25

Conservation Tillage

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25.1 Introduction

"For thousands of years, agriculture and tillage were considered synonymous. It was simply not thought possible to grow crops without first tilling the soil before planting and for weed control" (Triplett and Dick, 2008). Indeed, soil tillage as developed over the centuries permitted farmers to grow more and better crops by loosening and mixing soil and controlling weeds. However, with the introduction of herbicide 2,4-D[(2,4-dichlorophenoxy) acetic acid] in 1942 and continued development of new herbicides since then (Unger et al., 2009), the need to mechanically control weeds has slowly, but greatly, declined. Furthermore, the need to prepare seedbeds by plowing and disking has decreased with the increased adoption of no-tillage (NT) since the 1970s. Originally, the use of the moldboard plow was deemed necessary to produce high crop yields, but such plowing (clean tillage) in many cases accelerated erosion by water and wind, organic matter (OM) oxidation, and land degradation. Because of severe erosion, government conservation compliance regulations were implemented in an effort to reduce erosion on highly erodible lands. To meet these regulations and in an attempt to increase profit, many farmers have switched to using conservation tillage (CS) systems, including NT, during the last half century or so. Conservation tillage now is widely recognized as a best management practice that improves soil productivity, reduces runoff and erosion, protects water quality, and improves environmental quality (Sullivan et al., 2008).

Conservation tillage is a broad term used to define any tillage system that has as its primary objective reduction of soil and water losses. The primary reason, however, why farmers in many U.S. regions change from conventional tillage (CT) to some form of CS is to reduce farm input costs and to increase profits (Smart and Bradford, 1996). Secondary reasons include soil and water conservation and insulation of the soil surface from temperature extremes. The use of CS reduces traffic operations, thereby decreasing soil compaction and costs for labor, fuel, tractors, and other equipment. In some cases, however, costs are increased because herbicides cost more than the tillage they replace. Even so,

farmers often adopt the new technology because yields increase at a faster rate than the costs (Bradford and Peterson, 1999).

Timeliness of cultural operations is improved when using CS in many situations. With the development of effective herbicides and improvements in sprayer design (e.g., the hooded sprayer), weed control without tillage can be accomplished, even in subtropical areas of the United States where freezing temperatures seldom occur (Smart and Bradford, 1997). Possibly the most important benefit associated with CS is soil restoration (Langdale et al., 1992; Lal et al., 2004) or in the words of Crovetto (1996), "The great economic advantage of no-till is that low value soils can be brought into higher production without erosion risks."

In this chapter, we discuss the soil science principles of CS, but believe the ultimate goal of CS, especially NT, should be to conserve soil and water while improving food security and environmental quality. If herbicides fail to control weeds, alternative methods such as biological control, crop rotations, or other techniques should be pursued. Where soil compaction becomes a major crop limiting factor, deep-chiseling or zone tillage may be needed to loosen the soil. When surface residue is limited, emergency tillage that can quickly roughen the surface may be needed to control ongoing erosion by wind. Where cold soil temperatures and excess water at spring planting time are problems, it may be necessary to remove most residue from the seeding row in the fall (e.g., while band-applying fertilizer). With time, as soil resilience improves and as farmers become familiar with the total system, soil management becomes easier.

A large number of reports in the literature pertain to the performance of NT relative to that with CT. Most studies pertained to short-term (2–5 years) evaluations of soil and crop parameters. Only few of the studies pertained to long-term trends. Long-term evaluations provide a better overall assessment because many of the benefits or disadvantages develop after several years of using NT. The major benefits of NT agriculture can be more accurately assessed only after NT has been in place for a decade or more. Adoption of NT is an investment in the soils of our future. Adopting CS, particularly NT, has significant agronomic and environmental implications. NT agriculture reduces soil erosion, enhances soil and water quality, sustains crop production, reduces off-site transport of pollutants (e.g., sediment and sediment-bound chemicals), and sequesters soil organic carbon (C), thereby reducing net emissions of greenhouse gases. The organic C enhanced by CS is vital to soil and agricultural sustainability. It improves soil resilience, soil structural stability, microbial processes, water retention, and crop productivity.

25.2 Definitions

The term CS often is used interchangeably with minimum tillage, mulch tillage, reduced tillage, NT planting, and others, thereby creating confusion. We, therefore, begin by defining the various terms used in this chapter. The definitions are from the Glossary of Soil Science Terms (SSSA, 2001) and the Conservation Technology Information Center (Schertz and Becherer, 1994; Hill, 1996). These definitions were also discussed by Bradford and Peterson (1999).

Conservation tillage: Any tillage sequence, the object of which is to minimize or reduce loss of soil and water; operationally, a tillage or tillage and planting combination that leaves a 30% or greater cover of crop residue on the surface.

Conventional tillage: Primary and secondary tillage operations normally performed in preparing a seedbed and/or cultivating for a given crop grown in a given geographical area, usually resulting in <30% cover of crop residue remaining on the surface after completion of the tillage sequence.

No-tillage (or zero tillage; also know as slot planting): A procedure whereby a crop is planted directly into the soil with no primary or secondary tillage since harvest of the previous crop; usually, a special planter is necessary to prepare a narrow, shallow seedbed immediately surrounding the seed being planted. NT is sometimes practiced in combination with subsoiling or in-row chiseling to facilitate seeding and early root growth, whereby the surface residue is left virtually undisturbed, except for a small slot in the path of the subsoiler shank. The soil is left undisturbed, except for nutrient injection and the planting operation. Planters or drills may be equipped with coulters, row cleaners, disk openers, in-row chisels, or rototillers. Weeds are controlled primarily with herbicides. Cultivation may be used for emergency weed control. In essence, NT is the extreme CS method because it results in the least soil disturbance and greatest retention of crop residue on the soil surface.

Ridge tillage: A tillage system in which ridges are reformed atop the planted row by cultivation, and the ensuing row crop is planted into ridges formed in the previous growing season. The soil is left undisturbed from harvest to planting, except for nutrient injection. Planting on ridges is accomplished with planters having sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weeds are controlled with herbicides and/or by cultivation.

Strip tillage: Tillage operations performed in isolated bands separated by bands of soil remaining essentially undisturbed by the particular tillage equipment.

Mulch tillage: Tillage or preparation of the soil so that plant residue or other materials are left to cover the surface, also known as mulch farming, trash farming, stubble mulch tillage, or plowless farming. Operationally, mulch tillage is a full-width tillage or tillage and planting combination that leaves >30% of the surface covered with crop residue. The soil is disturbed prior to planting. Tillage implements such as chisels, field cultivators, disks, sweeps, or blades are used. Weeds are controlled with herbicides and/or cultivation.

Crop residue management: Disposition of stubble, stalks, and other crop residue (aboveground biomass) by tillage operations to remove them from the soil surface (burying), to partially anchor them in the surface soil while leaving them partially exposed at the surface (mulch tillage), or to leave them at the surface intact or cut into smaller pieces. With regard to crop residue management, CS pertains to using any tillage and planting

system that retains all or a portion of the previous crop's residue on the soil surface. The goal is to retain adequate crop residue on the surface to control erosion, increase water infiltration and its storage in soil, and decrease soil water evaporation. On some soils, particularly in semiarid regions, crop residue production is limited; therefore, most residue should be retained on the soil surface to provide protection against erosion by water and wind. The portion required depends on other conservation practices that may be included in the farmer's total conservation plan.

25.3 Erosion by Water and Wind

25.3.1 Erosion by Water

Soil erosion by water is a process of particle detachment, transport, and deposition. Sediment must first be detached from the soil mass before it can be transported. In interrill areas, soil is detached by impacting raindrops and transported by sheet flow. Sheet flow concentrates in low areas, thereby forming small channels or rills and detaching and transporting more particles. Reduced erosion by water is achieved, therefore, by limiting either the detachment or transport processes. Complete erosion control seemingly would be achieved by eliminating runoff or reducing it to a flow rate that cannot transport detached particles. Splash erosion that involves detachment and aerial movement of small soil particles due to raindrop impact (SSSA, 2001), however, may still occur when runoff is prevented or reduced to a low rate.

Tillage and surface residue influence soil erosion because they create soil surface conditions and affect surface processes that determine infiltration and runoff rates. Erosion is reduced under CS conditions due to greater crop residue cover that protects the soil surface from raindrop impact, increased consolidation and greater strength of the surface soil layer, increased tortuosity and hydraulic resistance of runoff flow paths, decreased capacity of runoff to detach and transport soil particles, less runoff due to greater infiltration, and increased deposition of sediment in small ponded areas created by surface residue (McGregor et al., 1990; Meyer et al., 1999; Dabney et al., 2004; Wilson et al., 2004; Knapen et al., 2008).

Results given for many studies have shown remarkable reductions in runoff and soil loss when using CS rather than CT. Norton and Brown (1992) reported significantly lower interrill and rill erosion rates in old consolidated ridges in a ridge tillage system as compared with freshly formed ridges. Interrill erosion rates were 40% and 59% lower with older than with freshly formed ridges for Hoytville silty clay (Mollic Ochraqualf) and Rossmoyne silt loam (Aquic Fragiudalf), respectively. For both soils, the rill erosion rate was 72% lower for older ridges than for freshly formed ridges. Interrill soil loss on a moderately well-drained Saybrook silt loam (Typic Argiudoll) under NT for 15 years was reduced to 0.01 kg m^{-2} h^{-1} compared with 2.45 kg m^{-2} h^{-1} for CT when water was applied at an intensity of 100 mm h^{-1} (Bradford and Huang, 1994). Runoff was 12 mm h^{-1} for the NT condition and 68 mm h^{-1} for the tilled soil condition with residue removed. In a study by Andraski et al. (1985), soil loss was consistently 80%–90% less with NT than with CT (moldboard plowing) on Griswold silt loam (Typic Argiudoll) near Arlington, WI. On some soils, however, the smooth consolidated surface with NT may encourage runoff, but the runoff leaving NT fields contains less sediment and sediment-bound chemicals than that leaving plowed fields. Runoff with NT on Pullman clay loam (Torrertic Paleustoll) was 56% greater than with CT in the semiarid environment of northwest Texas, but sediment loss was 54% less with NT than for the tilled treatment (Jones et al., 1994a).

In some cases, sediment loss from NT soils can be practically eliminated as compared with that from plowed soils. Harrold and Edwards (1972) reported negligible soil losses (0.07 Mg ha^{-1}) from a NT watershed having a slope three to four times greater than on nearby plowed watersheds. Soil losses were 7.2 and 50.7 Mg ha^{-1} from plowed contour- and sloping-row watersheds, respectively, in Ohio. In Nigeria, soil losses were negligible (<0.005 Mg ha^{-1}) from NT watersheds having slopes up to 15% (Rockwood and Lal, 1974). In contrast, soil losses were 16.0 and 3.9 Mg ha^{-1} from bare fallow and plowed watersheds on 15% slope. Raczkowski et al. (2009) reported a 2.6 Mg ha^{-1} $year^{-1}$ soil loss rate with NT for a soil having a 7.0 Mg ha^{-1} $year^{-1}$ tolerable loss rate. With CT (chisel plow/disk), soil losses totaled 448 Mg ha^{-1} for the 6 year study with 397 Mg ha^{-1} (89%) of the loss occurring during 3 months having multiple storms of high-intensity rainfall. The average loss rate with CT was almost 11 times greater than the tolerable rate for the soil.

NT management often reduces runoff and soil loss due to the accumulation of OM on or near the soil surface, which promotes soil aggregation and improves water infiltration. West et al. (1992) found that NT with residue removed resulted in a 60%–70% decrease in rill erodibility compared with CT systems. They attributed the reduction to increases of organic C from 9.3 to 12.9 g kg^{-1} and of water-stable aggregates from 50% to 76%, and to greater soil strength due to consolidation. Another study for which soil erosion decreased significantly with NT because of greater aggregation and infiltration was reported by Rhoton et al. (2002). In their study, average annual soil loss was 3.9 Mg ha^{-1} with CT while no soil loss was observed with the NT treatment. Greater aggregate stability and size for NT than for CT soils were reported also by Bruce et al. (1990), Cambardella and Elliott (1993), Drees et al. (1994), Beare et al. (1994a, 1994b), and Lal et al. (1994). The greater structural stability with NT is attributed to increased OM content, surface residue mulch, and biological activity (Doran, 1980; Rhoton et al., 2002). Surface cover provided by crop residue has a major effect on soil erosion by water (Figure 25.1). It is possible to obtain nearly complete surface cover by residue on most soils when using NT and, thereby, achieving maximum control of erosion.

The soil detachment rate due to surface flow in rills is a linear function of hydraulic shear stress. Foster et al. (1980) estimated that the critical shear stress required to initiate erosion in rills in an untilled soil is about 10–15 times greater than that in a freshly tilled soil. Rill erodibility was significantly greater for freshly tilled NT than for undisturbed NT Saybrook silt loam (Typic Argiudoll) in north-central Illinois. The critical shear stress of freshly tilled

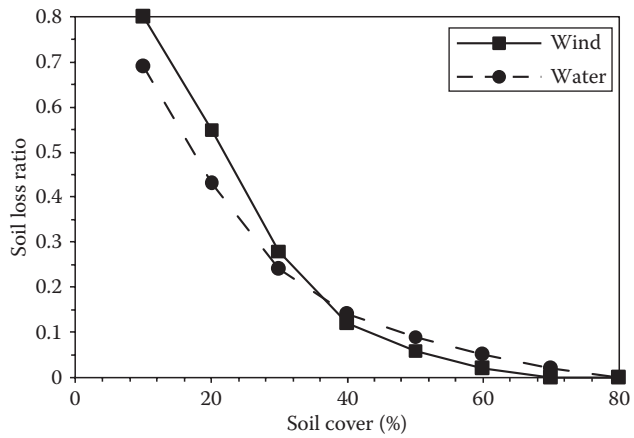

FIGURE 25.1 Relationship between soil loss ratio (loss with cover divided by loss from bare soil) and percentage of surface covered with residues. (Redrawn from Papendick, R.I., J.F. Parr, and R.E. Meyer. 1990. Managing crop residues to optimize crop/livestock production systems for dryland agriculture. Adv. Soil Sci. 13:253–272.)

NT soils is much less than for undisturbed NT soils. The critical shear stress increases with residue removal in NT soils, thus indicating the importance of surface residue for slowing runoff, reducing sediment entrainment by surface flow, and reducing raindrop impact forces due to greater ponding and greater flow depth. If a critical flow rate, slope steepness, or slope length is exceeded, massive rilling may occur in an NT soil, but these critical values are much greater for an NT than for a tilled soil.

