



United States Department of Agriculture

# **Soil Health Literature Summary— Effects of Conservation Practices on Soil Properties in Areas of Cropland**

A summary of more than 180 peer-reviewed, published documents relating to the effects of conservation management system practices on soil health, soil resiliency, and dynamic soil properties.



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# Soil Health Literature Summary—Effects of Conservation Practices on Soil Properties in Areas of Cropland

## Conservation Practice Standards Reviewed:

- Conservation Crop Rotation (328)
- Residue and Tillage Management, No-Till (329)
- Cover Crop (340)
- Mulching (484)
- Nutrient Management (590)

## Conservation Practice 328—Conservation Crop Rotation

**Definition:** Growing crops in a planned sequence on the same field (NRCS National Handbook of Conservation Practices, 2014)

**Purpose:** Plan and apply practice to support one or more of the following—

- Reduce rill and inter-rill erosion and wind erosion
- Improve soil quality
- Manage balance of plant nutrients
- Supply nitrogen through biological nitrogen fixation to reduce energy use
- Conserve water
- Manage saline seeps
- Manage plant pests (weeds, insects, and diseases)
- Provide feed for domestic livestock
- Provide annual crops for bioenergy feedstock
- Provide food and cover for wildlife, including pollinator forage, cover, and nesting

In regard to improving soil quality, overall results of the studies were variable. No consistent evidence showed that rotation practices alone affect the physical properties of soils, at least in the short term. In the long term, the production of organic matter may affect some physical soil properties, such as aggregate stability. The effects, if any, vary according to the crop and type of rotation. For some soils, the rotation may not affect aggregation (Filho et al., 2002). Benjamin et al. (2008) found that the rotation did not affect the stability of the aggregates, despite a high content of organic matter. Blanco-Canqui et al. (2004) reported that the effect of the rotation on physical soil properties may depend on the individual crop grown. For example, soils under corn had lower  $K_{sat}$  and slightly higher bulk density than soils under soybeans.

Use of tillage practices such as no-till may not have as much immediate impact on physical soil properties as crop rotation (Blanco-Canqui et al., 2004 and 2010). No-till cropping had little impact on the available water capacity to a depth of 1.5 meters. After 6 or 7 years, however, the available water capacity in the upper 15 centimeters of the soils under winter wheat in spring was highest in areas where a no-till cropping system was used.

Use of cover crops in the rotation had the greatest effect on physical soil properties. Winter cover crops associated with no-till cropping had a positive effect on these properties. All rotation sequences of winter cover crops under a no-till system improved the stability of the aggregates, reduced the bulk density and penetration resistance of the surface layer, and increased the porosity and available water capacity of the soils (Villamil et al., 2006).

Cropping systems had less effect on soil properties than traffic by wheeled equipment (under no-till systems). Wheeled equipment use negatively affected the mechanical and physical soil properties under most crop rotations. Compaction by wheeled equipment reduced the infiltration rate,  $K_{sat}$ , available water capacity, and macroporosity. Use of perennial grasses in the rotation (or permanently) benefited the hydraulic soil properties, particularly on slopes that are most susceptible to erosion (Jiang et al., 2007). In

a study by Benjamin et al. (2008),  $K_{sat}$  was significantly higher in soils under grasses than in soils with similar properties under a crop rotation system.

Use of agroforestry and grass buffers improved physical soil properties as compared to pasture rotation and continuous grazing. Restricting cattle grazing in buffer areas lowered the bulk density of the soil and increased  $K_{sat}$ , which increased the infiltration rate and reduced runoff (Kumar et al., 2010).

### **Conservation Practice 329—Residue and Tillage Management, No-Till**

**Definition:** Limiting soil disturbance to manage the amount, orientation, and distribution of crop and plant residue on the soil surface year-round (NRCS National Handbook of Conservation Practices, 2014)

**Purpose:** This practice allows for in-row tillage during the planting operation and use of equipment for closing the seed row or furrow. Full-width tillage is not allowed. The practice is used to support one or more of the following—

- Reduce sheet, rill, and wind erosion
- Reduce tillage-induced particulate emissions
- Maintain or increase soil quality and organic matter content
- Reduce energy use
- Increase efficiency of water use and precipitation storage
- Provide food and escape cover for wildlife

Purposes of this practice that directly relate to improving soil physical properties include: reduce sheet, rill, and wind erosion; maintain or increase soil quality and organic matter content; and increase efficiency of water use and precipitation storage.

