, depending upon the shape of a 2.4 percent slope (Williams and Nicks, 1988).

Another simulation of filter strip effectiveness using the CREAMS model estimated runoff and soil erosion on more than 200 fields in 29 states (Nicks et al., 1991). Reductions in sediment transport ranged from 10 to 80 percent. Filter strips proved more effective on concave slopes than on convex slopes. They also trapped more sediment on sandy soils, while longer strips were required to obtain similar results on clayey soils.

On northern Mississippi plots and watersheds, no-till in combination with grassed waterways and grass hedges to control concentrated flow controlled soil erosion (Meyer et al., 1999). Conservation tillage systems, including a vetch cover crop in winter, reduced winter and spring storm runoff and sediment transport to waterways and channels.

A modeling system using geographic information system (GIS) technology and a hydrologic/water quality model on a 400-ha (1,000-acre) watershed in southern Iowa demonstrated the value of combining conservation practices (Tim and Jolly, 1994). In a simulation, planting vegetative filter strips along streams reduced sediment leaving the watershed 41 percent. Separately, contour buffer strips provided a 47 percent reduction. When both vegetative filter strips and contour buffer strips were included, sediment yield declined 71 percent.

A North Carolina study demonstrated the value of riparian forest buffers. From 15 to 50 cm (6 to 20 inches) of sediment was deposited at the field-forest edge over a 20-year period as a result of water erosion on a cultivated field (Cooper et al., 1987). Sand was the dominant material deposited at the edge, while high silt and clay contents occurred farther downslope in the riparian area, between the field and stream. Estimates in the watershed study were that only 10 to 15 percent of the sediment that eroded from the cultivated fields left the watershed, meaning the riparian forest buffers served a valuable function.

In an Arizona mountain watershed, vegetative buffer strips acted as barriers to reduce soil movement (Heede, 1990). Ponderosa pine, pinyon-juniper, chaparral, willow, and cottonwood strips effectively caused eroded sediment to settle out and practically all overland flow to infiltrate in the strip. Depending upon the species and slope variables, vegetative buffers collected 95 to 99.5 percent of the sediment compared to slopes without buffers.

**When coupled with appropriate field treatments, including crop residue management, winter cover crops, nutrient management, and integrated pest management, buffer strips should enable farmers to achieve a measure of economic and environmental sustainability in their operations, and enhance wildlife habitat and protect biodiversity.**

Soil management

Water management / rain-fed

Water management / irrigated

Nutrient management

Pest management / noxious

Pest management / IPM

Landscape management

**Research shows the leading edge of buffers often performs a disproportionate share of denitrification function, and grass buffers can support as much denitrification as forested buffers**

Denitrification in both grassed and forested buffers was measured on well-drained silt loam and sandy loam soils in Rhode Island (Groffman et al., 1991). Those results suggest the ability of a vegetative buffer to remove nitrogen varies with soil type, pH, and available carbon. Denitrification in the forest soils increased as pH increased from about 3.5 to 5.5 and soil moisture increased from 20 to 90 percent. Availability of carbon likewise was important, suggesting that vegetative filter strips may remove nitrogen better from manure sources than from chemical fertilizers.

Research shows the leading edge of buffers often performs a disproportionate share of denitrification function, and grass buffers can support as much denitrification as forested buffers (Lowrance, 1992; Schnabel et al., 1996; Vershot et al., 1997; Addy et al., 1999; Lowrance et al., 2000). Where taking land out of crop production is an important economic issue, narrow buffers could be attractive and effective for some purposes.

Vegetative filter strips were researched with regard to their effectiveness in retaining constituents in surface-applied swine manure (Chaubey et al., 1994) and poultry litter (Chaubey et al., 1995) on Captina silt loam in Arkansas. The animal waste products were applied at the top of a 3 percent slope with fescue vegetation. Simulated rainfall was used to cause runoff that was collected at various distances from 3 to 21 m (10 to 70 feet) downslope. For the poultry litter experiment, the filter strips removed about 40 percent of ammoniacal nitrogen and phosphorus in the first 3 m (10 feet) and 90 percent after 21 m (70 feet). For swine manure, the comparable numbers were about 65 percent and 95 percent. The filter strips removed only half of total suspended solids and chemical oxygen demand (COD) with either animal waste product; almost all of that removal occurred in the first 3 m (10 feet). The filter strips did not reduce nitrate-nitrogen or fecal coliform at all.

Atrazine loss was reduced 65 to 90 percent in Pennsylvania research where oats were planted in a contour strip below a conventionally tilled cornfield on a 14 percent slope (Hall et al., 1983). During 11 erosion events (including a 100-year storm as a result of Hurricane Agnes), the small grain buffer strip intercepted 66 percent of the runoff water and 76 percent of the sediment. Where atrazine was applied on the rototilled surface at 2.2 kg ha<sup>-1</sup> (2 pounds per acre), losses of the chemical totaled 3.3 percent of the applied amount at the edge of the cornfield and 0.33 percent after passing through the oat strip, a 90 percent reduction with stripcropping. By comparison, at a higher rate of 4.5 kg ha<sup>-1</sup> (4 pounds per acre), the oat strip reduced atrazine runoff 65 percent.

In Virginia, vegetative filter strips were analyzed for removing sediment, nitrogen, and phosphorus (Dillaha et al., 1989). The ratio of drainage area to buffer area was low at 2:1 and 4:1. Rainfall simulation on freshly tilled ground soon after fertilizer was applied and disked in constituted an extreme precipitation event, greater than a 100-year-return storm. Orchardgrass strips effectively removed 60 to 80 percent of the sediment and attached nutrients. The soluble inorganic nitrogen and phosphorus in the effluent leaving the strips, however, were sufficient to cause eutrophication. These same researchers also visited 18 farms with vegetative filter strips. In hilly areas, the filter strips were judged to be ineffective generally because natural drainageways in the fields above the filter caused concentrated flow. In flatter areas, slopes were more uniform and runoff was more likely to enter the filter as shallow, uniform flow.

In Maryland, vegetative filter strips effectively removed sediment, but were unreliable for removing nitrogen and phosphorus (Margette et al., 1989). Source areas were 22 m (72 feet) long, and Kentucky-31 fescue filter strips were 4.6 and 9.2 m (15 and 30 feet) wide. In the study with simulated rainfall, the filter strips appeared to be less effective over time and with more runoff events. The wider filter strips proved more effective.

A physically based, one- and two-dimensional simulation model was used to compare grass buffer strips to terraces for reducing runoff and sediment transport (Hong and Mostaghimi, 1995). For the conditions chosen, the conservation practices were equally effective (50 percent reduction for terraces, 55 percent for filter strips).

In a North Carolina study, grass buffers and riparian forest buffers were compared at two sites (Parsons et al., 1994). Drainage-area-to-fescue-buffer-area ratios were approximately 4:1 and 9:1. Slopes at the Coastal Plain site were about 1 percent, but on the Piedmont site, the slope of the cropped land and grass filter were about 5 percent and the slope of the riparian buffer was 15 percent. Data from more than 40 storms at each site showed that at least 50 percent of the sediment was removed by the wider grass filter in every storm, and by the narrower filter in most storms. The forested riparian buffer reduced sediment yield at the Piedmont site, but less consistently, partly because of channelization on the steep slope. Infiltration played a major role in the riparian buffers. Even the poorly vegetated cover at the Coastal Plain site usually removed at least 50 percent of the sediment, nitrogen and phosphorus. The fescue buffers typically removed more than half of nitrogen and phosphorus.

In Iowa, researchers compared no-till to conventional tillage with grass filter strips for

removing sediment and atrazine (Mickelson and Baker, 1993). The filter strips consisted mainly of smooth brome and Kentucky bluegrass. Using a rainfall simulator and an inflow of artificial runoff (with sediment mixed in to simulate conventional tillage), the 4.6-m (15-foot) filter strip removed 72 percent of the sediment and 28 percent of the atrazine. The 9.1-m (30-foot) strips removed 76 percent of sediment and 51 percent of atrazine. The narrower strip represented a 10:1 ratio of crop area to filter area, and the wider strip represented a 5:1 ratio. For no-till (no sediment), the narrower filter strip removed 35 percent of the atrazine, and the wider strip removed 60 percent. Wider filter strips greatly increased the effectiveness of removing atrazine, and the effectiveness was slightly increased in the absence of sediment. For sediment removal, doubling the width had little effect.

Herbicide retention in vegetative buffer strips was measured over a 2-year period in Iowa (Arona et al., 1995). A source area was disked and planted to corn each year, with three herbicides applied. Established brome grass strips provided two drainage/buffer area treatments: 15:1 and 30:1. For the observed storm events, the narrower buffer strips did just as well as the wider ones. Retention varied by storm, and in some storms, 100 percent of the herbicides were removed from the runoff. The lowest retentions recorded were as follows: 8 percent for cyanazine, 11 percent for atrazine, and 16 percent for metolachlor. Infiltration was the key factor in removal, and sediment deposition accounted for only 5 percent of chemical removed from runoff. In another Iowa study on silt loam, reductions of the same three chemicals were 38 to 44 percent for the wider filter strip (15:1 ratio) and 33 to 37 percent for the narrower filter strip (Misra et al, 1994).

Trifluralin was effectively removed from runoff by a filter strip of bermudagrass and bahiagrass on Cowarts loamy sand in Georgia (Rohde et al, 1980). With simulated rainfall of 19 cm (7.5 inches) per hour, 86 percent of the trifluralin was removed, with 29 percent attributed to infiltration, in the 24-m (80-foot) wide filter strip.

At Amana, Iowa, a vegetative buffer of deep-rooted poplar trees was compared to corn on the effectiveness of removing nitrate-nitrogen from soil water (Paterson and Schnoor, 1993). In late September, there was a surge in nitrate concentrations in soil samples, most likely as a result of decaying plant material at the end of the growing season. The increase was greater in the corn plot than in the poplar plot. More than 26 percent of the nitrate percolated to shallow ground water with corn, 17 percent with poplar trees. The study demonstrates the value of poplar trees as

a vegetative filter strip. Although unstated, this study showed a potential benefit for a cover crop following corn to remove leftover nitrogen and mineralized nitrogen.

In Minnesota, vegetative filter strips were studied for controlling pollution from feedlots (Young et al, 1980). Although cropland was not involved, the results are applicable here. The vegetative strips were crops of oats and sorghum grown on a 4 percent slope. At 36 m (120 feet) in width, the strips removed 67 percent of runoff and 79 percent of total solids transported from the feedlot. Both nitrogen and phosphorus declined about 84 percent.