Transport of detached particles occurs via surface runoff under both interrill and rill erosion processes. Hence, soil erosion can be reduced by creating soil surface conditions that reduce surface runoff. Runoff from a 0.5 ha watershed on Rayne silt loam (Typic Hapludault) at Coshocton, Ohio, farmed 20 years for continual NT corn (*Zea mays* L.), averaged <2 mm year^{-1} when average rainfall was >1000 mm year^{-1} (Edwards et al., 1988). Storms with 1 min rainfall intensities >76 mm h^{-1} were required to generate surface runoff with NT (Dick et al., 1989). The high infiltration rates were attributed to large macropores resulting from earthworm (*Lumbricus* spp.) activity and old root channels. These macropores are destroyed to the depth of tillage under CT conditions each year. Earthworm populations are greater under high residue (CS) conditions than in CT soil (Kladivko, 1994; Buman et al., 2004).

The effectiveness of crop residue for controlling erosion with any tillage method ultimately depends on the amount of residue retained on the soil surface. Residue retained on the surface obviously is much more effective than incorporated residue for controlling erosion (Wischmeier and Smith, 1978). As indicated earlier, however, in some climates such as in semiarid regions (e.g., southwestern United States) and with some crops [e.g., cotton (*Gossypium hirsutum* L.)], it is difficult to achieve adequate residue cover to protect the soil from erosion by water (Bradford and Peterson, 1999). Also, when a crop such as corn is harvested for silage, too little residue may remain to provide protection against erosion by water.

Residue cover plays an important role in reducing runoff and sediment loss when using NT. On a soil with a loamy sand surface (Plinthic Paledudult-Typic Hapludult complex) in Alabama, Truman et al. (2005) evaluated CT and NT with and without surface residue and with and without soil loosening by paratillage under simulated rainfall conditions. Runoff was greatest from residue-removed, non-paratilled CT plots (58% of rainfall); it was 4% of rainfall from residue-retained, paratilled NT plots. Sediment loss was four times greater with CT than with NT. The use of NT with residue retained along with paratillage to loosen the soil improved soil properties, reduced runoff and soil loss, and resulted in the potential for greater plant available water for row crops. Also in Alabama, runoff from Decatur silt loam (Rhodic Paleudult) varied between times of water application, but it was 34% to 10-fold less from residue-retained, paratilled NT plots than from CT plots (without paratillage and without surface residue). Soil loss was 1.5–5.4 times greater with CT than with other tillage systems (Truman et al., 2003). For that location, NT along with a rye (*Secale cereale* L.) cover and paratillage was best for reducing runoff and soil losses and for increasing water infiltration and plant available water.

Soils that freeze and thaw may be highly susceptible to erosion in late winter and early spring, especially when the subsurface layer remains frozen and, thereby, limits water flow into or through the soil profile. For a study under simulated rainfall conditions, soil losses were 2.58 and 0.86 kg m^{-2} with 0% and 80% surface residue cover, respectively, from boxes inclined at 13% and having a frozen subsurface layer. Losses were 1.24 and 0.58 kg m^{-2} with 0% and 80% residue cover from boxes inclined at 5% and soil not frozen (Cruse et al., 2001). Residue cover was considered to be highly important for reducing erosion during the thawing period, especially on steeply sloping soils, and the residue cover was of greater importance when the subsurface was frozen (Cruse et al., 2001). Under field conditions in Minnesota, residue cover was shown to reduce runoff and soil erosion during the spring thaw period (Sharratt et al., 2008). Under many conditions, the use of CS, especially NT, should result in retaining adequate surface residue to reduce soil losses under frozen soil conditions.

25.3.2 Erosion by Wind

The effectiveness of surface residue cover for protecting soil against erosion by wind is similar to its effectiveness for protecting soil against erosion by water (Figure 25.1). In wind tunnel experiments, erosion by wind was reduced 57% with a 20% surface cover and 95% with a 50% cover (Fryrear, 1985). For a sandy Sahelian soil (Psammentic Paleustalk) covered with 1.5 Mg ha^{-1} of flat millet (*Pennisetum* spp.) stalks, sediment transport by wind was reduced 64%; a cover of 1.0 Mg ha^{-1} reduced sediment transport 42% (Sterk and Spaan, 1997).

Effectiveness of residue cover for controlling erosion by wind depends on the amount, kind, and orientation of the residue in relation to the soil surface (Siddoway et al., 1965; Lyles and Allison, 1976, 1981). Among seven crops and orientations tested

in a wind tunnel, standing winter wheat (*Triticum aestivum* L.) residue was most effective and flat, randomly positioned sunflower (*Helianthus annuus* L.) stalks were least effective for protection against erosion by wind (Lyles and Allison, 1981). On a weight basis, 5.5 and 8.7 times more standing grain sorghum [*Sorghum bicolor* (L.) Moench] and corn stubble, respectively, was needed to provide the same protection as standing wheat (*Triticum* spp.) stubble (Lyles and Allison, 1976).

Controlling erosion by wind may be unsuccessful with NT where the amount of plant residue produced is low or only a small amount is retained. Continued use of NT for several years, however, usually allows residue to accumulate because of positive feedbacks in the system. For example, residue accumulates over time with continuous NT in a semiarid environment because of its water conservation effect (see next section).

Small grain production (e.g., wheat) in semiarid regions sometimes results in short plants and low plant populations and, therefore, low amounts of plant residue remaining after harvest. When harvesting such crops with combines having cutter-type headers, plants are cut low to the ground, thus leaving short standing residue having low effectiveness for controlling erosion. Harvesting such crops with stripper-header combines has potential to leave taller residue and, therefore, maximize soil conservation while minimizing harvest losses of grain (McMaster et al., 2000; Henry et al., 2008).

Plant material production by crops can be extremely low during dry years. In a study in North Dakota by Merrill et al. (1999), residue yield by spring wheat (*Triticum* spp.) was 0.93 Mg ha^{-1} in 1988 compared with an average of 3.64 Mg ha^{-1} in other years (1989–1994). The low amount of residue produced was inadequate to control erosion by wind, even with NT. The spring wheat-fallow (SW-F) system was considered non-sustainable with regard to controlling soil erosion.

Controlling erosion by wind is highly important at the time of crop establishment and early crop growth. On sandy soils of the U.S. southern Great Plains and the Rio Grande Valley of Texas, sandblasting and burying of young cotton and grain sorghum seedlings requires that those crops be reseeded about 2 in 5 years. In the Lower Rio Grande Valley, however, fewer air-borne soil particles are observed under NT than under mulch-tillage conditions (Bradford and Peterson, 1999). In northern Mexico along the Rio Grande River, erosion by wind was much greater under CT than under NT conditions (de Quattro, 1997).

Soil erosion by wind can be greatly reduced by managing residue cover through the use of CS, but data on comparisons of the susceptibility of soils to erosion by wind under specific residue coverings are not available. Modeling of erosion by water and wind under different scenarios of tillage, cropping, and residue management systems can promote an understanding and estimation of soil erosion dynamics on a local and regional basis (van Donk et al., 2008).

Severe erosion by wind often occurs during fallow after wheat when CT is used for the wheat-fallow system in semiarid regions. Schillinger (2001) in the U.S. Pacific Northwest found that using minimum tillage and delayed minimum tillage systems significantly increased surface residue and clod retention, which improved control of erosion by wind.

The severe erosion in the Pacific Northwest (in eastern Washington and Oregon) results in air-borne soil particles that cause major concern regarding air quality (Saxton, 1995; Janosky et al., 2002). Erosion during the dust mulch (CT) fallow phase after winter wheat is the major source of the air-borne particles (Thorne et al., 2003). By maintaining a soil surface cover in spring and fall when the potential for erosion was high, cropping of spring cereals under NT conditions reduced the susceptibility to erosion as compared with the winter wheat-fallow system. Cover with NT results from both plant canopy and residue maintained on the soil surface; cover is the dominant factor regarding the reduction in soil erodibility. Adoption of spring cropping under NT conditions would significantly reduce erosion in crop-fallow areas (Thorne et al., 2003).

25.4 Water Conservation

Residue management and CS effects on soil water storage and use are highly dependent on climate and soil type. Soil water content generally is greater under NT than under CT conditions (Smika, 1976; Dickey et al., 1983; Unger, 1984; Díaz-Zorita et al., 2004). Greater soil water contents with NT result from increased infiltration and reduced evaporation with adequate residue cover. In contrast, greater water loss occurs from tilled soils because tillage exposes moist soil to the atmosphere, thereby increasing evaporative water losses.

In some situations, using NT has resulted in lower infiltration rates due to the development of a highly consolidated soil surface. Such was the case on a sandy loam Alfisol in Nigeria. Differences were not significant under CT and minimum tillage conditions for infiltration rate or accumulated infiltration, but were greater than with NT (Akinyemi and Adedeji, 2004). Apparently, benefits of surface residue remaining with NT regarding accumulative infiltration were negated on the consolidated sandy loam.

In the United States, the relative benefits of residue management for conserving water become greater when going from the wetter, more humid regions into the drier, semiarid regions. In humid or subhumid regions, additional soil water resulting from CS has increased crop yields relative to those obtained with CT, particularly when soil water becomes limited during the growing season. The water conservation benefits of CS normally decrease the adverse effects of short midseason droughts. In mid-summer, soil surface temperatures often are several degrees cooler under plant residue than those of bare surfaces because the surface residue insulates the soil surface against solar radiant energy. As a result, soil water evaporation is less from the residue-covered soil (Lascano and Baumhardt, 1996).

The water conservation benefits of CS have resulted in significant crop growth and yield increases relative to those obtained when using CT. In a study conducted in the Upper Piedmont region of North Carolina, corn and soybean (*Glycine max* L.) yields were 32% and 43% greater, respectively, with NT than with CT on a Pacolet sandy clay loam (Typic Hapludult) (Wagger and

Denton, 1989). The crusted soil surface with CT limited infiltration, thus resulting in lower soil water contents than with NT. In a study in the Lower Piedmont of North Carolina, total water-use efficiency (units of crop produced per unit of water used) for corn grain production increased from 0.18 Mg ha^{-1} cm^{-1} with CT to 0.22 Mg ha^{-1} cm^{-1} with NT in the fourth study year on a Hiwassee clay loam (Rhodic Kanhapludult) (Wagger and Cassel, 1993). For corn silage, water-use efficiency was 0.29 Mg ha^{-1} cm^{-1} with CT and 0.34 Mg ha^{-1} cm^{-1} with NT. Yields of both corn grain and silage were about 20% greater with NT than with CT.

In some cases, cooler and wetter soils can lead to slower crop development and lower yields. On a very poorly drained Hoytville silty clay loam (Mollic Ochraqualf) in Ohio, 10 year average yields of continual corn were 13% lower with NT than with plowed treatments (van Doren et al., 1976). For a study in Michigan where no residue, root only residue, and total wheat residue treatments were compared for NT corn production, soil water content was greater and soil temperature was lower with the total residue treatment (Kravchenko and Thelen, 2007). Residue mulch has mixed effects on crop yields, depending on soil nutrient availability and soil temperature fluctuations. In Colorado, lower grain yield of irrigated corn with NT than with CT probably results from slow early growth and delayed tasseling due to cooler springtime soil temperatures with NT (Halvorson et al., 2006).

In semiarid regions where water availability is a greater limiting factor for plant growth, increased water conservation with NT normally produces greater crop yields. Water content in a silty clay loam (Udic Boroll) in North Central Alberta, Canada, was greater with NT than with CT (Nyborg and Malhi, 1989). In Australia, greater and deeper water movement occurred with NT than with CT in Hermitage clay (Udic Pellustert) (Dalal, 1989). Infiltration on seven soils of the Pacific Northwest was 30% greater under NT or grass conditions than under CT conditions (Wuest et al., 2006), thereby providing for greater water availability for crop use. Over winter water infiltration and soil water storage in eastern Washington, however, are similar with CS and CT where stubble from the previous wheat crop is undisturbed and left standing (Kennedy and Schillinger, 2006).

The increased amount of water stored in soil by retaining crop residue on the surface is highly effective for increasing grain yields of subsequent crops. At Bushland, Texas, soil water contents were determined at grain sorghum planting after fallow following wheat harvest. The water contents and sorghum grain yields are shown in Figure 25.2a and b, respectively. The grain yield increases were 7 and 10 kg mm^{-1} of additional water stored with the sweep tillage and NT treatments, respectively, as compared with the moldboard treatment (Unger, 1984). The greater response with NT than with sweep tillage indicates an additional water conservation benefit due to the greater amounts of residue present with NT during the growing season. For an irrigated wheat-dryland grain sorghum study at Bushland, soil water storage efficiencies during fallow after wheat were 35% with NT and 15% with disk tillage (Unger and Wiese, 1979). Average grain yields of dryland grain sorghum planted after fallow were 3.14 and 1.93 Mg ha^{-1} with the respective treatments.

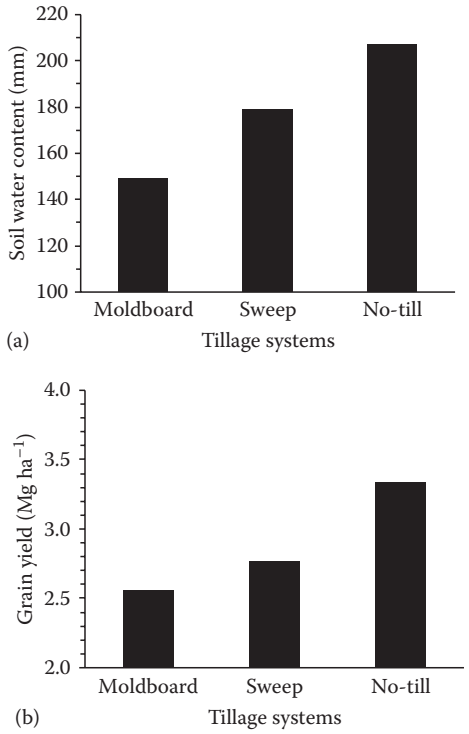

FIGURE 25.2 Soil water contents at planting (a) and grain yields of sorghum (b) as affected by different tillage systems at Bushland, Texas. All differences due to tillage systems were significant. (Adapted from Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:885–891.)