Degradation of agricultural soils as a result of excessive tillage has spurred interest in no-till cropping systems. These systems help to maintain the physical conditions of a relatively undisturbed soil. Residue is left on the surface of the soil, making it less susceptible to wind and water erosion (Baker and Saxton, 2007). Tillage accelerates mineralization (breakdown) of crop residue and loss of soil organic matter (Stubbs et al., 2004).

No-till (NT) systems have been compared to various tillage practices under a range of conditions. Studies on how the practices affect physical soil properties had mixed results. Overall, NT systems tend to increase macropore connectivity while generating inconsistent responses in total porosity and soil bulk density as compared to conventional tillage systems (Stubbs et al., 2004). This corresponds to a general increase in ponded areas or a near-zero tension infiltration rate and saturated hydraulic conductivity. In recent decades, investigations documenting spatially averaged comparisons among tillage practices, generally comparing “snapshots” of various tillage systems to NT systems, have become relatively common.

Table 1 provides a list of some of the key pieces of literature that were reviewed to evaluate the effects of conservation practices on soil properties. The impact of an NT system on physical soil properties varies and is somewhat dependent on the soil temperature and moisture regime, length of time the system has been in place, amount of disturbance resulting from the system, diversity and intensity of the crop rotation, limitations of the soil and site, removal of residue after harvest, and use of other practices, such as growing cover crops and mulching. The impact is especially affected if the no-till system includes crops with fragile residue (e.g., vegetables, edible beans, potatoes, peanuts, cotton, and soybeans) and if soil disturbance results from harvesting crops (e.g., edible beans, potatoes, rooted vegetables, and peanuts). Crops with fragile residue provide less cover on the surface and return less carbon to the soils, which can increase erosion and decrease soil organic matter content. Growing crops that require disturbance of the soil during harvesting is contrary to the no-till practice standard and its purposes.

The literature clearly shows the importance of applying additional practices to offset a lack of residue if crops with fragile residue are included in the rotation. These practices include growing cover crops, double cropping, eliminating fallow, mulching, and including perennial grass or small grain in the rotation. Use of a no-till system and these other practices is effective in improving physical soil properties. This is especially important for soils that have inherent limitations, such as those that are sandy, have a very high content of clay, have a claypan or fragipan, or have other physical limitations that affect the amount

of water available for plants, plant growth and vigor, and plant yields. These practices are particularly needed in areas of the United States that have a warm, moist climate (which promotes production of residue and mineralization of soil organic matter) and in areas that have a semi-arid, hot climate (which makes it difficult to produce enough biomass to increase soil organic matter content) (Jiang et al., 2007; Hubbard et al., 2013; Olson et al., 2013; Evett et al., 1999).

Many of the studies listed in table 1 are short term (less than 5 years) or medium term (less than 12 years). Most changes in physical soil properties take place gradually. Table 1 provides a summary of the impacts of no-till systems and other tillage practices in relation to length of time in use, soil temperature and moisture regimes, and soil limitations. In general, long-term use of a no-till system along with use of high-residue crops during the growing season will enhance physical soil properties through the development and maintenance of water-stable aggregates, which increase the infiltration rate and the available water capacity (Brock, 1999).

Examples of key variables that impact the effectiveness of a no-till system include: the amount of soil disturbance that occurs during fertilizer application at the time of planting and other field operations; cropping practices used in conjunction with a no-till system that provide a synergistic effect, such as diverse cropping systems that include high-residue crops; use of cover crops during the off season; and erosion control practices. In addition, the amount of biomass, the content of carbon, and the residue management practices used after harvesting through planting of the next crop impact the soil organic matter content. Other key variables include yields, soil limitations (e.g., claypan and other root-restrictive layers or the low organic matter content of sand, highly erodible soils), and climate differences (see table 1).