In Illinois, vegetative filters installed on feedlots were used to compare overland flow to channelized flow for removing nutrients (Dickey and Vanderholm, 1981). After settling for partial solids removal (an essential step for the prolonged life and effectiveness of the filter strip), runoff was applied directly to the filters. The filters removed as much as 90 percent of nutrients. Channelized flow required much greater lengths for similar effectiveness. Bacteria levels were not greatly reduced.

Cropland in the United States is identified as a major nonpoint source of water pollutants that include sediment, nutrients, and pathogenic microbes (USEPA, 2000). Table 14 lists recent research on the water quality impacts of vegetative strips. Field borders and vegetative filter strips have several identical purposes, so both are included in this comparison.

An economic analysis of vegetative buffers to reduce sediment was performed on a central Indiana watershed (Pritchard et al, 1993). Results showed that protecting all ephemeral and perennial streams with buffers could reduce sediment loading by 27 percent. By comparison, the authors found that converting all cropland in the watershed to grass would reduce sediment by 60 percent. (They did not report on the potential effect of no-till crop production.) Microtargeting to remove the most highly erodible spots, which was 11 percent of cropland, from production would reduce sediment loading 31 percent, about the same as the filter strips. The estimated cost per Mg of sediment abated, \$100 per Mg (\$91 per ton), was 17 percent higher for filter strips, but would likely be more cost effective overall considering the higher administrative and enforcement costs of the microtargeting program.

A practice similar in function to field borders in irrigated production systems is permanent cover or close-growing crops along the lower ends of surface-irrigated fields to slow flow velocity of furrow streams; this allows transported sediments to settle out before reaching a conveyance ditch



Vegetative filter strips are most effective when there is uniform sheet flow from the field into the buffer.

**Table 14. Effect of vegetative buffer strips on water quality.**

Effect	Impact	Reference
Nutrients	A 6-m buffer reduced total runoff, nitrogen, and phosphorus by 78%, 74%, and 80%, respectively; soluble N and P forms unaffected	Borin et al., 2005
	Narrow grass hedges (strips) reduced nitrogen and phosphorus losses in runoff from both manure and fertilizer applications	Eghball et al., 2000
	Vegetative filter strips did not remove iron, potassium, sodium, nickel, and zinc in runoff from poultry litter, but copper was removed as strip width increased	Edwards et al., 1997
	Grass filter strips reduced copper by infiltration and soil retention	Wu et al., 2003a
	Vegetative filter strips removed 79%, 73%, and 73% of the solids, total phosphorus, and total nitrogen in runoff, respectively, while soluble nutrients were the same or increased	Dillaha et al., 1989
	Vegetative buffer strips reduced feedlot runoff by 67%, total solids by 79%, and total nitrogen and phosphorus by 84%, while nitrates increased.	Young et al., 1980
	Grass filter strips reduced sediment by 50%, total nitrogen by 20%, and total phosphorus by 50%; during relatively small storm events, 20% of soluble phosphorus was retained	Daniels and Gilliam, 1996
	Most nitrate attenuation was by vegetative uptake, while ammonium and dissolved organic nitrogen declined as much as 48%	Bedard-Haughn et al., 2004
	Nutrient trapping efficiency of buffers was inversely related to storm intensity and total rainfall	Lee et al., 2003
	The leading edge of buffers removes a disproportionate share of nitrogen from runoff; grass buffers are equal to forested buffers	several references
	Uptake and leaching were dominant processes for nitrogen removal in surface flow, while denitrification was in subsurface flow	Verchot et al., 1997a; 1997b
	Fescue filter removed 40% of ammonia-nitrogen and phosphorus from poultry manure in the first 3 m (10 feet) and 90% after 21 m (68 feet); for swine, the comparable numbers were 65% and 95%.	Chaubey et al., 1994 Chaubey et al., 1995
	Deep-rooted poplar trees removed excess nitrate before it reached ground water more effectively than did corn plants	Paterson and Schnoor, 1993
Microbes	99.9% of <i>C. parvum</i> removed by 10-ft (3 m) strips	Atwill et al., 2002
	Vegetative strips reduced coliform populations in simulated feedlot runoff	Young et al., 1980
	Grass filter strips trapped 43 to 73% of fecal coliform, mainly by runoff infiltration	Coyne et al., 1995
	Total and fecal coliform populations did not decline in surface runoff across grass or forest filter strips, but decreased in soil water with distance	Entry et al., 2000
Herbicides	Retention ranged from 8 to 100%, and strongly adsorbed herbicides were completely retained	Arora et al., 1996
	Inflow infiltration in vegetative strip was the dominant mechanism for atrazine retention	Mickelson et al., 2003
	4.5-m brome and bluegrass strip removed 28% of atrazine; 9-m strip removed 51%	Mickelson and Baker, 1993
	Retention and degradation removes metolachlor as it passes through a vegetative buffer strip	Staddon et al., 2001
	Doubling filter strip width doubled the reductions due to infiltration and dilution, but not from sedimentation	Schmitt et al., 1999
	24-m grass strip on loamy sand removed 86% of trifluralin	Rohde et al., 1980
	Oats planted in a contour strip removed 65 to 90% of atrazine eroding from a corn field on 14% slope	Hall et al., 1983



that removes water from the field. There generally is a 45 to 70 percent reduction in sediment load in the runoff and accompanying nutrients; however, soluble nutrients are not appreciably affected (Anon, 1991; Brockway, 1997; Carter, 1985; Robison and Brockway, 1980). The strips are 3.6 to 6.1 m (12 to 20 feet) wide and can be seeded to perennial, biennial, or annual crops that provide a dense plant cover. The strips must be established before the start of irrigation to be effective. Typically, they are cereal crops across the lower ends of furrow-irrigated fields, although alfalfa or grass strips are sometimes grown. The latter can be left alive to provide effective filter strips. Annual grasses also can be allowed to grow in these areas, but producers must compensate for potential increased weed problems. These strips are a relatively easy conservation practice to use. An economic return may be possible if the strip is harvested; however, yields in the strip will probably be lower than in the field. Vegetative strips may or may not partially control weeds along the lower end of the field. It may be harder to control weeds because tillage would damage the strip; herbicides, of course, can kill the desired vegetation.

A disadvantage of filter strips is that they remove a portion of the field from normal crop production. In addition, once sediment builds up in the strip, runoff water will not flow into the normal tailwater ditch and may cut across furrows prior to the strip causing serious soil erosion. Once a strip reaches this condition, it will have to be taken out to reestablish the tailwater ditch, the soil lowered, and strip reestablished. Lowering the strip area requires additional financial resources for soil removal and transportation costs. As with the field borders, these filter strips can be enhanced if other practices are implemented that reduce irrigation-induced soil erosion on the field. The vegetative strips are not effective on soil slopes greater than 3 percent or on the end of fields with a large elevation drop between the field or end of furrow and the tailwater ditch, sometimes referred to as convex-shaped ends (Carter et al., 1993).

Narrow rows of grass hedges have proved effective in controlling wind and water erosion internationally (Kemper et al., 1992). Narrow rows (only a few inches wide when planted) of stiff, erect, densely tillered grass, such as vetiver, planted in parallel lines across the dominant slope inhibit the flow of water through the rows (Dabney et al., 1999; Dabney, 2002). Over time, sediment settles out, creating a series of benched terraces. In one Louisiana experiment, vetiver grass planted across an ephemeral gully flourished and in the first year accumulated more than 18 inches

of sediment upstream of the hedge (Kemper et al., 1992). Vegetation growing in fencerows has proven effective in accumulating sediment, either from wind erosion or where a waterway crosses a fence line. In no-till fields, intense rainfall can sometimes result in runoff that concentrates and causes gullies. Grass hedges planted across these gullies can cause sedimentation and smooth out the no-till field. In Texas, hedges of Alamo switchgrass, which have grown several feet tall, can protect crops, such as cotton, from wind erosion in sandy soils.

Flume studies using stiff-grass hedges grown in root boxes demonstrated that hedges planted in locations of concentrated overland flow can pond water up to 0.4 m (15 inches) deep; as a result, about 90 percent of sediment coarser than 125  $\mu\text{m}$  was caught (Meyer et al., 1994). Vetiver and switchgrass were more effective than tall fescue because they caused more ponding. There was little benefit from filtering action as the water flowed through the grasses.

**Soil quality effects.** Many factors influence the movement of carbon dioxide ( $\text{CO}_2$ ) in and out of the soil. Such factors as soil moisture and temperature, soil organic matter, and roots affect soil respiration. Jarecki and Lal (2003) reviewed several studies showing that soil organic matter increased when permanent vegetation was established on untilled soils. Higher soil respiration rates were recorded in buffer strips than in adjacent corn and soybean fields (Tufekcioglu et al., 2001). The higher rates were significantly and positively correlated with soil organic carbon content, greater fine root biomass, and higher soil moisture. This also showed that soil biological activity was greater in the buffer strip and suggests greater biological diversity than in the soil of the cornfield.

Alley cropping in the southern United States typically includes rows of trees, such as pecan or pine, combined with crops, such as cotton, peanut, corn, soybeans, oats, or pasture. The crops provide annual income while trees are growing. As the trees mature, they provide an environmental benefit by capturing fertilizer nutrients from deeper in the soil, reducing potential groundwater contamination, and recycling the nutrients to the soil surface in falling leaves. But tree roots can compete with the alley crop for nutrients and water (Wanvestraut et al., 2004), and aboveground competition for light reduces crop yields, especially in temperate climates.

In northwestern Florida, cotton was planted in a mature pecan orchard to study the effect of tree roots on nitrogen uptake by the crop (Allen et al., 2004a). Trees in rows spaced 18.3 m (60 feet)

**Alley cropping with leguminous shrubs can satisfy crop requirements for nitrogen, but long-range soil quality improvements may rely more on the soil's ability to sequester carbon.**

apart caused the cotton rows closest to the trees to grow much less than the middle rows (although the seed cotton yield was equal). Where a plastic barrier was placed from the surface to a depth of 1.2 m (4 feet), to separate tree roots from cotton, the seed cotton yield increased almost 60 percent. Cotton protected from tree roots accumulated 67 percent more nitrogen than cotton competing with tree roots. Tree roots appeared to remove nitrogen from leachate deeper in the soil (Allen et al., 2004b). Cumulative amounts of nitrate leached during the 15-month study period were 64 and 13 kg per hectare (57 and 12 pounds per acre) for the 0.3- and 0.9-m (1- and 3-foot) depths, respectively, in the non-barrier treatment. In the barrier treatment, which kept tree roots from affecting the cotton, the equivalent leached nitrate amounts were 122 and 45 kg ha<sup>-1</sup> (109 and 40 pounds per acre). Tree water uptake, in addition to cotton water uptake, probably reduced water drainage, which also tended to reduce leaching rates.