Surface residue maintained by using stubble mulching in U.S. Great Plains wheat-fallow systems increased precipitation use efficiency from 0.09 to 0.14 Mg ha^{-1} cm^{-1} (Greb, 1979). Conversion to NT, however, did not lead to further increases in the productivity of wheat-fallow systems. Other studies have shown that water is stored more rapidly with NT than with tilled systems during the early part of the fallow period, and that NT fallow systems usually result in as much stored water by early spring as when fallowing is done for an additional 3 months with tilled systems (Peterson et al., 1996). It has been clearly demonstrated from North Dakota to Texas that adding spring crops to the cropping system is the only way to more efficiently use the extra precipitation stored with NT. Conversion from wheat-fallow to systems such as wheat-corn (or sorghum)-fallow increased water use efficiency from 0.06 Mg ha^{-1} cm^{-1} with wheat-fallow to 0.08 Mg ha^{-1} cm^{-1} for wheat-corn (or sorghum)-fallow (Peterson et al., 1996). The more intensive cropping (IC) systems not only resulted in a 43% increase in water use efficiency, but also greatly reduced the potential for soil erosion by water and wind. Tanaka and Anderson (1997) observed that NT and minimum tillage stored 12% more water and increased precipitation capture by 16% compared with mulch tillage in wheat production systems on a Williams loam (Typic Argiboroll) near Sidney, Montana.

Precipitation amount is not the only issue involved in water conservation with NT. Its distribution is equally important when comparing effectiveness of NT in semiarid regions. In the

Pacific Northwest where average annual precipitation is 290 mm, greater water loss occurs during the fallow period with NT than with CT (Schillinger and Bolton, 1993). The major reason for different results with NT fallow in the Great Plains versus results in the Pacific Northwest is the long dry period (no summer rainfall) in the Pacific Northwest compared with mostly summer rainfall in the Great Plains. Hammel (1995) reported that depth and amount of water extracted by winter wheat grown under NT conditions were considerably less than with CT (moldboard plow) and minimum tillage (chisel plow) systems in the Pacific Northwest. The decrease may have resulted from higher surface layer impedance and possibly due to root diseases (Hammel, 1995).

In Oklahoma, Dao (1993) found water storage to be greater with NT than with tilled systems for continual wheat. In the northern Great Plains, Tanaka (1989) found that the response of spring wheat to tillage treatments varies yearly, depending on soil water storage during fallow and early spring temperatures. He pointed out that during years with little soil water storage after fallow and above average early spring temperatures, using chemical fallow (essentially NT) results in greater spring wheat yields than using stubble-mulch fallow. However, during years with abundant soil water storage after fallow and below-average spring temperatures, use of stubble-mulch fallow produces more spring wheat than use of chemical fallow. Based on a 4 year average, water use efficiency was greater with stubble-mulch and reduced tillage than with chemical fallow.

Soil desiccation that results from dry and strong winter winds that occur from south Texas to western Canada is reduced by the presence of surface residue. In south Texas and northern Mexico, greater soil water contents at planting under NT conditions often result in adequate seedling emergence as compared with no germination under other conditions (Bradford and Peterson, 1999). Conservation tillage practices that increase water storage have been developed for cotton in the central Texas High Plains (Harman et al., 1989) and for dryland grain sorghum at Bushland, Texas (Unger, 1991; Jones et al., 1994b).

During prolonged dry periods in the U.S. semiarid regions, cultivated soils and NT soils will dry out with time and reach the same water content. In some instances, the water content of upper soil layers even may become lower in NT than in CT soils because of capillary drying with NT. Surface cultivation under CT conditions decreases such drying in some soils (Bradford and Peterson, 1999).

A possible negative effect of greater water infiltration and higher soil water contents with CS is the potential for increasing saline seep problems on some soils. Saline seeps develop where relatively large amounts of water enter soils that have a relatively impermeable subsoil. As a result, the water table rises and water flows and seeps to the surface at down-slope sites, carrying with it dissolved salts. According to Halvorson (A. Halvorson, personal communication, 2009), the solution to the saline seep problem is more intensive dryland cropping to utilize the precipitation more efficiently.

Fresh water availability is becoming an increasingly important worldwide issue (Unger and Howell, 1999). It is a major agricultural concern where water is naturally limited and where the increasing needs of other users often clash with agriculture for available supplies (Rothfeder, 2001; Levy, 2003; Kuhn et al., 2007). Improved water conservation, therefore, is becoming increasingly important for agriculture and for society as a whole so that adequate water will be available for all users. Improved water conservation is possible by increased adoption of CS, which is important for rainfed and irrigated crop production. Greater soil water storage with CS can reduce irrigation requirements (Sullivan et al., 2007).

25.5 Residue Management and Decomposition

Unlike with CT, the main goal with CS is to minimize residue incorporation into the soil. For CS systems, farm implements are specifically designed to leave the maximum amount of residue on the soil surface, whereas for plow systems, the intent often is to incorporate the residue as quickly as possible to minimize problems associated with subsequent tillage operations. Residue amounts remaining on the surface after one pass with various implements are presented in Table 25.1. Implements such

TABLE 25.1 Percentages of Surface Residue Cover Remaining after One Pass with Various Implements

Tillage and Planting Implements	Percentages
Moldboard plow	0–10
Machines that fracture soil	70–90
Chisel plows	
Straight points	60–80
Twisted points	50–70
Sweeps and field cultivators	60–90
Disk machines	
One-way disk	55–80
Tandem or offset disk	
25 cm or greater blade spacing	25–50
18–25 cm blade spacing	30–70
Harrows and packers	60–95
Row cultivators	
Sweeps	75–90
Finger wheel cultivator	65–75
Rolling disk cultivator	45–55
Ridge-till cultivator	20–40
Drills and planters	60–95
Natural weathering	
Over-winter following summer harvest of small grain	70–90
Over-winter following fall harvest of summer crop	80–95

Sources: Adapted from Fenster, C.R., N.P. Woodruff, W.S. Chepil, and F.H. Siddoway. 1965. Performance of tillage implements in a stubble mulch system: III. Effects of tillage sequences on residues, soil cloddiness, weed control, and wheat yield. Agron. J. 57:52–55; Hill, P.R., K.J. Eck, and J.R. Wilcox. 1994. Managing crop residue with farm equipment. Agronomy Guide AY-280. Purdue University, West Lafayette, IN; Bradford, J.M., and G.A. Peterson. 1999. Conservation tillage, p. G-247–G-270. *In* M.E. Sumner (ed.-in-chief) Handbook of soil science. CRC Press, Boca Raton, FL.

as the moldboard plow and the tandem disk that invert and/or vigorously stir the soil leave less than 5% and 60% of the residue on the surface, respectively. Repeated passes with a tandem disk result in essentially no residue on the surface. In contrast, slicing-action implements such as chisels and sweep plows leave 50%–90% and 85%–90% of the residue, respectively. Managers thus have some control over residue cover, depending on the implement they use. NT relies on herbicidal weed control and no primary tillage; therefore, it provides for maximum possible surface residue cover.

Residue decomposition rates are affected directly by the amount of residue incorporation that occurs (Schomberg et al., 1994). Both surface and buried residue immobilized N, but surface residue immobilized N three times longer than buried residue, which reflects the residue decomposition status. Maximum decomposition rates occurred when residue was completely incorporated into the soil; slower decomposition occurred with NT. In the study by Schomberg et al. (1994), grain sorghum and wheat residue decomposed at about the same rate, and decomposition rates were highest under the wettest regimes. Residue decomposition rates with NT and other CS systems were highly dependent on surface soil water content and temperature. Decomposition rates were highest when soil temperatures were between 20°C and 30°C and the water content was near field capacity just under the residue cover.

Decomposition of surface residue is maximized in climatic regions where atmospheric water demand is low, relative humidity is high, warm temperatures prevail, and growing seasons are long. Peterson et al. (1995), working across a potential evapotranspiration (ET) gradient in Colorado under NT conditions, showed that surface residue loss from corn planting to harvest varied from 32% in the lowest to 62% in the highest ET zone. Higher temperatures in the high ET zone and the longer warm season promoted faster decomposition despite the drier conditions. Obviously, temperature controlled decomposition more than the relative humidity of the air at the soil surface.

The objective of CS farming is to maintain surface residue cover throughout the growing season, but especially during the preplant and seedling stages of a crop cycle because the soil is most vulnerable to erosion by either wind or water at those times. When the crop canopy provides adequate cover, residue cover becomes less important until after crop harvest. The importance of a residue cover after harvest depends on the particular climate. With high erosion potential after harvest, obviously residue cover is needed to help control erosion. On an average, a crop such as soybean leaves less cover than a crop such as corn. Furthermore, soybean residue that has a favorable C:N ratio degrades 20%–30% over winter whereas corn stalk residue that has a less favorable C:N ratio degrades 5%–20% over winter (Hill et al., 1994).

Planting equipment being used often dictates how much tillage is needed for seedbed preparation. Prior to the advent of CS, seedbeds had to be free of residue to ensure proper planter operation. Now, NT planters for both small grain and row crops are commercially available. Those planters minimally disturb the soil and leave most residue on the surface (Table 25.1).

25.6 Biological Activity

Biological activity generally is greater in CS than in CT soils. First, with CS, especially NT, there is a continuous and uniform supply of C as an energy source for organisms because the residue is not introduced all at once as is the case with CT. Secondly, the soil water content remains higher longer with CS, thereby allowing for more organism activity. Blevins et al. (1984) summarized the NT influence on soil biology.

High residue levels favor the activity of macroorganisms such as earthworms. Results of the following studies illustrate the large differences between NT and CT soils as well as the effects of crop residue management on earthworm populations. Kladivko et al. (1997) observed more earthworms in NT than in CT soils in paired sites under corn-soybean rotations across Indiana and Illinois. Similarly, Johnson-Maynard et al. (2007) found that when averaged across spring and summer seasons, NT soils had more earthworms (104 m^{-2}) than CT soils (27 m^{-2}) under spring pea, wheat, and barley in Palouse silt loam (Pachic Ultic Haploxeroll) in Idaho. In Ohio, Blanco-Canqui and Lal (2007a) reported that the number of earthworms decreased with a systematic increase in corn stover removal from Rayne silt loam (Typic Hapludult), Celina silt loam (Aquic Hapludalfs), and Hoytville clay loam (Mollic Epiaqualfs). In silt loams, earthworms averaged 78 m^{-2} in plots with <25% of stover removed and 32 m^{-2} in plots with >25% of stover removed, whereas 100% stover removal eliminated earthworms from a clayey soil.

Earthworm activity creates soil physical conditions that favor water infiltration. Runoff was <2 and 700 mm $year^{-1}$ from NT and CT watersheds, respectively, used for continual corn production for 20 years in an area that receives over 1000 mm of precipitation annually (Edwards et al., 1988). The difference was attributed to earthworm burrows in the NT watershed. Use of NT increases earthworm populations and allows their burrows to remain intact from season to season, thus providing continuous pathways for water infiltration. Furthermore, earthworm burrow diameters are much larger than the usual size of soil pores and, therefore, promote rapid intake of large volumes of water. This water is immediately transmitted past the surface soil and is stored at a depth from which evaporation is slight. Rainstorms causing the most flow in burrows were high intensity, short duration events (Edwards et al., 1989), which indicates that burrows would enhance seasonal water infiltration substantially in regions where high intensity thunderstorms are prevalent. Trojan and Linden (1994) showed that earthworm activity could more than double water penetration into NT soil as compared with CT soil under high intensity rainfall conditions.

Greater water infiltration due to earthworm activity decreases the potential for erosion and rapidly transfers water to greater depths, thereby enhancing water storage in the profile. Possible negative aspects of this rapid transfer are soluble fertilizer and pesticide movement to depths where they are less effective for their intended purposes (Hawkins et al., 2008) and groundwater contamination.

Biological activity at the microscale is also affected greatly by adoption of reduced tillage and NT systems, and these effects can be positive or negative. On the positive side, Dick (1984) observed increased activity of many enzymes in the top 7.5 cm of soil after 18 years of NT in Ohio, which was related to soil organic C contents. Furthermore, the herbicides and pesticides used for NT management did not appear to adversely affect enzyme activity. Other evidence for increased biological activity under NT was provided by Staley et al. (1988), who reported that soil biomass-C reached a maximum in surface soil after just 1 year under NT. Biomass-C approached levels found in pasture environments, and equilibrated in 10 years at a level 30% greater than with CT.

Processes that involve N are excellent indicators of microbiological activity and several authors have made interesting observations regarding contrasts between CS and CT systems. For example, Lamb et al. (1987) showed that N_2 fixation potentials in wetter NT soils were twofold greater than in drier plowed soils. Although the quantities of N_2 fixed were small (0.33 kg ha^{-1} $year^{-1}$), the data show the distinct difference that persists in microbial environments with NT as compared with those with CT. The increased microbial biomass present under NT conditions reduced potential N losses during periods of low crop demand because the N was incorporated into organic compounds that were less subject to loss through leaching and denitrification (Bremer and van Kessel, 1992). Wood et al. (1990) reported that adopting NT after long-term use of CT quickly increased the amount of surface residue and of potentially mineralizable N. When they used more intense cropping systems in conjunction with NT, they obtained the highest N mineralization.

Possible negative effects of microbial activity on soil-plant systems include greater loss of N from urea fertilizers, greater denitrification, and production of phytotoxic compounds. Dick et al. (1991) showed that soils with a 25 year history of NT had increased urease activity at the surface, making urea-based fertilizers more susceptible to N volatilization losses. Rice and Smith (1982) showed that the denitrification potential increased under NT because of the more conducive environment provided by the large amounts of C at the soil surface, which resulted in the high biological activity, and the wetter soil conditions under the residue cover.

Phytotoxic compounds synthesized by microorganisms during residue decomposition were identified many years ago. NT environments have regenerated interest in these compounds and in the processes involved in their production. The slower residue decomposition, the prolonged production period, and the colder temperatures in the soil or at the soil surface and very near the emerging plant seedlings create potentially enhanced phytotoxicity problems under NT conditions. Buchanan and Kin (1993) clearly demonstrated that the decomposition period with NT was longer than with tillage systems. Working in a warm North Carolina environment, they found that 45% and 20% of the C remained under NT and CT systems, respectively, after 50 weeks. The results were similar for wheat and soybean stalk residue. Cochran et al. (1977) demonstrated that surface residue of lentil (*Lens culinaris*), pea (*Pisum* spp.), wheat, barley, and bluegrass (*Poa* spp.) all produced phytotoxic materials at some point during the spring season. Toxicities were worst when wet weather and low temperatures prevailed. Lentil and pea materials were more toxic to wheat seedlings than the other materials, but toxin production fortunately was short-lived. Martin et al. (1990) found that microbially synthesized phytotoxic materials from corn residue were more damaging to corn seedlings than were the byproducts of soybean and oat (*Avena sativa* L.) residue decomposition. Corn planted back into corn residue, therefore, would be more prone to phytotoxin damage than corn planted into soybean or oat residue. These findings illustrate that to avoid potential seedling damage, it may be more important to use crop rotations when using NT than when using CT systems.