**Table 1.—Impact of No-Till Systems and Associated Practices on Physical Soil Properties**

(Definitions of abbreviations: AgS—aggregate stability; AWC—available water capacity; BD—bulk density; CT—conventional till; Ksat—saturated hydraulic conductivity; MT—mulch till; N/A—not applicable; NT—no-till; POR—porosity; PR—penetration resistance; RT—ridge till; SOM—soil organic matter)

<b>Impact of NT and associated practices (negative effects underlined)</b>	<b>Tillage system and associated practices with the most beneficial or least detrimental impact</b>	<b>Systems compared</b>	<b>Years of NT</b>	<b>Moisture regions</b>	<b>Soil temperature regime</b>	<b>Soil texture/ limitation; location of study</b>	<b>Reference (first author, date)</b>
Improved Ksat	NT; perennial grasses in rotation (328)	CRP, NT with corn, soybeans, and wheat rotation and clover cover crop; MT with corn and soybeans rotation; NT with perennial hay and corn rotation	Short term	Subhumid	Mesic	Claypan soil; Missouri	Jiang, 2007
<u>Higher BD, lower POR,</u> higher microporosity, higher AWC	NT; corn, peanuts, cotton-sorghum, and soybeans	NT, CT, organic crop production, plantation forestry-woodlot, abandoned-field succession, integrated crop–livestock	8 years	Humid	Thermic	Sandy loam and loamy sand; Goldsboro, North Carolina	Raczkowski, 2012
Slight improvement in SOM	NT; small grain without fallow (328)	NT, MT, and CT with small grain, with and without fallow	11 years	Semi-arid	Frigid	Coarse sandy soils; SW Saskatchewan	Campbell, 1996
Improved SOM, POR, AWC, BD, and PR	NT; corn and soybeans rotation with winter cover crops (hairy vetch and cereal rye) (340)	NT with corn and soybeans rotation and winter cover crops	Short term	Humid	Mesic	Silt loam; Illinois	Villamil, 2006
Improved SOM and overall physical properties	NT; cover crops (340)	NT with various cover crops and fallow	Short term	Humid	Thermic	Sandy soils; Coastal Plains of Georgia	Hubbard, 2013

<b>Impact of NT and associated practices (negative effects underlined)</b>	<b>Tillage system and associated practices with the most beneficial or least detrimental impact</b>	<b>Systems compared</b>	<b>Years of NT</b>	<b>Moisture regions</b>	<b>Soil temperature regime</b>	<b>Soil texture/ limitation; location of study</b>	<b>Reference (first author, date)</b>
Maintained SOM and overall physical properties (with stover removal)	NT without stover removal following harvest; stover harvest sustainable with NT	NT and CT, with and without stover harvest	Long term	Humid	Mesic	Silt loam; Chazy, NY	Moebius-Clune, 2008
Improved Ksat, infiltration, AgS, BD, compaction, and PR	NT with residue mulch (484)	NT, RT, and CT, with and without application of residue mulch	Long term	Humid	Mesic	Silt loam; Central Ohio	Kahlon, 2013
Significantly improved AgS/size, SOM, and overall physical properties	NT with corn, soybeans, wheat, and cowpeas rotation (328)	NT and CT, with corn and soybeans; continuous corn; and corn, soybeans, wheat, and cowpeas rotations	Long term	Humid	Mesic	Silt loam; South-central Ohio	Aziz, 2013
BD unaffected; maintained SOM (SOM decreased with CT)	NT, especially last 2 years of wheat and barley rotation following pasture	NT and CT, with wheat and barley rotation following short-term pasture (wheat, barley, linseed, and peas)	9 years	Semi-arid, subhumid	Mesic	Well drained silt loam; New Zealand	Francis, 1993
<u>Increased BD</u> ; slightly improved SOM in surface layer only	NT with wheat and barley rotation and continuous cropping	Same as above except with continuous cropping	9 years	Semi-arid, subhumid	Mesic	Poorly drained silt loam; New Zealand	Francis, 1993
Significantly increased SOM, POR, and AWC	7-year NT; no rotation differences noted	NT and CT, with continuous wheat, wheat and fava beans, and wheat sulla rotations	3 and 7 years	Subhumid	Thermic	Clay loam; Tunisia	Jemai, 2013
Significantly increased POR, infiltration, Ksat, SOM, and AgS; improved BD	NT with soybean and oat double cropping	NT and CT, with soybeans and oats rotation	14 years	Subhumid	Thermic	Silt loam with weak structure; Northwest Australia	So, 2009