As part of the same research project, Lee and Jose (2003) measured organic carbon at 3.7 percent in a part of the old pecan orchard with undisturbed sod, compared to 2.2 percent after 3 years of alley cropping cotton with conventional tillage. By comparison, land planted to "new" pecan trees, with or without cotton in the alleys, measured only 1.2 percent organic carbon as a result of annual tillage.

Alley cropping (agroforestry) offers potential to help manage nutrient buildup in soil caused by high levels of chemical fertilizer or animal manure application (Nair and Graetz, 2004). Tree roots can intercept nutrients that escape deeper than agronomic crop roots usually reach. In Florida, results indicate less fertilizer phosphorus was lost from the soil profile with alley cropping compared to conventional cropping.

In Georgia, alley cropping with mimosa hedgerows and no-till grain sorghum with winter wheat as a cover crop was grown for 3 years on a highly weathered Ultisol (Rhoades et al., 1998). The leguminous mimosa (*Albizia julibrissin*) hedgerows, spaced 4 m (13 feet), were pruned the same day as sorghum planting, with leaves and small branches applied as mulch. Mimosa leaf mass decomposes and releases nitrogen rapidly after pruning, losing about a third of its nitrogen in the first month. The prunings contributed about 100 kg ha<sup>-1</sup> (90 pounds per acre) of nitrogen to the alley cropping plots.

Alley cropping with leguminous shrubs can satisfy crop requirements for nitrogen, but long-range soil quality improvements may rely more on the soil's ability to sequester carbon. Based on the Georgia experience, alley cropping with leguminous hedgerows may be a way for organic

farmers to meet the nutrient needs of the main economic crop (Jordan, 2004). The dry weight of prunings in the aforementioned Georgia project was 18.4 Mg ha<sup>-1</sup> (8.2 tons per acre) per year, an amount adequate to maintain crop yields without hauling manure, mulches, or other organic material to the field.

Alley cropping with rows of black walnut or other trees for timber planted on the contour and agricultural crops in between was researched on marginal farmland in northern and southern Illinois (Campbell et al., 1991). Rows spaced 12.2 m (40 feet) apart, in the center of a 3-m (10-foot) wide vegetative buffer, such as crown vetch, provides a 9.2-m (30-foot) wide strip for grain, alfalfa, or other crops that produce a yearly income. Typically, continuous no-till corn provided the highest economic return for the first 6 to 10 years and experienced the least soil erosion. Black walnut performed better on better soils; red oak was more economical on poorer soils. As trees mature, cropland likely would transition from grain production to hay, then pasture. The possible economic return from nuts was not included.

In an Indiana alley cropping experiment with black walnut and red oak, tree roots took up soil nitrogen and water before the corn was planted (Jose et al., 2000). Despite applying 170 kg ha<sup>-1</sup> (150 pounds per acre) of nitrogen on the corn crop, there was lower nitrogen-use efficiency where the corn had competition from tree roots, compared to treatments where a plastic barrier prevented competition. There also was lower soil moisture and reduced water uptake for corn growing in the "no-barrier" treatment.

An economic analysis of alley cropping with hardwood trees in buffer strips and various crop rotations showed that on highly erodible land, with low value and low crop yields, contour buffer strips with trees represent an economically feasible conservation practice in Iowa (Countryman and Morrow, 2000). Tree plantations provide the best long-term economic return on low-value land if annual cash flow is not needed. Because buffer strips with ash, oak, or walnut trees require 40 to 80 years to produce any substantial income, the landowner is dependent upon row crops for annual income. Unlike many other conservation practices, however, the tree strips represent future revenue. Contour buffer strips with trees improve water quality and provide wildlife habitat.

In northeastern Missouri, contour buffer strips, with and without trees, were installed on two watersheds where no-till corn and soybeans were grown. A third watershed served as a control. The agroforestry treatment (newly planted oak in contour grass-legume strips of redbud, brome, and

birdsfoot trefoil) reduced runoff by only 1 percent after 3 years compared to the control (Udawatta et al. 2002). In an adjacent watershed, similar grass-legume strips reduced runoff 10 percent. Total phosphorus losses declined 17 percent and 8 percent, respectively. Total sediment losses during the 3-year experiment for the control, agroforestry, and contour-strip watersheds were extremely low: 200, 264 and 242 kg ha<sup>-1</sup> (180, 235, and 215 pounds per acre), respectively. Total nitrogen losses averaged only about 2 kg ha<sup>-1</sup> (about 2 pounds per acre) per year for all watersheds. Similar to many other erosion research projects, a few extreme precipitation events accounted for most sediment and nutrient losses.

A small experiment on a rocky slope on the Island of Hawaii demonstrated the potential for using a hedgerow of nitrogen-fixing trees planted in alleys between rows of fruit trees (Elevitch et al. 1998). Prunings from the hedgerows were spread carefully in a circle around each jackfruit tree. The mulch contributed the equivalent of about 5 kg (11 pounds) of urea and 1.5 kg (3.3 pounds) of muriate of potash per tree.

Permanent field borders offer other potential benefits. These include carbon sequestration, wildlife protection and corridors, and harbors for beneficial and/or harmful plant diseases and insects. In a field study of the effect of field borders on overwintering sparrow densities in the southeastern Coastal Plain, there were more sparrows on farms with field borders than on farms with mowed field edges (Marcus et al., 2000). Seven different sparrow species were identified in the field borders, compared to only three species in the mowed field edges. The greater numbers and diversity occurred primarily because the field borders provided additional food and cover during the winter months. Because field borders also can function as corridors between wildlife habitats, they have the potential to enhance population viability and diversity for many species (Henry et al., 1999).

Ecological theory predicts that complex plant communities should support a richer community of natural enemies of plant pest insects than a simple plant community. A study of ground beetle (Coleoptera: Carabidae) populations in hedges or grass edges surrounding corn fields showed that these borders supported abundant and diverse populations of carabids during most of the growing season (Varchola and Dunn, 2001). Ground beetles are predators of herbivore pests, for example, armyworms (Lepidoptera: Noctuidae).

**Water conservation effects.** In-field buffers and related practices have little positive effect on water conservation. They tend to pond runoff, or

at least slow it down so it infiltrates more so than otherwise. This water conservation occurs more in the buffer than in the crop field itself. Alley cropping conserves water except when trees are planted; trees usually take water away from the field crop rather than conserving water for crop use.

**Air quality effects.** In-field and edge-of-field buffers can, incidentally, improve air quality by reducing wind velocities in the immediate vicinity of the buffer. For more information, see the section on wind erosion control practices.

#### *Factors driving environmental outcomes.*

Among the key factors driving the environmental effects of in-field and edge-of-field buffers are the following: economics, ease of vegetation establishment and management of the conservation practice, how effective a practice is in improving the environment, effect on normal farming operations, and farm landscape aesthetics.

Contour stripcropping often is a more economical practice than other vegetative buffers because it involves a crop to be harvested. No land is taken out of production.

In the Palouse region of the Pacific Northwest, the number of farms using contour stripcropping and divided slopes has increased because farmers see the long-term value in protecting and improving soil resources, despite the difficulty of farming this variable landscape (Jennings et al. 1990).

In Maryland, economists surveyed 547 farmers in 1995 to determine adoption patterns of several conservation practices (Lichtenberg and Strand, 2000). Farmers were asked whether they used any of 11 different conservation practices: critical-area planting, filter strips, contour farming, stripcropping, cover crops, minimum or no tillage, grade stabilization, grassed waterways, rock-lined waterways, terraces, diversions, ponds, and sediment troughs. The State of Maryland reimburses farmers up to 87.5 percent of the cost of approved practices. Using multiple practices is common in the state. Three-fourths of farmers in the survey used at least one practice, and the median number of practices used per farm was four. Results showed that critical-area seeding, cover crops, and grassed waterways are used as a system of complementary practices. Cover crops are mainly used on farms with livestock, and often those cover crops are harvested for hay or grazed. Stripcropping and contour farming were most prevalent among farmers with crops and livestock. Stripcropping was most often a hay crop alternated with soybeans. Stripcropping and terraces were frequently used in combination on steep slopes, but on moderate slopes, stripcrop-

**Variable-width filter strips or riparian forest buffers can be designed using global positioning system and geographic information system technologies to determine the buffer width required to handle the drainage area for each segment of a field.**

ping alone was the choice. Use of diversions was unrelated to other practices.

Of federal cost-sharing expenditures in Maryland, almost half was spent on grassed waterways and critical areas over the 10 years prior to the survey. Cover crops were not eligible for federal funding. The economic analysis suggests that providing funds for cover crops would reduce the need for more expensive technologies, such as waterways, and provide more soil erosion control at lower overall cost. The authors did not address the issue of no-till as a practice that could, seemingly, also reduce the need for other practices.

In real-world situations, concentrated flow or channelization often occurs on sloping crop fields. To be most effective, filter strips must have runoff flowing into the strip uniformly along the upslope edge. Field runoff is commonly non-uniform, however, because of uneven topography (Dosskey et al., 2005). Variable-width filter strips or riparian forest buffers can be designed using global positioning system and geographic information system technologies to determine the buffer width required to handle the drainage area for each segment of a field. Other practices are available to protect those areas of concentrated flow, including grassed waterways and vegetative barriers.

The ratio of crop area to filter area varies widely, with most cited research conducted on plots with ratios of 4:1 to 10:1. In practice, the relative width of a field buffer will be much less. A ratio of 50:1 is not unusual. Because the first few feet of a buffer provide most of the environmental value, buffers are effective only if concentrated flow is avoided.

**Adequacy of scientific documentation.** This group of buffer practices represents a fairly diverse range of methods for controlling water erosion. Vegetative filter strips, which appear to have been well researched, help keep eroded soil in the field, but they do not keep soil particles from moving within a field. Buffer vegetation can improve water quality by sequestering and transforming nutrients, pesticides, and pathogens, regardless of tillage system. Gullies must be controlled where runoff cannot be managed. The cost-effectiveness of buffers in terms of dollars per ton of sediment trapped is reduced when buffers are combined with a good no-till system because the amount of sediment available to be trapped is reduced while the cost of the buffer is nearly the same (Yuan et al., 2002) and only maintenance costs are reduced.

Historically, various conservation practices, such as terraces, were combined with vegetative buffers to allow "conventional tillage" to

continue. Conservation tillage systems were not yet perfected or economical. As no-till and other conservation tillage systems become more successful, the relative need for some conservation practices could potentially decrease. At the same time, combining continuous no-till with one or more buffers, or other conservation practices, can create a conservation system that effectively improves soil and water quality, especially where concentrated flow is a risk.

General performance data suggests that field borders improve water quality by (1) removing a large portion of the transported sediment that enters the buffer from an adjacent cultivated field, (2) removing a slightly smaller portion of sediment-associated nutrients and other chemicals, and (3) reducing dissolved materials in general proportion to the amount infiltrated. The concentration of some soluble materials can increase. Field borders may improve farm aesthetics, function as habitat for wildlife and beneficial insects, and sequester carbon if they are left in permanent vegetation. Producers also may turn farm equipment on these areas and use the areas for forage production.