25.7 Carbon Dynamics and Sequestration in No-Tillage

In contrast to agriculture with tillage, NT soil management greatly alters the C cycle because plant residue C is added to the soil in a different manner. The traditional moldboard plow system is the antithesis of NT. Moldboard plowing inverts and incorporates most or all residue of the previous crop into the soil in one operation. In such case, microbes responsible for the residue decomposition process are stimulated by the instantaneous addition of large amounts of organic C. No matter what system is used, however, decomposition rates are controlled by soil water conditions, soil temperature, and inorganic N supply. If the water content is above the wilting point and the temperature is above 4°C, inorganic N supply limits decomposition. In tilled systems, if appropriate amounts of N fertilizer are added, soil organisms can complete decomposition of the incorporated crop residue and roots in the surface soil layer within a few months after plowing. Often, the surface soil is disked before plowing and/or the crop residue is shredded to enhance farm implement function, which creates more residue surface area for soil organisms and hastens the decomposition rate. Large quantities of CO_2 evolve from soils shortly after plowing. Soils usually are tilled several more times after plowing to prepare a fine, firm seedbed for planting. These operations stir the soil and residue mixture, and further stimulate decomposition of the organic materials if the soil contains adequate water. Tillage, however, also hastens soil drying, which may retard decomposition if no rainfall or irrigation occurs.

Continued use of any type of inversion tillage for a long time decreases soil aggregate size, which results in organisms having access to C that once was physically inaccessible within the larger aggregates. Therefore, organic C that literally required centuries to be stored is released as CO_2 within a few years. For example, when temperate-zone soils of North America were first cultivated, as much as 10^9 Mg of C were released as CO_2 (Paustian et al., 1997). Intensive tillage accelerates release of CO_2 and thereby increases organic C losses (Blanco and Lal, 2008). On Barnes

loam (Udic Haploboroll) in west central Minnesota, Reicosky and Archer (2007) observed that the CO_2 release from CT soils was consistently greater than from NT soils under spring wheat, particularly immediately following tillage. Deep and frequent tillage increases the release of CO_2 relative to shallow tillage. Retaining crop residue after harvest and reducing tillage depth are strategies to enhance organic C sequestration and reduce emissions of greenhouse gases.

When soils that have been managed with maximum tillage such as by moldboard plowing are converted to NT, a dramatic change occurs in the way organic C is introduced into the soil system, both in terms of timing and position. Furthermore, soil under NT management remains wetter for longer periods. The new system (NT) results in little or no mixing of residue with the soil. Crop residue remains on the surface and decomposition occurs much more slowly than under tillage conditions because much less surface area of residue is exposed to soil organisms, even if the producer shreds the residue. Roots at shallow soil depths also remain basically intact, again reducing their area exposed to decomposition. Soil surfaces with NT are generally moist enough, especially in the spring and early summer, so that water availability does not limit decomposition. The residue cover, however, keeps the soil cooler longer than for a bare surface soil, especially in northern latitudes, thus slowing decomposition.

Under NT conditions, N supply is more limiting for decomposition because the organisms have access only to the inorganic N in a much smaller soil volume than in a tilled system. Obviously, root mass decomposers have access to more N than surface residue decomposers, but overall residue decomposition is delayed with NT relative to that in a tilled soil.

After 5–10 years, the amount of surface residue in an NT system appears to reach equilibrium for a given soil and climate combination (Sherrod et al., 1996). Resident residue levels increase more in cooler than in warmer climates due to slower decomposition rates in the former. Within climatic zones, soil types also affect residue levels. Excessively drained soils have lower residue levels relative to well-drained soils primarily because less biomass is produced. At the other extreme, wetter soils have greater residue levels because biomass production generally is high and because the cooler soil environment in the wet soil delays decomposition, which, in turn, is accentuated by the heavy residue cover.

Generally speaking, the total C sequestered in surface residue plus the organic C in the uppermost soil layer (0–5 cm depth) is higher with NT than with the same soil under tilled conditions. Furthermore, substantial amounts of C still reside as crop residue in the upper 2.5 cm of soil. Ortega (1995) found residue C amounts within the upper 2.5 cm of NT soil equal to that present on the soil surface and Dell et al. (2008) found about 50% more C in particulate and mineral-associated pools in the upper 5 cm of NT soils than of CT soils.

Soil organic C tends to increase with NT relative to that with tilled systems, but the increase rate is slow and usually confined to the upper soil layers with little effect on deeper layers (Dick, 1983; Potter et al., 1998). Changes in soil C after 18 years were 0% to −11% with NT, −12% to −23% for minimum tillage, and −14% to −23% for CT (Dick, 1983). Organic P also was greater in surface soil layers with NT than with tillage. Wood and Edwards (1992) found that NT relative to CT resulted in C and N concentrations after 10 years that were 67% and 66% greater, respectively, than those with plow tillage at the 0–10 cm depth. Macroaggregates (>250 mm) under NT were more numerous and more stable than those under CT, probably due to greater biological activity under NT conditions. Microbiological activity was more episodic in the tilled system, which had a drier surface soil than NT. CT also caused more physical disruption coupled with less production of aggregate-stabilizing materials. For a drier climate (eastern Colorado), Wood et al. (1991) concluded that higher equilibrium levels of soil C and N could be maintained by increasing cropping intensity, which increased C input to the system. These changes were measurable even after only 4 years of NT. Less inorganic NO_3–N was present in the intensive system, indicating that the N loss due to leaching or denitrification was reduced.

Data from Colorado show that with some NT systems, OM contents have increased in the upper 5 cm of soil, but have declined in the 5–10 cm depth. The net result for the 0–10 cm depth generally was a decline after 7 years of NT, especially in systems that include fallow. Under climate and soil conditions that permit continual cropping, adoption of NT is likely to increase soil OM much more. This means that the more humid the climate (high precipitation coupled with low potential ET), the greater the probability that NT will promote soil OM accumulation. Conversely, under climates with low precipitation and high ET that usually require fallow periods in the cropping systems, there would be less chance of increasing soil OM; and net losses of C may occur, even under NT management, because of less plant material production under such conditions.

NT adoption promotes restoration of some of the C lost when soils were broken from their native condition. Potential C sequestration, however, can be small and slow relative to the losses from the original soil OM level, depending on soil, management, and climate. It will take years of NT farming to increase soil C because the amounts of available N and P required to provide the correct C:N and C:P ratio for C sequestration are limited. For example, producers usually apply adequate N for the crop, but plan to leave no excess in the soil system. Therefore, little N is available to balance the high C input from crop residue. The same situation can occur with P, especially in soils with low P availability. Paustian et al. (1997) provided an excellent summary of tillage effects on soil OM. They concluded that reduction in tillage, and especially using NT, provided an environment conducive to C storage in soils. Soil organic C storage is generally greater with NT than with CT at the 0–5 cm depth (West and Post, 2002). In a few cases, where NT reduces biomass production compared with CT, there may be no differences between NT and CT.

What is the net effect of NT on the C cycle? It is the amount sequestered in the soil. Carbon sequestration in soil has received

much attention in recent years because of the possible effect that increasing atmospheric CO_2 levels may have on global climate change. More soil organic C can be sequestered by using reduced tillage and NT in combination with diversified cropping systems than by using CT. It is estimated that about 60% of organic C has been lost due to intensive plowing, monocropping, simplified crop rotations, and short-sighted management systems (IPCC, 1996; Benjamin et al., 2007). These losses make up nearly 23% of the total greenhouse gas emissions in the atmosphere (Lal, 2004). Reducing or eliminating tillage is a strategy to restore the organic C pool. For example, NT, in addition to providing many other benefits, can enhance soil organic C sequestration. Across five soils in Kansas, McVay et al. (2006) showed that NT management resulted in more soil C at the 0–5 cm depth than CT management. The increase of residue-derived C in a silt loam in Minnesota was 2.3 times higher with NT than with CT or chisel-plowing (Allmaras et al., 2004).

NT is superior to CT for storing C in soil. In most cases, however, organic C in NT soils is concentrated near the surface (West and Post, 2002). The marked stratification of organic C in NT soils is partly due to surface residue mulching. The soil organic C with NT can be higher at the 0–5 cm depth and lower below this depth compared with plowed soils. Furthermore, substantial amounts of C still reside as crop residue in the upper 2.5 cm of soil. Ortega (1995) found residue C amounts within the upper 2.5 cm of NT soil equal to that present on the soil surface and Dell et al. (2008) found about 50% more C in particulate and mineral associated pools in the upper 5 cm of NT soils than in CT soils.

The difference in total organic C between NT and plowed soil profiles may not be significant if there is considerable stratification. It is important to note that organic C stored in deeper layers is important to long-term C sequestration (Lorenz and Lal, 2005). The organic C near the surface layers is subject to abrupt fluctuations in soil temperature and soil water content, which causes rapid mineralization of soil organic materials.

The NT impacts on C sequestration must be characterized for the entire soil profile and not only for shallow surface soil (<20 cm depth) (West and Post, 2002). Plant roots of most crops often extend to a 50 cm depth (Qin et al., 2006), which is much deeper than the typical soil sampling depth for organic C characterization (West and Post, 2002). Plant roots in plowed soils may penetrate to greater depths than in NT soils because of relatively loose soil following tillage. Recently, some researchers have argued that the greater C sequestration in NT systems reported in many studies may be simply due to shallow sampling protocol that biases the results (Baker et al., 2007). At this point, the limited information on organic C distribution for the whole soil profile hinders our ability to conclusively state the benefits of NT farming to sequester C at lower profile depths.

A study conducted under on-farm conditions in the eastern United states by Christopher et al. (2009) showed that organic C with 5–35 years NT systems was not greater than with CT systems in most soils at the 0–5 cm depth. Total organic C in the profile with NT and CT did not differ in 8 of the 12 soils. It was actually greater with CT than with NT in three soils after 8, 15, and 30 years of NT management. For a similar on-farm study for the same temperate region, Blanco-Canqui and Lal (2008) observed that NT management increased organic C concentration over CT in 5 out of 11 soils, but the increases were significant only at the 0–5 cm depth. Beneficial effects of NT for increasing organic C pools tend to disappear with increases in soil depth.

Impacts of NT farming on organic C can thus be variable and soil-specific (VandenBygaart et al., 2003). Length of NT management, degree of soil erosion, crop grown, and residue incorporation with CT are among the factors that cause differences between NT and CT. Increases in organic C with NT often are more pronounced with long-term (>10 years) management and for erosion prone soils. Indeed, NT farming may favor greater organic C storage in sloping terrains and soils with low clay content. NT benefits for increasing organic C concentrations, particularly at lower profile depths, are complex and should not be generalized for all soils.

25.8 Biofuel (Cellulosic) Production Implications

Crop residue retained on the soil surface greatly reduces the potential for soil erosion by wind and water (Figure 25.1) and enhances water conservation under many conditions. Such residue retention, therefore, is highly important for conserving the soil resource base to maintain its sustainability for crop production and to enhance production by effectively using the conserved water for greater crop production for an ever-increasing world population. These benefits generally increase with increases in the amounts of residue retained on the surface, as discussed in previous sections. Removing even some residue, at least from some soils, therefore, would negate the conditions essential for sustained or improved soil and water conservation and crop production.

One of the main differences between CS and plow tillage (CT) is that most crop residue remains on the soil surface when using CS, thereby enhancing soil and water conservation. Today, however, there are many competing uses for crop residue including soil and water conservation, animal feed, industrial raw material, and as feedstock for cellulosic ethanol production. Particularly, producing biofuel from crop residue is generating a lot of interest (Perlack et al., 2005). A number of commercial-scale cellulosic ethanol plants are being built in the United States to produce the second generation of biofuel (USDOE, 2007). Production of ethanol from cellulosic plant materials is projected to increase exponentially in the near future as concerns over increased food prices may slow ethanol production from grain. At present, corn stover is the main candidate as cellulosic feedstock for biofuel production (Graham et al., 2007). Residue of crops such as wheat and sorghum is also being considered as feedstock for biofuel as technologies for cellulosic conversion progress (Sarath et al., 2008). Production of cellulosic ethanol from renewable energy sources is important and should be pursued. But removing crop

residue as biofuel feedstock must be objectively examined and contrasted against its positive and negative impacts on soil conditions, crop production, and environmental quality. Dedicated energy crops (e.g., warm season grasses and fast-growing woody plants) are potential alternatives to crop residue removal.

25.8.1 Negative Aspects of Crop Residue Removal

Removal of crop residue can have more negative than positive impacts in the long term for conserving soil and water resources (Wilhelm et al., 2007). Although sometimes dubbed as "low-cost waste," crop residue is a valuable commodity. Indiscriminate removal of crop residue is not advisable particularly in semiarid regions with low and variable precipitation and biomass production. Crop residue mulch is important for precipitation capture and storage, and water use efficiency. By increasing soil erosion, residue removal can also accelerate losses of nutrients in runoff, thereby further increasing risks of non-point source pollution of downstream water sources such as ponds, lakes, rivers, and streams. Sediment and sediment-borne chemicals (e.g., fertilizers and pesticides) are the major pollutants in runoff. Total N and total P transport in runoff often increases with increases in crop residue removal (Lindstrom, 1986; Blanco-Canqui et al., 2009). Residue removal can also increase soil susceptibility to erosion by wind by leaving the soil partially or completely unprotected. Soils under NT conditions can be as susceptible to erosion by wind as CT soils unless adequate residue cover is maintained on the surface.

Crop residue mulch reduces the susceptibility of the surface soil to compaction by buffering impacting raindrops and traffic. Residue mulched soils are more resilient than unmulched soils (Wilhelm et al., 2004). Residue cover also reduces fluctuations in soil temperature and wetting and drying cycles. Soil aggregate stability, water infiltration, water retention, saturated hydraulic conductivity, macroporosity, and biological activity decrease, whereas soil cone index and bulk density increase with increases in crop residue removal (Karlen et al., 1994; Blanco-Canqui and Lal, 2007a).

Crop residue removal reduces soil organic C because residue contains about 45% C. Removal of crop residue for alternative uses reduces not only organic C, but also plant nutrient pools. Nutrients also may be lost via increased erosion (Blanco-Canqui et al., 2009). The magnitude of losses depends on soil and climatic conditions. For example, losses of organic C pools in some soils increase linearly with increasing removal rates of corn stover (Karlen et al., 1994; Clapp et al., 2000). Blanco-Canqui and Lal (2007a) observed that removal of corn stover from long-term NT soils decreased organic C pools in sloping and erosion-prone soils, but had little or no effects on nearly level, clayey, and cold soils 3 years after residue removal.