<b>Impact of NT and associated practices (negative effects underlined)</b>	<b>Tillage system and associated practices with the most beneficial or least detrimental impact</b>	<b>Systems compared</b>	<b>Years of NT</b>	<b>Moisture regions</b>	<b>Soil temperature regime</b>	<b>Soil texture/ limitation; location of study</b>	<b>Reference (first author, date)</b>
<u>Increased BD and PR</u> ; improved AgS	NT; no rotation/cover crop differences with or without grazing (slightly higher PR with cover crop and grazing)	NT and CT, with summer grain/winter cover crop and winter grain/summer cover crop, with and without grazing	2.5 years	Humid	Thermic	Sandy loam surface layer and clay subsoil (Cecil series); Piedmont Uplands, Georgia	Franzluebbers, 2008
Improved AgS, except at Alabama site; higher SOM in surface layer at all sites (nearly three times higher than with CT at Georgia site); <u>increased BD at all sites</u> ; no significant change in other properties	NT with continuous grain sorghum at Georgia site and continuous soybeans at other locations	NT and CT, with monoculture of grain sorghum at Watkinsville, Georgia and soybeans at other locations; no sites had cover crops	5 years at AL and MS sites; 9 years at TN site; 15 years at GA site	Humid	Thermic	Loamy sand at Auburn, AL; sandy clay loam at Watkinsville, GA; silty clay loam at Verona, MS; and silt loam at Jackson, TN	Rhoton, 1993
Increased macropore connectivity (all studies); inconsistent for all other physical properties; increased infiltration and AgS (most studies)	NT; no information on crop rotations, cover crops, and other management practices	NT only (29 studies cited)	No data	Varies	Varies	Varies	Strudley, 2008
Increased infiltration and AWC	NT with controlled traffic	NT and MT using a model, with and without controlled traffic	N/A	N/A	N/A	N/A	Li, 2008
Increased infiltration and AWC; improved BD and PR	NT with winter wheat	NT, MT, and CT, with winter wheat	8 years	Semi-arid, subhumid	Thermic	Silt loam; El Reno, Oklahoma	Dao, 1993

<b>Impact of NT and associated practices (negative effects underlined)</b>	<b>Tillage system and associated practices with the most beneficial or least detrimental impact</b>	<b>Systems compared</b>	<b>Years of NT</b>	<b>Moisture regions</b>	<b>Soil temperature regime</b>	<b>Soil texture/ limitation; location of study</b>	<b>Reference (first author, date)</b>
<u>Decreased K<sub>sat</sub></u> , <u>increased BD</u> ; improved macropore connectivity and structure	NT with winter wheat	NT, RT, and CT, with winter wheat	3 years	Humid	Mesic	Silt loam; Raasdorf, Lower Austria	Schwen, 2011
Decreased BD; increased infiltration and SOM	NT with summer/winter double cropping	Long-term CT with winter wheat, barley, and rye; long-term NT with summer/winter double cropping (i.e., sorghum cotton or soybeans with winter wheat, rye, barley, or crimson clover)	25 years	Humid	Thermic	Sandy loam surface layer and clay subsoil (Cecil series); ARS research farm, Piedmont Uplands, Watkinsville, GA	Franzluebbers, 2002
Increased infiltration and SOM	NT with summer/winter double cropping (328)	Long-term NT with summer/winter double cropping (i.e., sorghum cotton or soybeans with winter wheat, rye, barley, or crimson clover)	28 years	Humid	Thermic	Sandy loam surface layer and clay subsoil (Cecil series); ARS research farm, Piedmont Uplands, Watkinsville, GA	Campbell, 2005
Increased infiltration; minimal change in other physical properties	NT with wheat/soybeans-corn and wheat/soybeans rotations (328)	NT with continuous corn, continuous soybeans, wheat and soybeans double cropping, wheat and soybeans double cropping with corn, pasture, and tilled fallow	Short term	Subhumid	Thermic	Silt loam; Argentina	Sasal, 2010
Increased K <sub>sat</sub> ; improved soil structure	NT with highest level of mulching (484)	NT with straw mulch following hundreds of years of CT	4 years	Semi-arid, subhumid	Mesic, frigid	Silt loam; Northwestern Loess Plateau, China	Zhang, 2008