An economic study is needed on the feasibility of installing field borders versus cropping a field from fencerow to fencerow with conventional or no-till systems. A 6-m-wide (20-foot-wide) field border around an 8-ha (20-acre) square field would remove 8 to 10 percent of the land in the field from crop production. In addition, there are some costs associated with installation and maintenance of field borders. Crop yields often are lower on field edges adjoining woodlands, so the economic burden of using this conservation practice may be lessened. In addition, field borders might be harvested for forage and could even provide some income if used for contract or fee hunting.

Most research studies on the use of vegetative buffers to improve water quality were conducted on runoff from small plots and/or individual fields. Few studies evaluated the potential interaction of internal field conservation practices with field-edge practices. Neither do there appear to be any studies evaluating the placement or numbers of these practices in a watershed, although some modeling effort is underway (Verstraeten et al., 2002). Especially lacking is information that relates the change in pollutant loads to lakes, rivers, and streams with the installation of some of these conservation buffers (Dosskey, 2001). Data shows that placement is a critical factor in determining their benefits (Norris, 1993). Perhaps the research effort and management may both be facilitated when more accurate watershed models become available (Ducros and Joyce, 2003).



Precision conservation technology can provide information needed to vary the width of buffers between cropland and streams to account for the natural non-uniformity of runoff flow from non-uniform slopes (Dosskey et al., 2005). This global-positioning-system- and geographic-information-system-based technology should lead to more effective application of previous research to farm fields.

## Wind erosion control practices

During the last half of the nineteenth century and in the 1930s, the U.S. Great Plains experienced immense dust storms and extensive soil destruction as a result of wind erosion. More recently, soil erosion on all cropland declined over the period from 1982 to 1997 at the rate of 670 kg ha<sup>-1</sup> (600 pounds per acre) per year because of the widespread adoption of conservation practices (Lal et al., 2003). Wind erosion physically detaches and transports soil particles from a field. Usually, the most fertile portion of the soil is lost. The airborne dust obscures visibility, imperils animal and human health, fills road ditches, reduces seedling survival and growth, and contributes to several other plant-related production problems. PM10-sized particulates in agricultural areas are primarily fugitive soil dust particles (Pye, 1987; Kjølgaard et al., 2004).

The general relationship between the potential average soil loss from wind erosion is dependent upon soil erodibility (the susceptibility or ease of detachment and transport by wind), soil roughness (adjustment for wind flow at surface), climate (adjustment for soil moisture and wind speed), median travel distance of wind across a field (accumulative effect dependent upon wind speed and soil erodibility), and vegetative cover (Chepil and Woodruff, 1986; Woodruff and Siddoway, 1965; Skidmore, 1988). These variables initially were captured in the wind erosion equation (Woodruff and Siddoway, 1965). More recently, Agricultural Research Service scientists developed a computer-based model—WEPS, Wind Erosion Prediction System—to predict wind erosion (Nanney et al., 1993); this model captures the dynamic nature of the wind erosion process by including submodels for crops, soils, tillage, weather, hydrology, and residue decomposition.

Management options to control wind erosion include increasing soil surface roughness; increasing the amount of crop residue left on the soil surface; stabilizing the soil surface with additives; and using barriers, windbreaks, or stripcropping to reduce the wind's length of travel across a field (Chepil and Woodruff, 1986; Skid-

more, 1986; Skidmore, 1988). Wetting the soil surface, whether from rainfall or irrigation, also will control wind erosion so long as the surface remains wet.

Among the common conservation practices used to control wind erosion are herbaceous wind barriers (practice code 603), surface roughing (practice code 609), and windbreak/shelterbelt establishment (practice code 380). Windbreak/shelterbelt renovation (practice code 650) here is considered concurrently with the establishment conservation standard.

**Herbaceous wind barriers.** Herbaceous wind barriers are narrow strips or rows of vegetation established in a field perpendicular to the prevailing wind direction. These barriers may use perennial or annual vegetation, growing or dead. They do not use trees or shrubs. Artificial barriers, such as snowfences, wood or stone walls, or earthen banks may be used for wind erosion control on a limited scale. Herbaceous wind barriers can consist of a single row of plants, provided the row contains no gaps. Multiple rows are sometimes necessary to avoid gaps. Row spacing depends upon the deviation from perpendicular to the prevailing wind erosion direction and the height and density of the vegetation. In general, spacing of herbaceous wind barriers should not exceed 10 times the expected height of the barrier, plus any additional width permitted by the soil loss tolerance or other planned soil loss objective. Specific design information can be found in the NRCS National Agronomy Manual (USDA, 2002).

In addition to protection against wind erosion, herbaceous wind barriers protect crops from damage by wind-borne soil particles; trap snow, which increases soil moisture; and provide cover and food for wildlife. A variety of plants have been used in herbaceous wind barriers.

Plants in herbaceous wind barriers must remain upright for maximum protection. At least 30 to 60 percent of the surface area by flat cover is needed to control wind erosion adequately, while 5 percent of standing residue proved effective (Hagen, 1996). Tall annual plants that have been evaluated for barriers include maize (Geiszler, 1961; Kirkland and Keys, 1981), sorghum (Greg, 1980), and sunflowers (Hoag and Geiszler, 1971). These crops are sown in the spring and sometimes harvested for grain. Summer-seeded annual barriers include cereals, mustard, and flax. A perennial frequently used in barriers is tall wheatgrass.

Table 15 includes selected references for vegetative barriers. Barriers must be planted early enough to achieve sufficient height before killing

**...herbaceous wind barriers protect crops from damage by wind-borne soil particles; trap snow, which increases soil moisture; and provide cover and food for wildlife.**

**Table 15. Effect of herbaceous barriers on wind erosion, microclimate, and crop yields.**

Barrier	Effect	Reference
Flax or Mustard	Increased soil moisture; N removed by barrier reduced wheat yields	McConkey & Dyck, 1996.
Wheatgrass	Controlled wind erosion; Nearly doubled soil moisture, allowed annual cropping with N and P additions; annual cropping improved soil physical and chemical properties	Black & Siddoway, 1976.
Wheatgrass	Controlled wind erosion; increased wheat yields, higher early season soil temperatures	Aase & Siddoway, 1974.
Wheatgrass	Surface 4 cm soil remained wetter for 3 days within barrier after precipitation event	Aase & Siddoway, 1976.
Wheatgrass	Reduced potential yearly wind erosion 93%	Aase et al., 1985.
Wheatgrass	Reduced wind erosion; increased wheat yields from increased snow trapping	Aase et al., 1976.
Wheatgrass	Reduced potential wind erosion 93%; increase early soil temperatures; reduced soil drying rate following rainfall; increased winter wheat yields; increased probability of successful annual cropping 23% over an 18 year period	Black and Aase, 1988.
Simulated effect	Wind forces reduced more than wind speed; most effective when perpendicular to wind	Skidmore & Hagen, 1977.
Simulated effect	Stressed importance of low porosity and allows evaluation of barriers with an angular top boundary	Borrelli et al., 1989.
Simulated effect	Improved model permits the design of wind barrier system tailored to specific conditions	Fryrear et al., 2000.
Wheatgrass	Allows annual cropping, which increased total grain production 37-102%	Black & Siddoway, 1975.
Sorghum, millet, grains, grasses, or shrubs	Maximum effectiveness is perpendicular to erosive wind in conservation systems	Bilbro et al., 1987.
Sorghums, kenaf, switchgrass, or slat-fence comparisons	Switchgrass control was long lasting, while lodging resistant forage or sorghum was effective annual windbarrier	Bilbro and Fryrear, 1997.

frost. In addition, stem strength should prevent lodging during winter months so protection is present the following spring or when erosive wind conditions occur. Some barriers remove sufficient nitrogen to reduce crop yields near the barrier, but this is easily corrected with the addition of nitrogen fertilizer. Barriers also remove land from production, and perennial barriers must be maintained to be effective. Crop yields must increase sufficiently to offset the losses when barriers are used. Economic data from Black and Siddoway (1976) suggest that a combination of annual cropping and yield changes can more than compensate for land removal. The extra plant materials produced contributed to increased soil chemical properties and improved soil quality. The extra water stored between the barriers as a result of snow trapping can contribute to saline seep problems if not used by the sequence of crops. Barriers also can provide cover and feed for wildlife and protection for insects and diseases harmful to crops. In addition, barriers can reduce water erosion if surface runoff volume and

velocity are reduced (Dabney, 2003).

Herbaceous wind barriers protect soil from wind erosion and improve soil moisture and soil quality. Data also suggest that installation costs can be recovered by converting to annual crops to capture the extra stored water from snowmelt. While this practice may still have specific applications, it is being replaced by tillage and residue management practices that leave crop residues on the soil surface for protection against wind erosion.

#### **Windbreak and shelterbelt establishment.**

Windbreak and shelterbelt establishment involve the planting of single or multiple rows of trees or shrubs or "sets" of linear plantings. The installation generally is intended to have a 20-year useful life and should be oriented perpendicular to the prevailing wind as much as possible. Species selection depends upon soils, climate, site conditions, and planned practice purpose. The practice can have single or multiple purposes to protect against wind erosion; manage snow deposition;

provide shelter for livestock or homesteads; act as a noise screen; reduce air-borne particulate matter, chemicals, or odors; increase soil carbon; provide habitat for wildlife; and improve irrigation efficiency. Renovation of windbreaks and shelterbelts is the act of restoring or enhancing the original planned function of an existing windbreak or shelterbelt. Often, renovation is accomplished over a period of years.

In 1934, an Emergency Appropriation Act was passed by Congress to fund the Great Plains Shelterbelt Project. This project was undertaken in an attempt to ameliorate climatic and other agricultural conditions in an area constantly harassed by high wind and drought. The hundred-mile-wide belt of trees was to run through the Dakotas, Nebraska, Kansas, and Oklahoma and into the Texas Panhandle. This zone has a continental type of climate, with a wide range of temperature and 40 to 74 cm (16 to 29 inches) of annual precipitation, increasing from west to east and north to south.

Each windbreak was to be 30 m (100 feet) wide when completed [occupying 3.5 hectare per km (14 acres per mile)] and have four objectives: (1) reduce human suffering and crop losses, (2) provide wildlife habitat, (3) prevent soil erosion, and (4) conserve moisture (Sandness, 1979). Opposition to the project was based on the amount of land being taken out of agricultural production and the perceived negative effects of windbreaks and shelterbelts on adjacent crops. Opposition also was expressed over the cost of enclosing the trees with a fence, other financial concerns, lack of information, and political considerations. Most of these objectives and concerns are still studied, reviewed, and discussed today (Bird et al., 1992; Brandle et al., 2000; Brandle et al., 2004). A similar and more recent project has been undertaken in Australia (Cleugh et al., 2002), but it is being applied more to individual farms than regions.