Crop residue removal influences crop production because it reduces plant available water and causes abrupt fluctuations in soil surface temperature. Crop residue is a source of soil OM and essential plant nutrients and thus its removal can reduce the supply of vital nutrients. On a silty clay loam in Nebraska, complete removal of stover from a 4 year NT system reduced corn grain and biomass yields by about 23% (Wilhelm et al., 1986). Grain yield is often higher from residue mulched soils than from unmulched soils due to increased soil water content and favorable soil temperature in the growing season. Rates of crop residue mulch can explain as much as 95% of the variability in grain and biomass yield (Wilhelm et al., 1986; Blanco-Canqui and Lal, 2007a). Corn stover removal reduced corn yield by 1 Mg ha^{-1} during 3 years of a 12 year NT continual corn study on a silt loam in Minnesota (Linden et al., 2000). Residue removal impacts on corn production are site-specific and depend on soil, topography, duration of stover management, tillage, and climate. Crop production in sloping, erosion-prone, and well drained soils can be more adversely affected by residue removal than in flat and clayey soils.

25.8.2 Positive Aspects of Crop Residue Removal

In some soils or ecosystems, it may be feasible to remove a portion of the crop residue for alternative uses in the short term without increasing risks of erosion by water and wind, reducing the soil OM pools, or reducing crop production. Indeed, removal of some of the total residue produced may be beneficial to improve seed germination, facilitate planting, increase N mineralization, and reduce pest infestations. Dam et al. (2005) observed that corn emergence in mulched plots was reduced by as much as 30% relative to unmulched plots. In a similar study, Blanco-Canqui et al. (2006) observed that corn stover removal from long-term NT soils enhanced seed germination on three soils in Ohio. Without stover removal, emergence was delayed by up to 3 days as compared with that on soils where all stover was removed. These studies showed, however, that the delayed emergence did not reduce crop yields. Plants in plots with low amount of residue cover often grow taller during the first few weeks, but the height differences often diminish rapidly with time.

Excessively wet and cold soils during the germination period, proliferation of weeds and pests, and nutrient immobilization under mulched soils may lower crop yields. On two silt loams in southwestern Wisconsin, corn yield decreased when stover cover was doubled (Swan et al., 1994). On a silty clay loam in Iowa, corn yield decreased during the last 4 years of a 13 year continual corn system with the addition of 2, 4, 8, and 16 Mg ha^{-1} of stover mulch (Morachan et al., 1972).

25.8.3 Threshold Levels of Residue Removal

The magnitude of residue removal impacts on soils and crop production is site specific and information on maximum permissible rates of residue removal is limited. The positive and negative impacts of crop residue removal must, therefore, be characterized for different scenarios of tillage and cropping systems, soil characteristics, and climatic zones. Some computer-simulation model estimates in the United States, mainly for the Corn Belt region, show that 20%–50% of the residue produced

may be available for removal (Graham et al., 2007). These estimates, however, are mainly based on the residue requirements to control erosion. Permissible levels of residue removal must account for the residue requirements not only to control soil erosion, but also to maintain soil OM and nutrient pools, sustain corn yields, and maintain or enhance soil quality. Depending on the soil and climate, between 5.3 and 12.5 Mg ha^{-1} of crop residue is needed to maintain soil organic C levels (Johnson et al., 2006; Varvel and Wilhelm, 2008). This amount exceeds that needed for controlling erosion (Wilhelm et al., 2007). Thus, the amount that can be harvested may be limited by the amount needed to maintain soil organic C pools.

The amount of stover that can be harvested for biofuel production must be established for different soils and ecoregions based on the multiple roles of residue. Process-based models are valuable tools for predicting the impacts of different scenarios of crop residue management across regional and national scales on the potential for erosion by water and wind. These models allow the scaling up of information on residue management to larger geographic areas. Use of current models combined with advanced tools such as remote sensing and GIS is a promising approach to enhance our understanding of residue removal impacts on soil and water resources (Green et al., 2003).

25.9 Soil Fertility and Nutrition

25.9.1 Nitrogen

All soil biological processes are greatly affected by the organic and inorganic portions of the N cycle. The N cycle is inextricably linked to the C cycle. The presence of mineral N in soil for plant uptake depends on what is happening within the C cycle. Because N is the most plant-growth-limiting nutrient and because it has been widely demonstrated that conversion to NT and other reduced tillage systems alters the C cycle, it is important to understand the specific effects of tillage systems on N availability to plants. As a result, soil testing and plant analyses are highly important components of effective nutrient management for successful crop production under CS conditions (Schlegel and Grant, 2006).

25.9.1.1 Immobilization of Fertilizer N

All CS and CT systems tend to immobilize N, but CS systems do not immobilize more N than CT systems; they only keep the N immobilized longer. Net N mineralization is eventually equal in all systems, but the timing of N release is delayed when residue is either slowly incorporated into the soil or left on the soil surface. Rice and Smith (1984) reported that within the first 35 days after application, N immobilization was 19% and 11% with NT and CT, respectively. Use of subsurface N-fertilization techniques may minimize immobilization in NT systems. Separating N and crop residue by placing fertilizer in soil below the residue was considered more important under CS than under CT systems (Schlegel and Grant, 2006). Because of immobilization differences, crop yields could be affected. Kelley and Sweeney (2007) showed that wheat grain yields averaged 3.68, 3.40, and 3.19 Mg ha^{-1} with subsurface knife, surface band, and surface broadcast applications, respectively, of N and P fertilizer in Kansas on Parsons silt loam (Mollic Albaqualf). Subsurface band application of N at greater rates was considered especially important when wheat followed grain sorghum in a rotation. Because of reduced immobilization, band applications of N fertilizer were more effective for production of durum wheat (*Triticum* spp.) (Grant et al., 2001) and canola (*Brassica* spp.) (Grant et al., 2002) in Canada. In Kansas, winter wheat yields were 8% greater with springtime point-injected than with broadcast N fertilizer application (Schlegel et al., 2003).

According to Schomberg et al. (1994), surface and buried residue both immobilized N, but net immobilization was longer than 1 year for surface residue and about 0.33 year for buried residue. Residue type, either grain sorghum or wheat, made little difference in terms of decomposition rate. Smith and Sharpley (1990, 1993) studied effects of residue type and placement on N immobilization and mineralization. Surface residue caused temporary N immobilization and the C:N ratio of the materials governed the duration of immobilization. Alfalfa (*Medicago sativa* L.) residue had the maximum mineralization followed by peanut (*Arachis* spp.), soybean, oat, sorghum, wheat, and corn in decreasing order. Although surface-placed residue had less N mineralized than buried residue, the difference between placements was minor compared with differences among residue types.

Soil OM contents are often very low under dryland conditions. In New Mexico, NT soils had less inorganic N and more organic C and N than a stubble mulch tillage soil after 5 years (Christensen et al., 1994). Unfertilized grain sorghum was very N deficient with the NT compared with the stubble mulch treatment. Soil organic C increased with time with NT and stubble mulch systems, but a point was not reached in the 5 year study where N mineralization with NT equaled that with stubble mulch tillage.

Immobilization delays N availability to plants, but the impact of N fertilizer management appears not to be as significant as once thought. Crop yields where no N is applied can be lower with NT than for other tillage systems due to immobilization with NT (Bundy et al., 1992). Nitrogen immobilization, however, may be affected by residue amounts on the soil surface. In Nebraska, increased residue levels resulted in greater grain yields in a tillage experiment and the additional residue increased stover production and N uptake by subsequent crops (Maskina et al., 1993). Nitrogen immobilization seemed not to be a factor. Tillage per se, that is, NT versus disked, did not affect grain yields. Vigil and Kissel (1991) developed equations to predict net N mineralization for a season based on N content and/or N + lignin/N ratio of the residue and concluded that net N mineralization would not occur if the C:N ratio of the residue was above 40.

25.9.1.2 Soil N and C Mineralization with Time with No-Tillage

Converting crop production to reduced tillage and NT systems affects the formation, size distribution, and strength of

soil aggregates. Changes in aggregate properties alter the rates at which both physical and biological processes proceed. When soils are not tilled, macroaggregates that form from natural processes tend to remain longer and have an opportunity to become strengthened. The more stable the soil aggregates, the greater the organic C stabilization in soil.

Soil organic C mineralization is a function of the interactive physical, chemical, and physicochemical processes that occur inside soil aggregates. Soil organic C is physically protected inside macro- and microaggregates through entrapment, and chemically through adsorption and recalcitrance (Blanco-Canqui and Lal, 2004). The confinement of C inside of aggregates prevents OM from rapid mineralization by microbial processes while enhancing long-term C sequestration. There is a mutual interrelationship between soil C and aggregates. The protected C pool enhances macro- and microaggregate formation and stabilization, while the microaggregates, in turn, protect the organic C from rapid mineralization.

The soil organic C residence times (mineralization rates) range from a few minutes to hundreds of years. Particulate OM or relatively labile OM can be mineralized in 5 or 10 years, while stable C can be mineralized in 500 or 1000 years (Blanco-Canqui and Lal, 2004). The residence times of C in soil aggregates is influenced by the type of organic binding agents, type of soil, size of aggregates, tillage, and climate. Mineralization of C normally increases with increases in aggregate size because of the differences in physical and chemical protection (Jastrow et al., 1996). In some cases, the C inside microaggregates can be protected physically, but be highly susceptible to rapid mineralization. The mechanisms of C mineralization or residence times inside aggregates are complex.

Macroaggregate formation often is greater in NT than in CT soils. These large aggregates with NT store more C because they are made up of a large number of C-enriched microaggregates. Beare et al. (1994a, 1994b) found that macroaggregates from NT soil protected soil OM from decomposition. In their study, 19% of the total mineralizable C and N in NT soils came from these larger aggregates, while only 10% and 5% of the C and N, respectively, came from them in CT soils. This aggregate-soil OM association under NT conditions may explain why conversion to NT results in a need for higher N fertilizer rates at the outset (Bradford and Peterson, 1999). Adjustments in N application rates during early years of adoption of NT were considered important also by Schlegel and Grant (2006). Apparently, a new steady state is reached and the immobilization capacity due to macroaggregate formation is fulfilled. In fact, Follett and Schimel (1989) inferred from data collected from a 15-year NT experiment that less tillage helped conserve mineral N. In other words, the greater, but temporary, immobilization of N under NT conditions reduced the opportunity for both leaching and denitrification losses of mineral N.

How long does the net immobilization period of NT last before mineralization processes equilibrate? Rice et al. (1984) observed that after 10 years, N mineralization with NT was equal to that with CT. The authors suggested that the net immobilization phase is transitory when NT is adopted. For a wheat-fallow system in western Nebraska, Lamb et al. (1985) reported that for the first 5–7 years after adoption of reduced tillage and/or NT, less NO_3–N accumulated during the fallow period than in plowed soils. Approximately 7 years after adoption, NT and stubble mulch tillage soils had NO_3–N accumulations during fallow equal to those in plowed soils and continued to have equal contents in subsequent years.

25.9.1.3 Fertilizer N Conservation and Efficiency

Perhaps of more concern than immobilization of N fertilizer is the potential loss of N from urea fertilizers applied directly to a residue-covered NT soil. In Missouri, substantial N losses occurred from urea-based N fertilizers under NT conditions when the fertilizer was not injected into the soil (Stecker et al., 1993a, 1993b). When N was injected below the residue, time and source of application had no effect on corn yield. In Wisconsin, ammonia losses reduced the effectiveness of urea-containing fertilizers, but such loss did not fully explain the observed N source differences. The N source effects were similar with all residue levels, which suggested that applying extra N can overcome yield reductions with high residue levels (Andraski and Bundy, 2008).

Under drier climatic condition, the effect of placing N below the residue depends on the season when crops are grown. For fall-planted wheat, hot and dry weather conditions at planting time in fall apparently stimulate N losses from urea compounds that are broadcast over the residue. In contrast, cooler and wetter weather at corn planting time diminishes the loss mechanisms, thereby causing minimal N losses (Kolberg et al., 1996).

Cold springtime soil temperatures are the rule in northern regions such as, for example, the U.S. northern Great Plains and, therefore, influence crop responses to N fertilizer. Spring wheat in a wheat-fallow system in the northern Great Plains responded most to N fertilizer in years when springtime NO_3–N levels were lowest, apparently because of greater N immobilization due to lower soil temperatures with CS systems (Halvorson et al., 2000). The NT and minimum tillage systems are considered suitable for spring wheat production in the northern Great Plains, but yields are slightly reduced when compared with CT systems in some years.

25.9.1.4 Crop Responses to Starter Fertilizer

Cool soil temperatures under NT conditions often slow early growth of spring-planted crops and, therefore, may affect their yield. To improve early growth and crop yields under such conditions, starter fertilizers are sometimes applied, but there appears to be no clear evidence indicating where the use of starter fertilizer is effective for improving crop growth and yields. Studies under varying conditions at different locations showed various responses to the use of starter fertilizers.

Wortmann et al. (2006b) in southeastern Nebraska applied NP and NP + S starter fertilizers as in-furrow, over-the-row, and 5 cm deep and 5 cm to the side of the seed treatments for grain sorghum planted under NT conditions. The soil orders were Mollisols, Alfisols, and an Entisol. The use of starter fertilizer

increased early growth by 48% in some trials where soil P was low, but grain yield responses to starter fertilizer were not related to the soil P content. Including S did not affect yield. Fertilizer placement effects on yields varied, but the frequency and magnitude of NT sorghum responses to starter fertilizer were not adequate to be profitable at the southeastern Nebraska sites. In contrast, in a similar study in eastern Nebraska where soil orders were Eutrudepts, Ustorthents, and Mollisols, application of starter fertilizer increased early corn growth by 30% in irrigated trials and by 10% in some rainfed trials. The use of starter fertilizer increased grain yields by 0.86 Mg ha^{-1} with irrigation, but only slightly without irrigation. Yields were similar with the different placement treatments. The yield response to starter fertilizer was greatest and most profitable under irrigated conditions where soil P was low. The conversion of early growth response to starter fertilizer into a grain yield response appeared to depend on soil water availability and on the soil P level (Wortmann et al., 2006a).

Under precision agriculture conditions for NT corn in Iowa, application of liquid NPK starter fertilizer in the seed furrow and beside and below the seed was compared with a no starter fertilizer treatment. The use of starter fertilizer often increased early growth and increased yield in some fields having a low soil P value, but decreased yield in one field. With high P values, yield responses were 0.08–0.19 Mg ha^{-1} with starter fertilizer applied in the furrow and 0.16–0.46 Mg ha^{-1} when applied beside and below the seed. Across fields, the early growth response was linearly but poorly correlated with the yield response (2.4%). With NT, corn yield responses to starter fertilizer are apt to be greatest when the soil P value is below optimum or when preplant or side-dress N rates are deficient (Bermudez and Mallarino, 2002).