Windbreaks or shelterbelts are barriers used mainly to reduce wind speed. As such, they obstruct wind flow and alter flow patterns both up-wind and down-wind of the barrier. As the flowing air moves over the barrier, the flow lines are compressed (van Eimern et al., 1964). Lower surface wind speeds extend up-wind for a distance of two to five times the height of the barrier, while down-wind protection extends for a distance of 10 to 30 times the height. The effectiveness of a windbreak is determined by its height, orientation, continuity, width, and cross-sectional shape (Brandle et al., 2004). As consequences of the airflow changes, windbreaks affect the microclimate in the sheltered zone (temperature, humidity, and associated water, heat, and carbon

dioxide fluxes); compete for water resources; and suppress soil erosion by wind. The magnitude and importance of windbreaks and shelterbelts on crop growth and yield or animal productivity will vary with climate, soil type, and farming practice (Cleugh et al., 2002; Nuberg et al., 2002; Brandle et al., 2004).

Wind effects on plants have been reviewed extensively (Grace 1988; Coutts and Grace, 1995; Miller et al., 1995). As a shelter modifies the microenvironment, it also impacts plant productivity because the shelter affects the gradients of temperature, humidity, and carbon dioxide in the leaf or canopy. It is beyond the scope of this review to discuss those changes in detail, but in general, the microclimate is changed to promote the growth and development of sheltered plants. Plant genetics also can influence the response, but average yield increases vary from 6 to 44 percent (Kort, 1988). Responses usually are greater with sensitive horticultural crops (Baldwin, 1988; Norton, 1988; Brandle et al., 1994; Hodges and Brandle, 1996).

Three windbreak systems to provide different degrees of crop protection were evaluated over a range of yield increases and economic conditions for 50 years in east central Nebraska (Brandle et al., 1992). Crops included in the analysis were corn, wheat, and soybeans in rotations. All comparisons showed a positive economic return, with yield increases between 5 percent and 15 percent.

Another simulated study also showed that the additional yields needed to recover costs decline significantly as the lifespan of the windbreak lengthens and the protected area becomes wider (Grala and Colletti, 2003). In addition, a mixed-species (tree/shrubs) windbreak performed better than a single-species windbreak, provided the life span was greater than 30 years with a protected zone 12-times the mature height. The high initial establishment cost may discourage producers from planting windbreaks when only relatively short times are considered; however, a field shelterbelt of cottonwood with conifers was found to be effective after 4 years of growth, even with some second- and third-year replanting due to mortality (Miller et al., 1975).

Windbreaks can concentrate insects in certain areas by providing a sheltered site, usually on the leeward side. This area also may serve as a source area for beneficial or natural enemies of the invading insect (Pasek 1988). Knowledge of the factors influencing insect distribution and abundance should be used to develop pest-management strategies.

Windbreaks and/or shelterbelts also provide wildlife protection from wind and adverse weather, escape or refuge cover, food and forag-

**Most  
windbreaks/  
shelterbelts  
do not  
receive  
adequate  
management  
to keep them  
as effective  
barriers.**

ing sites, reproductive habitat, and travel corridors. Johnson and Beck (1988) reported that at least 108 species of birds and 28 mammal species are known to use shelterbelt habitats. To enhance wildlife benefits, these areas must be designed to provide for the needs of the wildlife most desired throughout the year, given local climatic conditions. Overgrazing by livestock seriously degrades the benefits of shelterbelts to wildlife, especially those species that use the understory layer (Yahner, 1983).

Care and maintenance of a windbreak/shelterbelt are continuous tasks. The two goals of renovation are to maintain and improve the vigor and growth of individual trees and shrubs for optimum foliage density and longevity and to maintain and improve the structure of the windbreak in its entirety (Read, 1966). Most windbreaks/shelterbelts do not receive adequate management to keep them as effective barriers. In 1977, 50 to 75 percent of the windbreaks in the United States needed restoration (USDA, 1977). The general attitude seems to be in favor of fortifying old windbreaks with expansion plantings or complete removal (Fewin and Helwig, 1988).

A common negative impact of windbreaks is the competition between the windbreak and adjacent crop. Under limited moisture conditions, the windbreak will have negative impacts on crop yields. Crop yields within the zone of competition also may decline because of allelopathy, nutrient deficiency, shading, or temperature (Kort, 1988). The degree of competition varies with crop, climate, and windbreak species. Root pruning is one way to reduce competition, but it may also reduce windbreak effectiveness (Kort, 1988; Brande et al., 2000; Rasmussen and Shapto, 1990). Lyles et al. (1984) estimated the economic return from root pruning on winter wheat returns in Kansas at \$164 per 800 m (2,625 feet), although no long-term studies are reported.

Shelterbelts are intended to reduce wind erosion. Other reported benefits include an increase in soil organic carbon and 15-bar water content in a strip about 9 m (30 feet) wide adjacent to the belt (DeJong and Kowalchur, 1995). In addition, soil bulk density and electrical conductivity declined, the latter probably from increased leaching as a result of snow accumulation and melting. Soil pH also declined, but depth to carbonates did not change over about 40 years. Carbon sequestration potential in a fast-growing, tree-based intercropping system was four times more than reported for tilled agricultural fields (Thevathasan and Gordon, 2004). In addition, there was less nitrogen fertilizer needed for crop production, which potentially could reduce nitrous oxide emissions. Brande et al. (1992) also reviewed

the use of windbreaks as a means to sequester carbon. They estimated that planting 2 million ha (5 million acres) would store 20 million Mg (22 million tons) of carbon.

Kort and Turnock (1999) estimated that a shelterbelt planting of six million trees and shrubs a year could potentially sequester 363,000 Mg (400,000 tons) of carbon per year in the Canada Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The fixation of carbon in the shelterbelt could be considered an ongoing process if the shelterbelt is maintained. However, if the shelterbelt is removed and burned at the end of its life span, then the carbon is returned to the atmosphere and the sequestration benefits lost.

Evidence suggests that windbreaks and shelterbelts benefit wildlife and sequester appreciable amounts of carbon, while providing protection from wind erosion and damage to plants. These benefits are offset by the costs associated with nearly continuous care and maintenance and the competition between windbreaks and adjacent crops for limited nutrient and water resources. Windbreaks used for whole-field protection may not be better than that obtained by conservation tillage. Windbreaks do provide protection if sufficient crop residue is not produced to cover the soil adequately.

Shelterbelts also protect houses, farmsteads, and other enterprises, greatly improving the comfort level for livestock and humans. There is a need to conduct a comprehensive economic study comparing windbreak protection with that provided by residue management systems for the life-cycle of the windbreak.

**Tillage orientation, surface roughening, and cross-wind ridges.** Controlling wind erosion with vegetation and surface residue generally is preferred. But this is not always possible, so tillage must be used to reduce wind erosion. On soils with a wind erodibility factor value (I) of 104 or less, as defined in the National Agronomy Manual (USDA, 2002), an emergency tillage operation can be used to increase the random roughness of the soil surface sufficiently to achieve a 25 percent reduction in the rate of potential wind erosion. The effectiveness of surface roughening can be improved if the tillage produces ridges perpendicular to the direction of the damaging wind (e.g., cross-wind ridges). Tillage should be sufficient to reduce or eliminate surface creep, or shear and saltation, and trap soil particles. Cross-wind ridges, as a conservation practice, usually are applied to soils stable enough to sustain effective ridges and clodiness, such as clayey, silty, and sandy loam soils. Generally, surface roughening and cross-wind ridge practices only are



applied when other wind erosion control systems fail for reasons beyond the control of the producer, a crusted soil condition occurs when crops are emerging, or inadequate crop residues are present. Cross-wind ridges constitute a major wind erosion control practice that is regularly used by producers, especially with low residue crops.

Two important surface soil physical properties affect wind erosion: particle-size distribution and mechanical stability of clods and crusts (Nordstrom and Hotta, 2004). An increase in random roughness (clods) and oriented roughness (ridges) can significantly reduce wind erosion (Chepil, 1941; Fryrear, 1984). As ridges and clods dry, wind erodes the smaller particles from both and fills depressions, reducing the effectiveness of the ridges and clods over time. Smooth ridges with loose, erodible material on the surface crust must be tilled to generate a layer of nonerodible aggregates because soil particles less than 0.84 micron are most susceptible to wind erosion. In addition, deep tillage of moist subsoil usually brings clods to surface. One of the major sinks for moving soil is trapping between tillage ridges. Trapping efficiency depends upon ridge height and spacing between the ridges because the aerodynamic roughness length index increases as the ridge height:spacing ratio increases (Hagen and Armbrust, 1992). Ridging soils susceptible to wind erosion reduced soil loss rates in wind tunnel experiments 85 to 89 percent, with the largest reductions for 125- to 250-mm (5- to 10-inch) ridges (Fryrear, 1984). Ridges 50 to 100 mm (2 to 4 inches) high eroded little because of the trapping of soil particles between the ridges at wind speeds up to 134 km per hour (83 miles per hour) (Armbrust et al., 1964).

Effect of random roughness on relative soil erosion losses has an exponential decay relationship, being flatter at increasing residue cover (Horning et al., 1998; Fryrear, 1995). Ridging a smooth sandy loam soil with 50 to 70 mm (2 to 3 inches) ridges reduced wind erosion 98 percent (Fryrear, 1995). Comparisons of chiseling and moldboard plowing showed that the soil dust flux upward was approximately two-fold larger when soil was plowed with a moldboard (López et al., 1998). In a crop-fallow rotation, soil surface roughness was two- to fivefold less in dry years than in wet years for a number of different crop residue systems (Merrill et al., 1999). Soils losses estimated by the revised wind erosion equation were 11 to 6,100 times greater in the dry years. Deeper tillage operations increased surface soil clods larger than 50 mm (2 inches) in diameter nearly 60 percent and grain yields 20 percent, but tillage costs also increased because ground speed declined in a fallow-wheat rotation (Schillinger

and Papendick, 1997). The diameter of the largest clods exposed and their distribution on the soil surface are important factors affecting wind erosion. When average clod diameter increased from 10 mm (0.4 inch) to 50 mm (2 inches), wind erosion declined 21-fold (Zhang et al., 2004). Artificial clods covering 60 percent of a flat soil surface also reduced wind erosion 89 percent.