To evaluate corn responses to starter fertilizer and tillage treatments, Bermudez and Mallarino (2004) in Iowa had starter or no starter fertilizer treatments in addition to farmers' normal broadcast application rates of NPK. Tillage treatments were spring disking, strip tillage on previously managed NT fields, and non-tilled NT fields. The use of starter fertilizer increased corn grain yield in some fields (up to 0.52 Mg ha^{-1}) and tillage increased yield up to 0.50 Mg ha^{-1} in some fields, but the overall average yield increases were small. Dry matter and nutrient uptake responses to both treatments did not result in large or consistent yield responses. Soil test results or soil series could not always be used to identify fields where an application of starter fertilizer would increase corn yield.

In Kansas, Niehues et al. (2004) applied starter fertilizer containing N, P, K, and S (with subsurface placement) as direct seed contact, dribble over-the-row, and subsurface band 5 cm below and 5 cm to the side of the seed row treatments for NT corn production. For all treatments, N was balanced at 0.17 Mg ha^{-1} by applying ammonium nitrate (AN) at planting, even for the nonstarter check treatment. Regardless of placement, the use of starter fertilizer often increased early dry matter production and significantly increased corn grain yields. Including S sometimes increased early dry matter production, grain yield, and nutrient uptake. For this study, the use of a starter fertilizer was an effective and efficient way to stimulate early growth and improve grain yields of NT corn grown continually in Kansas.

The aforementioned studies showed that there is no universal response to the use of starter fertilizer for improving crop growth and yields. The different studies under varying conditions at different locations clearly showed different responses to the use of starter fertilizers. Early growth often was greater where such fertilizer was applied and yields increased in some cases, but the yield increases were slight in most cases. Consequently, the question regarding whether starter fertilizer should be applied remains unanswered.

25.9.1.5 Crop Responses to Fertilizer (Nonstarter)

As for any other tillage method, crops grown under CS conditions respond to applied fertilizer. The degree of response depends on the inherent soil nutrient level. A response difference with CS, especially NT, relative to that with CT may occur due to the method of application. With CT, the fertilizer generally is placed into the soil before or when planting occurs. With NT, the fertilizer may be broadcast on the surface. Broadcast application, however, is satisfactory under NT conditions as indicated for a study with cotton in Tennessee (Howard et al., 2001). Relative to no N application, broadcast application of AN at 67 kg N ha^{-1} increased average lint yields from 0.74 to 1.28 Mg ha^{-1} on Loring silt loam (Oxyaquic Fradiudalfs) and from 1.09 to 1.54 Mg ha^{-1} on Lexington silt loam (Utlic Hapludalfs). A rate of 101 kg N ha^{-1} was needed to increase average yields on Memphis silt loam (Typic Hapludalfs) from 0.82 to 1.17 Mg ha^{-1}. Broadcasting AN was satisfactory for producing lint yields equal to or higher than those obtained by injecting urea-AN or splitting AN applications on the loess soils having different surface covers or residue.

25.9.2 Phosphorus and Potassium

Reduced and NT systems tend to keep soils cooler than clean tillage systems (see explanation in previous sections). For spring-planted crops in northern latitudes of the northern hemisphere, this results in slower plant root growth with reduced tillage systems. Because P is an immobile nutrient and uptake depends greatly on root interception, cold soils can create temporary P deficiencies. Starter fertilizers placed near the seed at planting may be beneficial in such cases. Failure to correct the temporary P deficiency stunts plant growth and delays development so that the crop may fail to mature before frost occurs in the fall. For a wheat-fallow system, placing P fertilizer with the seed was more beneficial under NT than for plowed and/or reduced tillage (stubble mulch) systems (Stecker et al., 1988). Apparently, cooler soil temperatures under high residue conditions in the spring were responsible for this difference.

In contrast to P, K is much more mobile in soils. Uptake of K and its effect on crops, however, may be influenced by placement as a fertilizer under NT conditions. In Iowa, P and K at various rates were broadcast, banded with the planter, or deep banded (at 15–20 cm depth) to determine their effect on early

growth, grain yield, and nutrient uptake by NT soybean. The study involved nine soil series on Argiudolls, Endoaqualfs, Endoaquolls, and Hapludolls. Yields increased with P fertilization when soil-test P was <9 and <12 mg kg^{-1} at the 0–15 and 0–7.5 cm depths, respectively. Band placement of K resulted in slightly higher yield than broadcast placement. Responses to K were not related to soil-test K values or stratification in the soil. Placement of P and K had little effect on early soybean growth, but affected early P and K uptake. Banding with the planter was more effective than broadcast application for P uptake, but both depths of band placement were more effective than broadcast application for K uptake (Borges and Mallarino, 2000).

No clear-cut recommendation can be made regarding when and how to apply K fertilizer. Therefore, producers should rely on soil test results and associated recommendations for their particular soil, cropping system used, and crop to be grown. Xinhua and Vyn (2002a) in Indiana found that NT soybean responded to K applications on some soils, but there was no yield difference whether the K was banded or broadcast. In another study involving different row spacing for soybean, band placement was superior to broadcast application of K fertilizer (Xinhua and Vyn, 2003). The response was greatest when soybean was seeded over the K bands. Also in Indiana, Vyn and Janovicek (2001) found that NT or zone-tilled corn responded to starter K fertilizer applied at a high rate, even when no K fertilizer was applied the previous fall. Fall or spring application of K fertilizer for corn was equally beneficial for the subsequent soybean crop under continuous or intermittent NT conditions (Xinhua and Vyn, 2002b).

When soils are sampled to determine P fertilizer requirements, the test results may be influenced by the previous P application method. The P fertilizer application method under NT conditions may affect P distribution in soil for months or even for years because P is highly immobile in soils. To quantify the spatial distribution and temporal dynamics of band-applied P and to assess its availability to crops, Stecker et al. (2001) obtained soil samples in a grid pattern around bands where 10 and 20 kg ha^{-1} of starter fertilizer P was applied about 6, 12, and 24 months previously. Soils were Mexico silty clay loam (Mollic Epiaqualf), Putman silty clay loam (Vertic Albaqualf), and Dockery silt loam (Aquic Udifluvent). The P concentrations decreased outward from the band center, were highest at either 6 or 12 months, and varied substantially along the direction of band application. The results indicated that including bands in soil tests would increase the risk of overestimating the amount of P that is available to crops.

Application of P and K fertilizers under continuous NT conditions may result in their stratification similar to that which occurs with band application. As a result, special sampling techniques may be needed to adequately determine the nutrient status of NT soils. For a study on three silt loams (Memphis, Lexington, and Loring) in Tennessee to which K had been broadcast at various rates for NT cotton production, Howard et al. (1999) determined P and K distribution with depth at in-row and between-row positions. Sampling depths were 0–8, 8–15, and 15–30 cm. The soil-test P level varied with soil, sampling position, and soil depth, but differences due to sampling positions (in-row or between-row) did not affect soil test ratings. Additional years under NT cotton production, however, could increase position influences and, therefore, affect P fertilizer recommendations. The soil-test K level was greater at the in-row position at the 0–8 cm depth of all soils. As a result, sampling only between rows could give a lower test value in some cases. The differences varied with fertilizer K rates and could increase with time of NT cotton production.

25.10 Surface Sealing, Crusting, and Seedling Emergence

Conservation tillage, particularly NT, reduces surface sealing and crusting compared with CT by maintaining permanent residue cover. Seal formation on a freshly cultivated soil exposed to the beating action of falling raindrops is due to two mechanisms, namely, the breakdown of soil aggregates by the impact force of raindrops and a physiochemical dispersion of soil clays. The initial water condition of aggregates at the beginning of a rainstorm affects their resistance to breakdown or dispersion (le Bissonnais, 1990). For initially dry aggregates, the breakdown is mainly due to slaking. The dry surface slakes rapidly under wetting and forms a seal of lower permeability. If the water content of the soil surface is high before rainfall, the degree of aggregate breakdown and surface sealing is low and results primarily from the mechanical impact of raindrops (Bradford and Huang, 1992). Wetting and drying of newly formed crusts (dry seals) normally act to weaken the crust and it may largely disappear as the soil surface granulates. Even though drying forms new aggregates, their size and stability are less than those of the original surface, and the final infiltration rates at the end of subsequent storms are lower than rates at the end of the first storm (Ben-Hur et al., 1985).

Soils crusts reduce seedling emergence, but their final effect on yield is crop dependent. For example, in the coarser-textured soils in the Lower Rio Grande Valley of Texas, cotton under CT conditions often must be replanted due to crusting following an intense rainstorm that prevents or greatly limits seedling emergence (Bradford and Peterson, 1999). The same is true for many soils in the southeast United States (Miller and Radcliffe, 1992).

The extent of soil crusting and its effect on seedling emergence are highly dependent on the tillage system used and the amount of residue cover. Maximum crusting usually occurs with moldboard plowing followed by disking several times. While surface sealing and crust formation are minimized in CS systems by maintaining high crop residue cover percentages, the high levels may have some negative effects, for example, reduced and uneven seedling emergence, particularly in regions with cooler and wetter climates. In regions where spring planting is delayed by snow melt and warming of the soil, seedling emergence is less with CS than with CT unless crop residue is partially removed from the row. Uneven crop emergence and reduced stand density

were reported in the northern Corn Belt in Wisconsin (Carter and Barnett, 1987), Iowa (Mock and Erbach, 1977), Minnesota (Ford and Hicks, 1992), and Illinois (Nafziger et al., 1991). By using injection knives to apply fertilizer and till the soil ahead of planting, Greiner (2008) reported that the tilled zone at planting time usually is warmer, the seeding zone is somewhat drier, and seedling emergence occurs sooner than where residue is not removed. Row-zone tillage in which narrow bands are tilled to satisfy the seedbed requirements allows most of the area between rows to be managed to improve infiltration and control runoff and erosion (Burwell et al., 1968).

25.11 Compaction

Soil compaction is defined as the volume change produced by momentary load application caused by rolling, tamping, or vibration. It is the process by which soil grains are rearranged into closer contact to decrease void space. Compaction removes air from the soil without significantly changing the amount of water in the soil. Compaction can result from external forces such as traffic by tractors, implements, and other farm machinery or from internal forces (sometimes termed consolidation) resulting from increased drying, overburden, or changes in the groundwater table. The usual effects of compaction are increased soil bulk density, shear strength, resistance to probe penetration, and decreased soil compressibility and permeability. Soil drying or desiccation not only results in increased soil bulk density, but also soil cracking and development of macropores if expanding lattice clays are present (Bradford and Peterson, 1999).

One of farmers' primary concerns in switching to NT systems is the problem of soil compaction. Bulk density and soil strength can be less for plowed than for NT soil (Mielke et al., 1986; Bruce et al., 1990; Hill, 1990; Cassel et al., 1995). Bulk densities in the surface 75 mm were higher in four Midwestern U.S. NT soils, no differences in two, and less in one (Mielke et al., 1986). At the 75–150 mm depth, bulk density was greater with NT for only two soils. Clay contents were similar, ranging from 23% to 36%, and time in NT ranged from 6 to 13 years. After 28 years, bulk density of Wooster silt loam (Typic Fragiudalf) at Wooster, Ohio, was lower for continual corn with NT than with other tillage (moldboard plow and chisel plow) and crop rotation treatments (Lal et al., 1994). For a regional study across Ohio, Indiana, and Pennsylvania, Blanco-Canqui and Lal (2007b) reported that NT farming had moderate impacts on soil compaction. They observed that cone index, a parameter of soil compaction, was greater with NT than with CT in 9 out of 13 soils, while bulk density was greater with NT only in 2 soils. These increases in soil compaction parameters with NT were, however, small and well below the threshold levels of excessive compaction.

In poorly structured soils with low OM, long-term NT can lead to higher soil strengths that may limit root growth and crop yields. In most soils, however, even though strength and bulk density under NT conditions are often greater than under CT conditions, crop yields are seldom reduced (Radcliffe et al., 1988). Detrimental effects of greater compaction are often negated by more positive effects of increased water infiltration, reduced soil temperature, reduced soil water evaporation, and greater water storage. Also, roots under NT conditions grow into existing root channels, worm holes, or fractures between soil structural units. As a result, root growth may actually be greater under NT conditions (Merrill et al., 1996).

Although use of NT provides various benefits on soils subject to compaction as mentioned earlier, cotton yield reductions have jeopardized NT adoption in the Tennessee Valley region of northern Alabama. Subsoiling reduced the compaction index 12% and 15% compared with non-subsoiled CT and NT soils, respectively. Fall deep non-inversion tillage by either paratilling or in-row subsoiling with a narrow-shank subsoiler resulted in cotton yields 16% and 10% greater than with CT and NT, respectively, for which the soil was not loosened. Non-inversion in-row deep tillage in fall coupled with a rye cover crop that produces adequate residue to provide for erosion control and water conservation is a highly competitive and practical CS system for the region (Schwab et al., 2002).

In addition to soil compaction that may result from performing cultural operations for crop production, compaction may result from other traffic in fields such as spreading fertilizer or manure, pesticide applications, and harvesting operations (harvester and grain hauling). In many cases, the weight of such equipment plus their loads is greater than that of equipment used for cultural operations and, therefore, may lead to severe soil compaction. To some extent, the degree of compaction may be controlled by the tire pressure or type of tires on the equipment. For a study on Hublersburg silt loam (Typic Hapludult) in Pennsylvania, NT soil was not compacted or compacted annually with a truck having road tires (700 kPa inflation pressure) or flotation tires (250 kPa pressure) that provided a 10 Mg axle load. In-row tilling the compacted soil 40 cm deep resulted in corn yields similar to those with NT without compaction in 3 years and greater yields in 1 year. The results showed little need for in-row tillage to manage compaction under long-term NT conditions when axle loads do not exceed 10 Mg and when using flotation tires that have inflation pressures <250 kPa (Sidhu and Duiker, 2006). Also, practicing controlled-traffic farming minimizes the potential for the development of severe compaction problems (Tullberg et al., 2007). Clearly, careful management regarding equipment used for cultural operations and other equipment traversing fields is important for minimizing soil compaction.

The degree of soil compaction is gradually reduced with time under NT conditions. Macroporosity and earthworm channels generally are greater in NT soils (Drees et al., 1994). In the subtropical, semiarid regions of Texas, earthworms are abundant in NT soils, but absent in CT soils (Bradford and Peterson, 1999). Even in colder semiarid regions such as North Dakota, changing to an NT system greatly enhances earthworm populations (Deibert and Utter, 1994).