Ridges generally are more effective than clods (Batt and Peabody, 1999). Tillage effects on aerodynamic roughness length index was as follows: deep lister greater than the moldboard plow greater than the shallow lister greater than the chisel greater than disk for perpendicular orientation and similar but much lower for parallel orientation (Saleh et al., 1997). The larger the index the greater the potential to reduce wind erosion. In general, the effectiveness of tillage on random roughness fits into three categories: rolling cultivator and lister greater than chisel, knife sweep, and cultivator greater than other tillage tools (Zobeck and Popham, 2001). Additional tillage for seedbed preparation further reduces roughness (Römken and Wang, 1986). Random roughness declines exponentially with precipitation amount (Zobeck and Onstad, 1987; Eltz and Norton, 1997), with the greatest rate of reduction at the highest initial random roughness (Zobeck and Popham, 1997).

These conservation practices have few if any positive effects on soil properties, except for reducing soil loss from wind erosion. Prevention of soil loss by wind erosion reduces loss of soil fertility and a potential soil texture change (Lyles and Tatarko, 1986). Increasing tillage increases gaseous emissions and also can reduce soil carbon content (Follett, 2001). Producers should be encouraged to adopt conservation tillage systems to maintain some level of residue cover on the soil surface at all times. Winter cover crops also are an option where wind erosion is a problem. Both conservation practices are applied largely to soils stable enough to sustain effective ridges and clodiness, such as clayey, silty, and sandy loam soils. Generally, surface roughening and cross-wind ridges only are applied when other wind erosion control systems fail for reasons beyond the control of the producer, a crusted soil condition occurs when crops are emerging, or inadequate crop residues are present.

### Contour farming and row arrangement

Contour farming (practice code 330) involves performing all operations on or near the contour of the field slope. Its purposes are to reduce water erosion and sediment transport. It is most effective on slopes of 2 to 10 percent. It is not well

suited to rolling topography with irregular slopes. Contour farming often is used in combination with other practices, such as conservation tillage, terraces, or contour buffer strips.

The contour orchard practice (practice code 331) involves planting orchards, vineyards, or small fruits so all cultural practices are done on the contour to reduce soil erosion and water loss, essentially the same as contour farming.

Contour buffer strips or barriers are a similar practice. Terraces or other water diversions may or may not be present.

Row arrangement (practice code 557) often is used to facilitate optimum use of water in furrow irrigation systems. In dryland farming, row arrangement can enhance use of available rainfall and minimize soil erosion. Row arrangement also can facilitate surface drainage systems where rows are planned to carry runoff to drainage areas. Contour strips or farming are examples of row arrangement in conjunction with other conservation practices. Row arrangement often is practiced for improved crop yields because of light or soil temperature advantages, without consideration of impact on other resource variables.

Most comparisons of contour farming were done to identify practices that reduce soil erosion and runoff. Several factors should be considered when designing contour farming systems to reduce soil erosion. These are slope steepness, critical slope length, soil cover and roughness, row and tillage grade, tillage/row ridge height, and soil hydrologic group. At one extreme, a comparison of contour farming with up-and-down-slope farming/cultivation showed that contour farming reduced soil losses 62 percent and water runoff losses 57 percent (Gupta and Babu, 1977). Similarly, in a continuous corn production system, contour farming resulted in 65 percent less soil loss than up-and-downhill farming (Jasa and Dickey, 1991). Contour farming in a seasonal ridge no-till system reduced predictive soil losses below the soil loss tolerance (Shi et al., 2004), where without those measures the predictive soil loss approached 52 Mg ha<sup>-1</sup> (23 tons per acre) on steeply sloping land. In most situations, contour farming combined with other conservation practices, for example, reduced tillage, is most effective in reducing soil erosion (Prato et al., 1989). Contour farming also can significantly reduce tillage erosion caused by moldboard plowing (St. Gerontidis et al., 2001). Correction areas, where contour farming strips or lines converge, should be planted to permanent sod or low-growing plants for soil cover, as in field borders.

Few published studies document either positive or negative effects of row arrangement on soil and water quality or other environmental

characteristics. When planted on the contour, row arrangement advantages and disadvantages would be similar to those for contour farming or contour strips. Surface-irrigated systems use row arrangement, with consideration of field slope, to control water flow across the field to reduce soil erosion and facilitate infiltration. Row arrangement in rain-fed systems can be used for similar purposes and to facilitate drainage from poorly drained areas.

Contour farming generally must be used in combination with other conservation practices to meet the goals of a conservation management system. In many respects, use of conservation tillage and cover crops has reduced use of contour farming, especially if tillage operations are done on the contour.

Similarly, row arrangement under rain-fed agricultural conditions is being replaced by reduced tillage practices and cover crops. Where row arrangement is used in surface-irrigated agriculture, it likely will continue until the producer adopts an overhead irrigation system.

### Cropland conversion

Conservation cover (practice code 327) is the practice of establishing and maintaining a permanent vegetative cover to reduce soil erosion, improve water quality, and promote wildlife. The practice applies on land retired from farming and includes land enrolled in the CRP. Critical-area planting (practice code 342) is done to prevent soil erosion on sites with physical, chemical, or biological conditions that keep vegetation from growing with normal cultural practices. Tree and shrub establishment (practice code 612) is the practice of establishing woody plants on any area for a variety of environmental reasons.

**Water quality effects.** CRP is the dominant stimulus for cropland conversion. Government decision-making regarding administration of the CRP has involved many variables and diverse objectives. Social benefits have been weighed against the costs to individual farmers and agricultural communities. Adopting a strategy to achieve the desired enrollment of highly erodible acres proved to be a challenge (Reichelderfer and Boggess, 1988). As the CRP sign-up process evolved, the goals moved more toward removing land from production at the lowest cost per ton of soil erosion prevented. In the beginning, the overriding goal appeared to be removing as many acres from production as possible at the least cost, rather than minimizing soil erosion per dollar spent. The relationship between CRP and other farm programs has a major impact: high

commodity program benefits are a disincentive to CRP participation. Using CRP to control soil erosion represents much higher social economic efficiency than using the program to reduce the supply of a commodity crop.

The 1985 farm bill removed 13.7 million ha (34 million acres) of highly erodible and other environmentally sensitive cropland from production and placed it in CRP. A computer simulation projected the additional net government cost for CRP at \$8.5 billion (undiscounted) for the 1986-2000 period (Barbarika and Langley, 1992). This net increase consisted of \$18.2 billion in CRP payments to farmers, offset by a reduction of \$9.7 billion in commodity program payments for corn, soybeans, wheat, and cotton.

In Ohio, two watersheds that contain about half the total cropland draining into Lake Erie from both the United States and Canada were evaluated for effective use of conservation payments to reduce soil erosion (Forster and Rausch, 2002). During the 1987-1997 period, farmers in Ohio received \$143 million as incentive payments, mostly from CRP; this amounted to about \$5 per ha per year (\$2 per acre per year). But those funds were not allocated effectively to achieve the most soil savings per dollar. Expenses and soil savings were analyzed based on county boundaries. NRCS estimated the average soil loss for 1982 and 1992; these estimates then were used to calculate the cost per Mg (ton) of soil saved. For example, in Williams County in the Maumee River watershed, payments totaled \$21.6 million, or \$16.50 per ha (\$6.67 per acre) per year. Soil loss declined from 9.8 Mg ha<sup>-1</sup> (4.4 tons per acre) in 1982 to 5.7 Mg ha<sup>-1</sup> (2.5 tons per acre) in 1992, an estimated annual soil loss reduction of 4.1 Mg ha<sup>-1</sup> (1.9 tons per acre). This translates to a cost of about \$4 per Mg (\$4 per ton) of soil saved. At one extreme the cost in Mercer County (Maumee River) was \$2.64 per ha (\$1.20 per acre), but soil loss was reduced by only 0.3 Mg ha<sup>-1</sup> (0.1 ton per acre), for a cost of about \$9 per Mg (\$8 per ton) of soil saved. In neighboring Van Wert County, an expenditure of \$1.22 per ha (\$0.50 per acre) per year resulted in soil savings of 2.1 Mg ha<sup>-1</sup> (1.0 ton per acre) per year, for a cost of about \$0.60 per Mg (\$0.55 per ton) of soil saved. The most cost-effective investment in the Sandusky River watershed was in Crawford County, \$0.75 per Mg (\$0.70 per ton) of soil saved; the least effective was in Wyandot County, about \$3.25 per Mg (\$3.00 per ton) of soil saved. This analysis illustrates the difficulty of maximizing the economics of soil erosion prevention when a voluntary program, like CRP, is the main component. In 1995, roughly 45 percent of the 4.5 million ha (1.1 million acres) of corn and soybean land in both

watersheds was farmed with no-till or mulch-till, up from virtually zero in 1980.

In the northern Great Plains, almost 11 million acres of CRP will at some point be returned to crop production. Research in North Dakota on Williams loam demonstrated that no-till cropping with a 3-year rotation of spring wheat-winter wheat-dry peas had the same low erodibility as permanent hay land (Zheng et al., 2004). Tillage with a tandem disk before seeding increased soil erodibility six-fold. These measurements were taken 6 years after conversion from CRP, indicating that long-term no-till effectively continued the environmental benefits gained by the CRP.

In South Dakota, CRP land in an alfalfa-brome-grass sod was converted to continuous corn using no-till, chisel plowing, and moldboard plowing (Schumaker et al., 1995). Corn yields were the same for all three tillage treatments. But soil erosion was severe with the moldboard-plow treatments, with a soil loss of 30 Mg ha<sup>-1</sup> (13 tons per acre) in a 2-hour simulated rainfall of 6 cm (2.5 inches). Chisel-plow plots had a soil loss of 6.7 Mg ha<sup>-1</sup> (3 tons per acre); no-till treatments resulted in nearly zero loss. Surface cover was critical to reduce surface runoff because the cover prevents sealing of macropores.

Floodplain alluvial forests (riparian forest buffers) located below intensively managed cropland in the Southeast appear to filter out nutrients effectively in runoff (Yates and Sheridan, 1983). Floodplains, wetlands, and other vegetated areas near streams trap or utilize significant portions of nutrients, improving water quality.

Tree establishment is one of the best ways to manage soil erosion and water quality, especially in the Southeast. Pine trees were planted on 283,500 ha (700,000 acres) of eroding land in northern Mississippi (Williston and Ursic, 1979). Loblolly pine grew best among several varieties tested and produced more litter to stabilize the soil. Successful practices included planting seedlings up to 5 cm (2 inches) deeper than normal (because the surface might erode during the first growing season) and putting seedlings in spots where they are most likely to survive, as opposed to planting on a grid. Applying fertilizer or interplanting with legumes did not improve tree survival or growth in the first 5 years.