NT soils develop an intrinsic ability to resist excessive soil compaction with time, depending on OM input, soil type, management, and climate. Accumulation of soil organic C is one

of the main causes for the reduced susceptibility of NT soils to compaction in the long term. Soil OM confers elasticity and resilience to soil because of its low density and high specific surface area. Accumulation of organic C near the soil surface in combination with residue mulch cover can reduce compaction and compression. In turn, CT accelerates decomposition of soil OM, reducing the soil's ability to resist compaction and compression. Thomas et al. (1996) and Assis and Lancas (2003) reported that soil compactibility as determined by the Proctor test was much lower with NT than with CT in temperate and tropical soils, due to the greater organic C accumulation in NT soils. Soil compactibility is negatively correlated with organic C content.

The potential for plow pans or other mechanically compacted layers to develop is sharply reduced when using smaller tractors, performing less tillage, and making fewer trips across the field, which occurs for crop production under CS, especially NT, conditions. Furthermore, compaction of soil surface layers by raindrop forces or surface sealing is less under CS due to protection of surface soil layers by greater residue cover. Consolidation of surface layers due to desiccation is reduced with greater residue cover under CS because of less soil water evaporation.

The degree of reconsolidation and compaction that occurs when plowing is eliminated depends on the crop rotation, amount of surface residue, control of wheel-traffic, climatic factors (rainfall and temperature), and soil variables. Soil variables include soil texture and structure, clay mineralogy, OM content, and others. Compaction due to tractor and machinery traffic and consolidation from desiccation are more of a problem in coarser-textured soils with massive structure and low OM levels, especially with monocultures of low residue crops such as cotton and soybeans, than in fine-textured soils. For example, reduced yields due to soil compaction have been reported for the highly weathered soils of the southeastern United States (Touchton and Johnson, 1982), whereas compaction is less of a problem for deep loessial soils in Illinois and Indiana (Bradford and Peterson, 1999).

Soil compaction problems must be corrected by mechanical means before starting an NT system (Radcliffe et al., 1988), or crop yields on some soils may be reduced for several years until biological forces loosen the soil. To reduce soil reconsolidation or if traffic compaction occurs, a paratill or similar tool that loosens the soil from beneath, leaves the surface relatively smooth, and maintains residue of the previous crop on the surface can be used (Unger, 1993). Soil compaction in the upper horizons can also be reduced with strip-tillage in the row (Radcliffe et al., 1989; Raper et al., 1994) or while applying fertilizer with fertilizer knives.

By controlling traffic patterns, compaction is generally confined to the wheel track areas (Larney and Kladivko, 1989; Liebig et al., 1993; Sweeney et al., 2006). About 70%–90% of traffic compaction occurs during the first pass of a tractor or machinery. By not controlling traffic patterns, therefore, compaction in the entire field is possible. With time, soil compaction is gradually alleviated by biological means when using a CS system. After 3 years on Willacy fine sandy loam (Udic Argiustolls) in south Texas, soil structure was improved, yields were equal to those with CT, and the compaction problem was gradually reduced by using NT (Bradford and Peterson, 1999). Wheel track compaction can also be reduced by performing chisel tillage (Sweeney et al., 2006).

25.12 Cropping Systems

Production of any crop involves some type of cropping system. The system may involve growing the same crop each year (continual cropping), the same crop grown alternately with fallow periods, or two or more different crops grown in a rotation. Some results were given and some comments were made regarding cropping systems in previous sections. In this section, we stress, among other factors, including the use of CS, the importance of cropping systems for storing and making better use of soil water, crop production by using shorter fallow periods, recognizing concern about herbicide carryover to succeeding crops in a sequence, identifying possible substitute crops if one crop is destroyed (hail damage, delayed planting, etc.), and cropping system effects on soil properties.

In the 1930s, the combination of a major drought and clean tillage used for crops at that time resulted in catastrophic erosion by wind in the semiarid U.S. central and southern Great Plains. Stubble mulch tillage was developed during that period to help control erosion and it also improved soil water conservation (Greb, 1979). When stubble mulch tillage is used repeatedly to control weeds, it can result in less than 30% surface residue cover when the next crop is planted. This is especially the case for a wheat-fallow cropping system that results in one crop in 2 years with a fallow period of about 15 months between crops. The low amount of residue remaining increases the potential for erosion and has generally resulted in low water storage efficiencies, often <25% (Haas et al., 1974; Johnson et al., 1974; Farahani et al., 1998). As a result, fallowing that has long been a controversial practice because of the low water storage efficiencies associated with it has, therefore, been replaced by more IC systems in some cases.

With the development of herbicides in the 1940s and continued development of even more effective herbicides through the years, reduced tillage and even NT crop production became possible. This resulted in further improvements in soil water conservation because of less water use by weeds, improved water infiltration, and decreased soil water evaporation. As a result, the controversial practice of using long fallow periods has been replaced by more IC systems in some cases.

With adequate surface residue, which is possible by using CS, especially NT, water conservation is improved and conditions become favorable for reducing the length of fallow periods and increasing cropping intensity. For the southern Great Plains, a winter wheat-grain sorghum-fallow (WSF) system that results in two crops in 3 years is well adapted. This system involves fallow periods of about 11 months between the crops and increases annualized grain yields relative to those with a wheat-fallow system (Baumhardt and Anderson, 2006). For a WSF study at Bushland, Texas, wheat straw was placed on Pullman clay loam

at rates ranging from 0 to 12 Mg ha^{-1} at the time of wheat harvest. Plots were not tilled during the ensuing fallow period. When grain sorghum was planted about 11 months later, fallow period precipitation storage as soil water averaged 23% and 46% with the 0 and 12 Mg ha^{-1} residue treatments, respectively. Dryland sorghum grain yields averaged 1.78 and 3.99 Mg ha^{-1} with the respective treatments (Unger, 1978).

The use of some type of CS has been shown to be suitable for various cropping systems in the central and northern Great Plains. A winter wheat-corn (or grain sorghum)-millet-fallow cropping system avoids long fallow periods and results in three crops in 4 years in the central Great Plains (Wood et al., 1991). Cropping systems that reduce fallow length in the northern Great Plains include spring wheat-winter wheat-fallow (two crops in 3 years); safflower (*Carthamus tinctorius* L.)-barley-winter wheat; spring wheat-corn-peas; spring wheat-winter wheat-sunflower; and spring wheat in rotation with soybean, peas, safflower, sunflower, buckwheat (*Fagopyrum esculentum* Moench), or canola (Black, 1986; Black and Tanaka, 1996; Unger and Vigil, 1998).

By increasing cropping frequency, the proportion of fallow that occurs in fall, winter, and spring months is increased, thereby resulting in the highest precipitation storage efficiency. Also, it greatly decreases or avoids the fallow extending in the second summer when no additional precipitation is stored as soil water (Peterson and Westfall, 2004).

The foregoing examples stressed the importance of improving soil water storage in an effort to increase cropping intensity by reducing the length of fallow in the cropping system. Even with fallow, however, water availability for dryland crop production is strongly influenced by precipitation amount and time of occurrence, which are highly unpredictable. Rigid cropping systems rely on growing certain crops at predetermined times. Occasionally, however, substantial amounts of precipitation occur late in the growing season or soon after harvesting a crop, thereby possibly negating the opportunity for storing much additional water during the ensuing fallow period. When such condition develops, opportunity cropping can be used to grow an adaptable crop to use the water that has become available and to eliminate or shorten the originally planned fallow period. In the southern Great Plains, for example, short-season grain sorghum can be grown after harvesting winter wheat and winter wheat can be grown after harvesting grain sorghum. Other crops evaluated for opportunity cropping in a study at Bushland, Texas, were forage sorghum (*Sorghum* spp.), pearl millet, oat, triticale (X *Triticosecale* Wittmack), kenaf (*Hibiscus cannabinus* L.), pinto bean (*Phaseolus vulgaris* L.), and fall and spring canola (Unger, 2001). Crops suitable for opportunity cropping were winter wheat, grain sorghum, triticale, forage sorghum, pearl millet, and oat. Opportunity cropping is a more intensive system than fixed cropping systems. As a result, precipitation use efficiency is greater than with systems involving long fallow periods. For a 5 year study in the central Great Plains, economic precipitation use efficiency (i.e., value of crops produced) was 45% greater with opportunity cropping than for set rotations that included fallow (Nielsen et al., 2006).

The producer's goal for cropping systems generally is maximum crop yields, but the economics of production are important also with tillage system often influencing the economic returns. For a dryland study in North Dakota, DeVuyst and Halvorson (2004) evaluated the economics of SW-F and spring wheat-winter wheat-sunflower IC systems under CT, minimum tillage, and NT conditions and various N levels. For the IC system, minimum tillage resulted in greater profits than CT and NT under the same N treatments, but profits were more variable with minimum tillage. The highest N rates resulted in the greatest profits. The IC system with minimum tillage or NT was more profitable than the best SW-F system with CT at that location. Analyses revealed that the SW-F system and the IC system with CT were economically inefficient as compared with the IC system using minimum tillage or NT.

Under more humid conditions than in the Great Plains, crops are grown without fallow, but crop rotations are still widely used. For a corn-soybean rotation study in Minnesota, NT after soybean reduced corn yields in 2 of 4 years compared with full-width fall chisel tillage and spring field cultivation. Also, full-width tillage for soybean in rotation with zone tillage or fall strip tillage for corn resulted in greater corn yields and economic returns than annual full-width tillage. Soybean yields were greater with rotational tillage, but the difference among tillage systems was not large enough to provide an advantage to full-width tillage. Considering both crops, rotational tillage provided for greater yields, but not greater economic returns (Vetsch et al., 2007).

Simplified crop rotations lead to deterioration of soil physical, chemical, and biological attributes and adversely impact crop production. Diverse and consequently more IC systems in combination with reduced tillage and NT that improve soil attributes and sequester C are potential alternatives to crop-fallow systems (Pikul et al., 2006; Benjamin et al., 2007). Impacts of cropping systems on soil properties differ from those of tillage treatments. Cropping system impacts on soil conditions and C sequestration are often detectable for longer periods than with tillage treatment impacts (Benjamin et al., 2007).

Cropping systems alter soil functions because of differences in the amount of above- and below-ground biomass input and rooting patterns. Differential surface cover among cropping systems influences changes in surface soil processes (e.g., surface crusting) and properties (e.g., water infiltration, aggregate stability). High-biomass producing crops in combination with reduced tillage and NT systems improve soil surface conditions. Plant roots through deep extension and proliferation can alter pore-size distribution by creating fine and coarse root channels within the soil profile (Benjamin et al., 2007).

Impacts of cropping systems on soil properties are not always consistent, depending on soil, length of management, and climate. After 15 years of management, Benjamin et al. (2007) observed no differences in soil bulk density, pore-size distribution, water retention capacity, and saturated hydraulic conductivity due to using wheat-fallow, wheat-corn-fallow, wheat-corn-sunflower-fallow, and wheat-corn-millet rotations under NT on a silt loam

in eastern Colorado. Also in eastern Colorado, Shaver et al. (2003) found that the use of NT for 12 years in IC systems including continual cropping, wheat-corn-fallow, and wheat-sorghum-fallow reduced soil bulk density and increased soil porosity, but had no affect on sorptivity when compared with a wheat-fallow system. On a regional study across eight locations in the Great Plains, Pikul et al. (2006) observed that cropping system effects on soil structural properties were highly soil dependent.

25.13 Cover Crops

Cover crops may play an important role within a CS system by protecting the soil against erosion by wind and water, increasing soil OM, improving soil structure and other soil physical properties, altering soil temperature and soil water content, and increasing fertility by recycling nutrients and providing biologically fixed nitrogen (in the case of leguminous cover crops). Cover crops also can improve weed control through competition (Vasilakoglou et al., 2006) or allelopathic effects, and may improve environmental quality through the protection of surface and ground waters. Efficient use of cover crops in management systems, however, depends on the purpose of the cover crop and on factors such as prevailing temperatures, length of growing season, and rainfall amount and distribution (Bradford and Peterson, 1999).

Cover crops generally are more adaptable to farming systems in the southeastern United States because of greater rainfall than in drier climatic regions (Bradford and Peterson, 1999). The goal for a study by Schomberg et al. (2006) in Georgia was to achieve a better understanding of cover crop and tillage system interactions that can lead to greater productivity and economic returns for cotton production. That study on Bonifay fine sand (Grossarenic Plinthic Paleudults) involved seven different cover crops and strip tillage or NT. Cover crop biomass was greatest with rye and hairy vetch (*Vicia villosa* Roth) and the most N (80 kg ha^{-1}) resulted from Austrian winter peas (*Pisum sativum* ssp. a*rvense)*. Other cover crops were balansa clover (*Trifolium michelianum* ssp. *balansae*), crimson clover (*Trifolium incarnatum* L.), oil seed radish (*Raphanus* spp.), and black oat (*Avena strigosa* Schreb.). Strip tillage increased yields and annual returns over those with NT, probably because of improved availability of water. Strip tillage with black oat as a cover crop was the best combination for maximizing profit under the conditions studied. It increased profits for cotton by \$50–\$75 ha^{-1} over those for systems where rye was the cover crop.

Although cover crops seemingly are more adaptable to the more humid regions, they may have advantages in other regions also. In Missouri, maximum dry matter yield in spring resulted from a hairy vetch cover crop that provided 44 and 57 kg N ha^{-1} in corn and grain sorghum experiments, respectively. Greatest corn and grain sorghum yields, however, were obtained with either hairy vetch or Austrian winter pea cover crops (Reinbott et al., 2004). In California, the presence of cover crops increased the steady infiltration rate by 37%–41% and cumulative infiltration by 20%–101% as compared with conditions without cover crops (Folorunso et al., 1992). Timely killing of cover crops is essential to achieve maximum benefits from their use (Wagner-Riddle et al., 1994; Duiker and Curran, 2005).

In northern climates, cover crops often are not used because they generally result in soils being cooler in the spring, reduce the water supply for subsequent crops, and tend to shorten the growing season for subsequent crops. In U.S. semiarid regions, greater water stress and, therefore, potentially lower yields of subsequent crops are major constraints to using cover crops (Unger and Vigil, 1998; Baumhardt and Lascano, 1999). Also, farmers are reluctant to use cover crops because of the additional cost for their establishment and termination.