Experiences establishing trees on reclaimed strip-mined land in southern West Virginia can relate to success on CRP and other steep land. On an acid (4.8 pH) "returned" sandy loam topsoil with a 40 percent slope, two ground-cover treatments and three tree-establishment treatments were applied (Torbert et al., 1995). Direct seeding of white pine (with a hydroseeder) was not a practical method of establishing a commercially



Conversion of cropland to native prairie under the Conservation Reserve Program over the past two decades has produced multiple environmental benefits.

**Returning CRP acres to crop production presents its own set of opportunities and challenges.**

**But many benefits gained during the CRP years are rapidly lost if the land is tilled and remains fallow for a period of months**

valuable white pine forest. Black locust was successfully hydroseeded, but this practice resulted in too many locust trees that crowded out planted pine trees. Because the cost to hand-plant pine seedlings was about equal to the cost of hydro-seeding, and gave better results after 5 years, pine seedlings proved to be the best choice to provide an excellent opportunity for forest management if the land is reclaimed in a way that favors long-term tree growth. If desired, black locust can be seeded in spots, rather than broadcast, among the pine seedlings.

**Soil quality effects.** Cropping with conventional tillage greatly reduces carbon and nitrogen concentrations in soils throughout the Great Plains. To determine the ability of CRP to restore carbon and nitrogen, soils were sampled at 10 sites from Texas to North Dakota and Minnesota (Amelung et al, 2001). At each site, samples were taken from native grassland, CRP, and cropland. The CRP had been established 6 to 10 years, and cropland had been in production for at least 80 years. Compared to native grassland, carbon levels in the 10 cropland sites ranged from about 50 to 85 percent less. The carbon levels in the 10 CRP sites ranged from the same to 75 percent less than native grassland. Those results indicated that 6 to 10 years of CRP had, on average, restored less than one-fifth of soil organic matter that had been lost over 80 years of continuous cropping. Total carbon on grassland ranged from 0.11 percent (11 g kg<sup>-1</sup>) in Oklahoma to 0.64 percent (64 g kg<sup>-1</sup>) in Minnesota.

Conservation cover on CRP land in Minnesota varied greatly, depending upon how the ground cover was established (Jewett et al., 1996). Land planted to smooth brome grass or reed canarygrass mixed with alfalfa or birdsfoot trefoil gave the best long-term cover to protect the soil from erosion. Clovers and bunch grasses (timothy and orchardgrass) were not persistent. Accepting fields with previously established legume-grass cover into CRP often did not provide acceptable results because of poor stands. Mowing at least once a year was critical to maintaining the population of desirable plant species and controlling weeds.

In central Kansas, continuous cropping was compared to CRP on two soils (Huang et al, 2002). On Harney silt loam, a nonirrigated no-till rotation of corn-wheat provided soil quality measurements as good or better than 10 years of CRP fields with a mix of little bluestem, indiangrass, and switchgrass. Although no carbon measurements were taken at the start of CRP to verify a baseline, carbon in the top 5 cm (2 inches) of no-till land was about one-third higher than in CRP,

and aggregate stability, an indicator of resistance to water and wind erosion, was essentially equal. On Naron fine sandy loam, the cropping system was continuous winter wheat with disk tillage. Aggregate stability was significantly less with disking. Total carbon in the top 5 cm (2 inches) was about one-quarter less with disking than in CRP.

Returning CRP acres to crop production presents its own set of opportunities and challenges. CRP land in perennial grass for several years has significantly increased soil organic carbon. Returning CRP acres to crop production must be done appropriately to extend the residual benefits from CRP on soil quality.

Huang et al (2002) moldboard-plowed both the Naron and Harney soils in the fall. The mixing caused carbon levels measured the following May to be uniform to a 10-cm (4-inch) depth on the Naron soil and equal to the disked continuous-wheat system.

Integrated dryland crop and livestock production in the Great Plains can be the most economical farming system for landowners at the end of CRP contracts (Krall and Schuman, 1996). Surveys indicate that two-thirds of all CRP acres would return to crop production even though research in Wyoming has shown that soil quality is quickly degraded when CRP land is converted to wheat-fallow. Convincing farmers to add livestock to their operation faces many challenges, despite the benefits to soil quality. Lack of managerial experience and necessary alterations to the land (fences, for example) are major obstacles. Variations in climate across the Great Plains would require site-specific crop and livestock systems to assure economic and ecological sustainability.

Soil quality (specifically organic carbon) of rangeland has been reduced greatly by continuous cultivation. The greatest rate of change in carbon occurs in the first years of tillage. The practice of converting cropland back to sod through CRP, for example, resulted in a rebound of carbon levels. But many benefits gained during the CRP years are rapidly lost if the land is tilled and remains fallow for a period of months (Gilly et al, 2001).

In northeastern Colorado, six CRP sites were returned to cropping with winter wheat using various tillage systems (Bowman and Anderson, 2002). No-till gave the highest grain yields and retained more soil organic carbon than either reduced tillage or conventional tillage. A reduced-till system, using a sweep plow designed to sever weed roots at a depth of 5 to 8 cm (2 to 3 inches) while leaving most residue undisturbed, proved to be a good alternative in a low-rainfall region where fall weed control with glyphosate is not



always an effective option.

In Iowa, land returned to crop production after 7 years in CRP gave high yields with no-till (Karlen et al. 1998). No-till corn averaged 12 Mg ha<sup>-1</sup> (174 bushels per acre). In a comparison of four conditions for soybeans (no-till or moldboard plow with either fall- or spring-killed CRP), no-till with fall kill resulted in the highest yield, 5 Mg ha<sup>-1</sup> (70 bushels per acre); the other three treatments yielded no worse than 4.4 Mg ha<sup>-1</sup> (66 bushels per acre). On-farm measurements show that biological indicators, including microbial biomass and respiration, were affected most quickly and to the greatest extent when tilled land was converted to CRP grassland. Also, to preserve the soil quality benefits of CRP, land should be returned to crop production only with no-till or reduced tillage.

Moldboard plowing to turn sod under can have detrimental effects on soil erodibility, soil quality, and soil productivity. These negative effects may not show up in the first year and only become apparent later. Gilly and Doran (1998) conducted rainfall-simulator tests at three sites in Mississippi, Nebraska, and South Dakota to determine soil erosion factors for land coming out of CRP. Immediately after tillage, the former CRP land was much less erodible than continuously cultivated fields. In fact, soil loss rates on the three soils immediately following tillage were no different than on the undisturbed CRP treatments. But if the tilled land were left fallow, the erosion-reducing effectiveness of the previously sodded field declined in less than a year (Gilly and Doran, 1998). Where tillage is necessary, such as to smooth out flow channels, it is important to establish a crop quickly to provide vegetative cover. With no-till or minimum till, where crops are planted directly into the sod, residual residue initially protects the soil, and the vegetative material produced by the crop reduces the potential for soil erosion. Rhoton et al (2002) found that the benefits of long-term sod can be severely impacted immediately, in terms of both runoff and soil erosion, by using conventional tillage for planting a subsequent crop.

**Water conservation effects.** Water conservation is not a goal for these practices. Permanent vegetation tends to encourage greater infiltration of precipitation, so there is a potential for water conservation on a watershed scale. On the negative side, growing vegetation may remove more moisture from the soil profile.

**Air quality effects.** Conservation practices that establish permanent vegetation usually provide an air quality benefit, primarily by the minimization

or elimination of wind erosion.

#### *Factors driving environmental outcomes.*

Economic considerations largely drive cropland conversion decisions. How successfully a conservation practice is established and maintained affects the environmental outcomes. The dominant current practice for converting cropland is the CRP. Tree and shrub establishment and critical-area planting practices are limited to relatively few acres.

Balancing CRP payments to achieve a fairly uniform cost per ton of prevented soil erosion is a major challenge.

Using CRP for soil erosion prevention is much more effective than using it to manage commodity supplies. Achieving a uniform cost to the taxpayer per unit of "erosion prevented" is practically impossible. Costs per ton of sediment kept out of waterways varied widely in cited studies. In the Pacific Northwest, specifically southeastern Washington, the CRP policy of paying the same amount per acre over a multicounty region meant the government's cost per ton of soil conserved varied threefold, depending upon the land's productivity (Young et al. 1991). Rather than setting a uniform bid cap over a region, calibrating the bid caps more closely to productivity and susceptibility to soil erosion would improve the program's cost effectiveness. This targeting would reallocate CRP funding from low-yielding areas with moderate soil erosion to areas with severe soil erosion. The result would be more fair to farmers and taxpayers.

Land going into CRP requires preparation and management to achieve maximum environmental benefits, both for landowners and taxpayers. Goals include soil erosion control, higher soil organic matter levels, nutrient enrichment of soil, and improved "soil quality." Investing extra dollars and time in establishing the best cover for the geographic area and soil conditions pays dividends in the long term. Starting CRP "on the cheap" means that after 10 years of no crop production the soil often is no better than at the beginning—much like money in a bank account drawing zero interest.

How CRP land is returned to crop production is a critical decision. Any accrued environmental benefits (soil erodibility, soil organic carbon, nutrients, etc) can be lost in a year or two. Using proven no-till practices can allow a smooth transition with high crop yields and minimal environmental risk.

On badly eroded soils and soils at high risk of erosion, establishing trees or other permanent vegetation often is the most economic choice for society.

In southern Illinois, landowners who signed up

**Research on the value of CRP for cropland conversion is clear and thorough. The necessity for use of caution in returning CRP acres to crop production also is well documented.**

to participate in CRP were surveyed to determine reasons for their decisions on tree planting (Olmstead and McCurdy, 1989). A majority (52%) of tree planting participants had fewer than 6 hectares (14 acres) enrolled in the CRP. About 90 percent or more of those who planted trees believed the benefits included soil erosion control, wildlife habitat enhancement, and improved water quality. Only 72 percent of those who planted trees expected any income from the future sale of forest products. Major reasons for those who did not plant trees on CRP land were length of time before timber harvest (41 percent) and lack of information (31 percent).

**Adequacy of scientific documentation.** Research on the value of CRP for cropland conversion is clear and thorough. The necessity for use of caution in returning CRP acres to crop production also is well documented. There is little scientific information on critical-area planting and tree-establishment practices.

#### **Key interactions and tradeoffs**

Residue management systems provide the best environmental outcomes when practiced consistently. For water erosion, the most damage usually occurs during infrequent, intense rainstorms. Keeping a high percentage of the soil protected year-round is important, either with crop residue, a cover crop, or crop canopy. Being prepared for a rare storm, whether it's one expected every 10 years or every 100 years, is somewhat like wearing a seat belt in the car. Even if you go years without a wreck (major rainstorm), you never know if it could happen next week or next year. So always wearing a seat belt on the highway and always protecting the soil are smart practices.

Fields often are most susceptible in the first month or so after planting because of relatively low residue levels and a lack of crop canopy to intercept raindrops. For example, ridge-till in Mississippi has fairly high soil erosion compared to ridge-till in the Midwest because of the frequency of intense rains in May and June. No-till or use of a high residue cover crop would be a better choice in that situation.