Intense management is required to achieve success with cover crops (Unger and Vigil, 1998). Time to kill the cover crop in the spring is critical to yield of the ensuing crop due to factors such as soil drying and warming, insect and weed pressure, and planter performance. Late April or early May kill dates consistently resulted in greater corn yield than earlier kill dates in Maryland (Clark et al., 1997). Soil water conservation during summer resulting from the presence of cover crop residue was more important than spring water depletion by growing cover crops in determining final corn yield.

25.14 Comparison of Conservation Tillage with Conservation Agriculture

Conservation agriculture (CA) "is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment" (FAO, 2008). Based on several reports, CA is a system of integrated soil, water, and agricultural resources management. The main objective is economical, ecological, and socially sustainable agricultural production while the soil is regenerated or soil degradation is reversed. The system involves maintaining a permanent soil cover, practicing minimum soil disturbance, and using crop rotations. Benefits include fuel, implement maintenance and replacement, labor (time) savings, greater and more stable crop yields, and a lower requirement for heavy work. Other benefits are crop diversification; food security and diet improvements; improved water availability, amount, and quality; improved soil fertility and regeneration; less erosion; improved air quality; and greater agricultural biodiversity, namely, more diverse crop rotations, enhanced soil biodiversity, and less pressure on marginal lands, forests, and natural reserves (Hobbs, 2006; Unger, 2006). In essence, many characteristics of CA are also embodied in CS, especially the NT type of CS.

The key principles of CA are minimum mechanical soil disturbance, permanent soil surface cover with organic materials, and use of crop rotations involving more than two crop species (FAO, 2008). In its maximum condition, NT could meet the principles of CA, but, according to its definition, requirements

for NT do not meet the requirements for CA. For example, soil disturbance with a subsoiler is possible with NT whereas no such disturbance is appropriate with CA. Also, complete cover of the surface is required for CA, but not for NT. It is, however, important to recognize that a high level of residue cover is also essential for NT if soil and water conservation and soil C sequestration are priorities. Finally, CA requires use of crop rotations with more than two crop species. In contrast, NT can be practiced with one crop grown continually. Both systems, however, can provide for excellent control of erosion by wind and water and improve water conservation, crop production, and environmental conditions as well as many of the benefits mentioned earlier. As a result, either system may have its place in a given locale.

Although CA is a highly beneficial system, as previously mentioned, there are problems associated with its use (FAO, 2006, 2008). First, there may be financial constraints for producers to adopt CA because of the need to purchase new equipment and the initially lower crop yields with the system (CA is based on establishing an organic layer and producing its own fertilizer, which may take time and thereby cause yields to be lower than those previously obtained). Second, there seemingly is not enough pressure to adopt CA in some parts of the world because the need for an intensive conservation system as CA is not fully recognized and, therefore, it is not adopted. Finally, with the initial reduction in crop yields when changing to CA, it may be difficult to produce adequate food for the ever-increasing world population.

25.15 Soil by Climate Interactions

Surface residue has major benefits for agriculture, among the foremost being improved soil and water conservation. The level of benefits is controlled by the particular soil and climatic conditions at a given location. Surface residue also may have effects on agroecosystems that are detrimental to plant growth and require management adjustments to ameliorate. For example, soil temperatures are reduced by residue cover, which can negatively affect spring-planted crops in northern latitudes.

The interactive effects of surface residue with soil and climatic factors determine whether the residue effects are positive, neutral, or even negative. Primary issues are problems with cold soil temperatures, excessively wet soil conditions, and high runoff situations; interactions affecting crop rotation choices and weed control; and using surface residue management in conjunction with other conservation measures.

25.15.1 Problems Related to Cold Soils and Excessive Soil Water

In cold and humid climates, lower crop yields obtained with NT are often attributed to lower soil temperatures and excessive soil water contents during the early growth of spring crops, especially when crop residue is not removed from the row (Fausey and Lal, 1989). McCalla and Duley (1946) showed that corn residue mulches decreased soil temperatures in midsummer (July–August) at Lincoln, NE, by 3°C–7°C as mulch rates varied from 5 to 20 Mg ha^{-1}. This exemplifies an ameliorating effect of residue on a negative process, namely, summertime evaporation. In contrast, Al-Darby and Lowery (1987) showed that a cover of 55%–87% under NT conditions lowered soil temperatures by as much as 4°C compared with those with CT under spring conditions in Wisconsin. Corn seedling emergence (100%) was delayed by 2–8 days with NT compared with those with CT systems. Although emergence was delayed and plant growth was slower early in the season, corn grain yield differences were not significant. Al-Darby and Lowery (1987) concluded that the additional water saved with NT compensated for the early delays in plant growth. Also in Wisconsin, Carter and Barnett (1987) reported that for continual corn with NT, soil temperatures were cooler, emergence percentage and stand establishment were lower, and phenological development was delayed compared with corn produced using a moldboard plow system. Soil temperature at the 2-cm depth in barley plots in the semiarid region of southern Alberta, Canada, averaged 13.9°C with NT and 14.7°C with CT in spring (May), but these differences disappeared later in the growing season and grain yield was not affected (Carefoot et al., 1990).

Residue cover does delay plant development. For example, corn grown in residue-covered plots in Michigan required 3.5 more days to reach the VT (designated as the transitional stage between the vegetative and reproductive stages, namely, tasseling) stage in 1987 and 8 more days in 1988 (Fortin and Pierce, 1990). Producers must be prepared to deal with delayed growth of spring crops in reduced and NT systems because of low soil temperatures. Delayed emergence, for example, may reduce crop competition with weeds and allow them to flourish; such weeds use water and nutrients (e.g., N) and could ultimately decrease crop yields. Therefore, proper attention to weed control, planting dates, cultivar selection, and possibly starter fertilizer application is needed when it is known that cold stress will occur. In general, the need for intense management increases whenever additional stresses are imposed.

Soil properties that affect water infiltration, permeability, and drainage must always be properly assessed when making residue management decisions. Factors that cause soils to remain wetter longer generally cause them to be colder. Again, this is only a problem with spring-planted crops such as spring cereals, soybean, corn, and grain sorghum at northern latitudes. The latter two species are much more sensitive than small grains under these conditions. Research in the Corn Belt of the United States, showed that use of NT on poorly drained soils results in lower yields than use of CT. Long-term research has shown, however, that continued use of NT and disease-resistant cultivars has overcome the negative response. Also, grain yields after 18 years of NT are now equal to or greater than those with CT. Grain yields on well-drained soil increased with time under the NT system (Dick et al., 1991). Producers with poorly drained soils should expect lower productivity in the initial years after switching to high residue systems. It even may be best to avoid complete NT in these situations. Better choices may be ridging and bedding that reduce adverse effects of high residue systems on poorly drained soils.

Soil texture, slope, and drainage classification are the key factors in making decisions about tillage system choice (Peterson, 1994). Poorly drained soils are not easily adapted to high residue systems. Coarse-textured soils, even when poorly drained, are less of a problem than fine-textured soils in the same drainage category. Well drained soils are good candidates for NT or reduced tillage if they have a silt loam or coarser texture. Silty clay loam and silty clay soils may present problems for planting equipment if they are wet and, therefore, would be best managed with a more disturbed-soil system; perhaps ridge tillage. All steeply sloping soils regardless of textural class are best managed with reduced or NT systems because their runoff and erosion potentials are high.

25.15.2 Weed Control Problems Related to Soil, Climate, and Tillage Choice

Weed control problems usually increase, at least in initial years, when converting to high residue (CS) systems. With less burial of weed seeds, greater weed emergence seems to be the norm. Grassy weeds like downy brome (*Bromus tectorum*) are particularly favored when tillage is reduced. Furthermore, substitution of sweep tillage for mixing and inverting operations (disks and plows) decreases ease of grassy weed control. The problem is greatest when weeds and crops have the same or similar growth cycles. This is the case with downy brome, which germinates at about the same time that winter wheat is planted. Such weed is especially difficult to control in monoculture systems like continual wheat or wheat-fallow.

Crop rotation is one of the best ways to combat weed problems in any system and this is especially true with reduced tillage and NT. By changing crop type, weeds can be controlled at a different phase of their growth cycle. For example, following wheat (a cool season crop) with a warm season crop (e.g., grain sorghum, sunflower, millet, or corn) provides an opportunity to control weeds that are a problem for wheat.

Herbicides are used to replace part or all of the tillage operations in high residue (CS) systems. Close adherence to specifications for these products is essential to achieve maximum weed control benefits. Also, application methods may need refinement to minimize interception of the herbicide by the residue. Required rates of material can vary with soil texture and OM content. In general, finer-textured soils and those of higher OM content require higher rates of soil-applied herbicides to satisfactorily control weeds than coarse-textured soils. Soil clays and OM inactivate these herbicides and, therefore, rates must be adjusted as prescribed by the manufacturer. Also, caution must be exercised regarding herbicide carryover to the next crop. Coarse-textured, low OM content, and high pH soils are particularly susceptible to carryover problems. Again, applying herbicides at rates no greater than label specifications minimizes these potential problems (Bradford and Peterson, 1999).

When converting to high residue systems, producers must have or must acquire herbicide management skills. Correct sprayer operation from calibration to nozzle type selection is a key requirement to success with residue management systems. New technology, namely, site-specific application for which herbicides are applied only where weeds are present in a field, will greatly aid in judicious use of herbicides (Wilkerson et al., 2004; Goudy et al., 2008).

25.15.3 Surface Residue and Other Conservation Measures

Maximizing snow catch is a vital water conservation measure in dry regions where snow constitutes 20%–50% of the annual precipitation and, therefore, represents a valuable resource for agriculture. Stubble height strongly influences snow catch. Taller stubble retains more snow, but also can increase runoff from snowmelt in spring. Soils that freeze deeply prior to snowfall may be non-conductive to water and, therefore, potentially provide the worst scenario for runoff from snowmelt. With warmer climates like in the central and southern Great Plains, snowmelt is more easily captured because soils do not freeze as deeply and often thaw under the snow; thus, substantial snow and its melt water may be captured after spring thawing occurs. Greb (1979) reported that the efficiency of storing water from snowmelt often is double that of water received as rain.

Contour farming in conjunction with residue maintenance (CS) further maximizes water capture from either rain or snowmelt. Terraces also effectively capture water, but are less necessary on land with good residue cover and contour farming. Obviously, land on slopes >7%–8% may still be best managed with terraces in addition to residue maintenance. Use of contour farming, terracing, and possibly strip cropping in conjunction with CS may be especially important in regions where major high-intensity rainstorms commonly occur and, therefore, may lead to severe soil erosion where only CS, even the NT system, is used.

Maintaining residue on the soil surface by using CS is an invaluable management practice. It enhances water capture and retention, but the cost of storing the additional water with improved residue management can decrease profits if producers are not prepared to effectively and efficiently use the water. Finally, producers should be aware that residue may have negative effects in terms of cold soil temperatures at the time of spring planting. Appropriate system choices including planting method, crop choice, possibly starter fertilizer use, etc. can help ameliorate the potentially negative cold temperature effects.

25.16 Disadvantages

By definition, at least 30% of the soil surface must be covered with residue when the next crop is planted in order to qualify as CS. With NT, a CS method, much greater amounts of residue often are present. Surface residue is highly important for conserving water, controlling erosion, and minimizing environmental pollution under many conditions, but the residue along with the NT method itself also may cause disadvantages under some conditions. Through proper management, most disadvantages usually

can be avoided or overcome, thus generally leading to favorable results when using CS. Potential disadvantages of CS include:

1. Conservation tillage involves an increased use of herbicides, which may increase production expenses that are not offset by decreased tillage costs.
2. Increased use of herbicides may increase the risk of non-point-source pollution, for example, of runoff water and groundwater under some climatic conditions and on some more conductive soils.
3. Some weeds are difficult to control with herbicides or have become tolerant of herbicides. As a result, tillage may be required to control such weeds.
4. Greater amounts of N fertilizer may be needed when first switching to CS (especially NT) systems; also, reduced N mineralization due to heavy residue mulch can require the use of increased amounts of fertilizers. Changes in fertilizer application methods may be needed when using CS systems and it may be necessary to apply a starter fertilizer under some conditions.
5. High earthworm populations and preferential water flow through the deep burrows may cause leaching of agricultural chemicals to depths beyond the reach of plant roots and into groundwater.
6. Soil compaction may occur under some conditions, particularly in nearly level and clayey soils, thus requiring occasional tillage or subsoiling to overcome the problem.
7. The NT method of CS may not be suitable on hard-setting soils because water infiltration often is lower than where such soils are loosened by tillage.
8. The NT method may not always be better than CT on clayey, cold, and wet soils. Cold soil (delayed warming) due to large amounts of surface residue may delay crop planting, reduce the seed germination rate, cause low plant populations, and possibly result in freeze damage if maturity is delayed. Also, reduced runoff and evaporation aggravate excessive water problems on poorly drained soils.
9. Leachates from residue of some crops may cause phytotoxicity problems for subsequent crops.
10. New crop-planting and herbicide-application equipment may be required, thus initially resulting in additional expenses for the producer.
11. Crop planting may be difficult where large amounts of residue are on the surface. For example, NT planting under irrigated conditions at Bushland, Texas, was difficult because the large amount of surface residue kept the clay loam moist, thus causing the soil to severely adhere to the planting equipment (S. Evett, Personal communication, 2008).
12. Surface residue provides habitat for some rodents, insects, etc., which may damage some crops.
13. Conservation tillage, especially NT, is a major departure from CT and, therefore, requires good management for it to be successful. As a result, special training may be required, which may not be readily available or may entail additional expenses for the producer.

25.17 Conclusions

Conservation tillage, especially the NT method, represents the most dramatic change in soil management for crop production in the history of agriculture. Historically, farmers prepared their whole field as a seedbed, even though seeds were placed only in a small area. Now, major soil disturbance is no longer necessary because only a small area needs to be disturbed to prepare a seedbed or plant seeds. Quite obviously, these changes decrease labor and power requirements for the farmer. By not disturbing most of the soil, fields are kept in a more "natural setting." When disturbance is minimized, soil aggregate integrity is maintained and soil physical, chemical, and biological components respond positively. As a result, water conservation is improved, erosion is minimized, plant nutrients are retained, and soil biological processes proceed with fewer interruptions. The greatest benefits of CS, especially NT, agriculture will be achieved when farmers, technology-transfer persons, and scientists learn how to fully exploit this ecologically beneficial system. NT is a pioneering method of agriculture. The large benefits of NT for minimizing soil erosion, reducing tillage costs, improving soil quality, and many others outweigh the disadvantages associated with this tillage method. Conservation tillage combined with residue mulching, cover crops, crop rotations, and other best management practices is a win-win strategy for soil and water conservation and for sustained agronomic production (Blanco and Lal, 2008).

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