Having a field protected at all times by residue or a growing crop may be impractical in low rainfall areas. Growing a cover crop requires moisture, and without irrigation, there may not be enough moisture available for the main crop. Other practices, such as vegetative buffer strips, can provide some protection against wind and water erosion.

Government policies that encourage adoption of a "good" practice sometimes has the unin-

tended effect of creating a "bad" practice that offsets much of the environmental benefits of the good one. For example, paying farmers to take highly erodible land out of production is good, but if other policies lead to risky practices on the remaining cropland that minimize the net overall soil loss, then the benefit is less than it should be.

Where practical, the best soil management practice always will be one that keeps soil particles in place. Other practices designed to slow down or stop eroded soil after it has moved a considerable distance must be secondary. A practice that causes sediment, nutrients, and other chemicals to collect at the edge of a field, in a terrace, or in intermittent vegetative strips is better than allowing them to enter a stream, but is not equal to one that protects against any movement. A practice that tends to encourage raindrops to infiltrate is preferred to installing a grass waterway designed to guide runoff safely from a field. Of course, multiple practices often are desirable and necessary to provide a satisfactory outcome, but policymakers should never lose sight of the best practices. NRCS has embraced and adopted this philosophy, which is codified in the RUSLE2 (revised universal soil loss equation) program, and is used to determine conservation compliance and eligibility for the Conservation Security Program.

The extra cost of a practice and the possibility of reduced farm income are important considerations. A practice that builds soil quality will have a long-term payoff for the farmer, but if net income is significantly reduced in the short term, farmers are reluctant to adopt it. Government support is important to overcome such income losses.

Where society as a whole is a primary beneficiary, government support is easy to justify. Scientific goals often conflict with political or economic goals. For example, the best expenditure of funds would be to pay equally for each ton of prevented erosion, regardless of location. Some adjustment could logically be made for more sensitive areas, such as upstream from a municipal water supply. But payments often are based on dollars per acre, with less consideration for environmental outcomes than for political reasons, such as the perception of equal treatment for all farmers or one county's insistence on receiving as much as a neighboring county.

Precision technology applied to conservation practices will improve the cost effectiveness of various practices. With global positioning systems and geographic information systems available to help farmers and governmental agencies "manage" conservation practices on a site-specific basis, the environmental benefits per dollar invested on a practice should improve.

## Research priorities

Continuous no-till offers the most environmental benefits among the many soil management practices used by farmers. The challenge is to meet the goal of continuous no-till while providing just enough tillage, exactly where it is needed, to make crop yields competitive. For example, strip-till for corn has proven successful in overcoming problems associated with cold, wet soils in northern climates, but research is still needed on more soil types, fertilizer placement, and use in a controlled-traffic system. Deep tillage with subsoiler shanks designed to leave the surface relatively undisturbed (including the paratill) has proven successful in the Southeast. Variable-depth subsoiling also works, providing the benefits of subsoiling while minimizing cost. Strip-till and paratill exemplify modifications to a pure no-till system that may be necessary only in the short term. Once a no-till system is established, perhaps with controlled traffic to minimize soil compaction problems, there may be no need for any tillage.

Getting started with no-till or any other conservation tillage system, without reducing net crop income, is a roadblock for many farmers. Perhaps it should be considered a speed bump rather than a roadblock, but more research on how to "jump start" a no-till cropping system could help reduce the risk of lower yields. In one Ohio research project, adding three or four times as much manure as normally recommended seemed to help establish the desired soil quality quickly at the field surface. In 2004, only 23 percent of U.S. cropland was no-tilled; 40 percent was in conservation tillage. So, farmers managing from two-thirds to three-fourths of all cropland in the United States could potentially benefit from research on improving first-year no-till.

Continued development and refinement of no-till planting machines is needed. For many crops, precise seed placement is essential for maximum economic yield. This includes uniform coverage depth, precise placement relative to fertilizer and protective chemicals, placement in firm contact with moist soil, and a soil surface immediately above the seed that is clear of residue and any physical impairment to seedling emergence.

In 1984, Sojka et al. (1984) suggested that, to greatly expand adoption of no-till, better technology was needed to manage cover crops, along with a better understanding of nutrient cycling associated with cover crops. Water requirements and nitrogen-fixing efficiency of legume cultivars in various climates, soils, and cropping systems are high-priority research needs. In spring, cover crops must not remove water needed by the pri-

mary crop in regions where soil moisture is short.

Progress has been made over the past 20 years, but more work is needed on use of cover crops, especially in the northern half of the country. With a very limited "growing season" for northern cover crops (for example, following corn silage or soybeans), the need is for a variety that can quickly produce cover to protect against soil erosion and perhaps "sequester" nitrogen left in the soil. A grass is preferable to a legume because nitrogen need not be added to the soil.

A grass variety that can be "planted" inexpensively during or immediately following the primary crop is a high priority. That grass should be easy to manage (or kill) in the spring and offer desired traits related to soil moisture, which will vary with climate. One potential planting option could be a "delayed-release" seed coating, making it possible to scatter seeds during a normal operation, (corn or soybean planting; cultivation; or sidedress nitrogen application) and allowing the seeds to lay dormant in the field until germination is "triggered" in late summer. For corn silage, any cover crop growth would be severely limited by almost total shading prior to harvest. For soybeans, the cover crop could start growing once soybeans lose their leaves.

In areas with limited rainfall, a cover crop variety is needed that can protect the soil surface, add organic matter, but not use soil moisture needed for the main crop. Existing plants, including "weeds," may offer opportunities for developing effective new cover crops. For example, a perennial plant might grow after crop harvest, form a protective mat over the field surface, then die off naturally in the spring as temperatures rise. Such a plant might produce seed in early spring that lays dormant during the summer and germinates with cooler temperatures.

Additional research also might be directed toward slowing plant residue decomposition rates or improving soil aggregate stability.

Trees and shrubs for windbreaks or shelterbelts that use less moisture and have less detrimental effect on adjoining crops could be valuable as well, especially in dry areas.

## In summary

Continuous no-till, with cover crops where feasible, provides the best overall environmental protection, adds to soil quality, and protects water and air quality. Prescribed tillage (such as variable-depth subsoiling, strip-till, or light surface tillage), which leaves the surface generally protected by crop residue, should be used where necessary to produce competitive crop yields. Combining no-till with controlled traffic to limit

compaction can reduce the need for even limited prescribed tillage, at least after a soil adapts to the no-till system in a few years.

Conservation crop rotations often provide more environmental benefits and increase crop yields. Increased cropping intensity with winter or off-season cover crops and/or annual cropping offers advantages, including protection of soil and water resources and improved soil quality.

Cover crops can provide several environmental benefits that will vary across the country. Development of short-season cover crops, especially for northern climates, could be important to reducing soil erosion over winter and minimizing nutrient movement to surface or ground water. Where the cover crop has more time to grow, using a legume to add nitrogen to the soil can be an added benefit. A cover crop that returns enough nitrogen to equal the cost of establishing the crop will be cost-neutral for farmers.

In semiarid climates, use of cover crops, instead of fallow, can provide soil quality benefits. Finding a cover crop that does not use too much water is a major challenge in much of the Great Plains, Southwest, and Northwest.

Infrequent, intense storms are responsible for most water erosion in many areas. The unpredictability of these events increases the importance of keeping soil protected by residue, a growing crop canopy, or cover crop at all times.

Tillage translocation and tillage erosion are often underestimated factors in soil movement within fields. Decades of tillage on undulating slopes creates knolls and convex slopes with exposed subsoil and low areas and field boundaries with accumulated topsoil. If tillage is required, a low-disturbance subsoiler can loosen the soil with minimal translocation.

Conservation buffers, in various configurations, can provide important environmental benefits, especially where conservation tillage alone is not adequate. Vegetation planted in contour strips on steep slopes, or downslope from row crops, can slow runoff, cause sediment deposition, and remove nutrients and pesticides. Vegetation that is dense, tall, and stiff can be established intermittently in gullies or on badly eroded slopes to cause sediment to deposit above the vegetative barrier, which, over time, fills gullies. Vegetative buffer strips should only be used in combination with other practices, like conservation tillage. This keeps most soil in place, where it belongs, instead of being transported and then trapped in a filter strip. The vegetative barrier must then trap only a relatively small amount of sediment being transported by water or wind to be effective.

Precision-agriculture technology offers opportunities to improve the effectiveness of conserva-

tion practices. Farmers can use global positioning systems, geographic information systems, and related technologies to manage cropland on a site-specific basis. Decisions related to tillage system, cover crops, crop selection, and drainage system installation are a few that can be varied, depending upon location and soil properties within a field, rather than treating a whole field in the same way. The same technology allows governmental agencies to improve selection and sizing of conservation practices, such as vegetative buffers. Targeting conservation practices to the ideal landscape position should maximize economic and environmental benefits.

On irrigated agricultural land, managing salinity requires specific water and crop management practices that are properly designed and applied. Preventing a saline or sodic problem is much preferred to having to reclaim unproductive land. Depositing of excess salts or other compounds that are leached by irrigation continues to be a significant water quality and environmental issue.

For both surface and overhead irrigation systems, applying water-soluble anionic polyacrylamide (PAM) can minimize or control irrigation-induced soil erosion. When used as recommended, PAM substantially reduces sediment in runoff. There have been no adverse effects reported from use of PAM, although there is some concern that PAM either contains or decomposes into the monomer acrylamide and somehow enters the food chain.

Several management options are available to producers to control wind erosion. Often, these practices are used in combination. Keeping crop residue on the soil surface is ideal. Use of barriers, windbreaks, or stripcropping to reduce the field length wind travels unimpeded is likewise beneficial. When drought or other acts of nature render these practices ineffective, roughening the soil surface with tillage becomes a temporary emergency measure.



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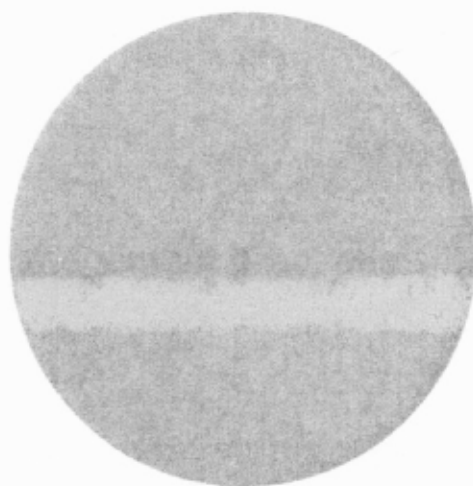
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# Environmental Benefits of Conservation on Cropland

## The Status of Our Knowledge

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