<b>Impact of NT and associated practices (negative effects underlined)</b>	<b>Tillage system and associated practices with the most beneficial or least detrimental impact</b>	<b>Systems compared</b>	<b>Years of NT</b>	<b>Moisture regions</b>	<b>Soil temperature regime</b>	<b>Soil texture/ limitation; location of study</b>	<b>Reference (first author, date)</b>
Maintained physical soil properties with NT and MT	NT and MT with corn and soybeans rotation (328)	NT, MT, and CT, with corn and soybeans rotation and continuous cultivated fallow	13 years	Subhumid, humid	Mesic, thermic	Claypan soil; Kingdom City, Missouri	Blanco-Canqui, 2004
Improved Ksat and POR	NT with highest level of mulching (484)	NT with three levels of straw mulch	10 years	Humid	Mesic	Silt loam; Central Ohio	Blanco-Canqui, 2007
Highly improved Ksat, BD, PR, structure, and SOM	NT with highest level of mulching (484)	NT, RT, and CT, with three levels of mulch	20 years	Humid	Mesic	Silt loam; Central Ohio	Kahlon, 2013
Minimally improved Ksat, SOM, BD, and POR (long-term and short-term NT had similar impact with corn and soybeans rotation)	NT with corn and soybeans rotation only slightly better than CT (both long-term and short-term); short-term NT similar to long-term NT; sod best with NT (surface only)	NT and CT, with corn and soybeans rotation; short-term NT after long-term CT; CT after long-term NT; CT after long-term sod; long-term sod	Long term and short term (4 years)	Humid	Mesic	Clay loam; Essex County, Ontario, Canada	Reynolds, 2007
Improved Ksat, POR, SOM; <u>decreased infiltration rate</u>	NT with continuous barley	NT and CT, with continuous barley	20 years	Semi-arid	Cryic	Silt loam; Interior Alaska	Sharratt, 2006
<u>Increased BD; decreased Ksat and infiltration rate</u>	Use of fallow in cropping systems (328) had a more negative impact than tillage system (MT and NT) on soil properties	NT and MT, with wheat-fallow and wheat-sorghum-fallow rotations	12 years	Arid, semi-arid	Thermic	Clay loam; Bushland, Texas	Evet, 1999
<u>Increased BD, decreased POR, improved AgS</u>	NT with corn and soybeans rotation (cover crop improved BD and POR as compared to no cover crop)	NT and CT, with corn and soybeans rotation with no cover crop, early-terminated cover crop, and late-terminated cover crop	3 years	Humid	Mesic	Silt loam; Southeast Purdue Agricultural Center, Indiana	Stipesevic, 2002

Impact of NT and associated practices (negative effects underlined)	Tillage system and associated practices with the most beneficial or least detrimental impact	Systems compared	Years of NT	Moisture regions	Soil temperature regime	Soil texture/ limitation; location of study	Reference (first author, date)
<u>Slightly decreased SOM</u> (even with NT)	NT with corn and soybeans rotation maintained most SOM	NT, MT, and CT, with corn and soybeans rotation and no cover crops	24 years	Humid	Mesic	Silt loam with fragipan; Southern Illinois	Olson, 2013

Physical soil properties that are affected by Conservation Practice 329 are discussed in the following paragraphs.

### **Bulk Density**

Most studies show that bulk density (BD) will increase slightly in the early stages of implementation of a no-till system after conventional tillage (CT) has been used (Stipesevic and Kladvko, 2002; Schwen et al., 2011). Some studies also show that bulk density may increase more with long-term use of NT systems than with CT (Evelt et al., 1999; Blanco-Canqui et al., 2004; Rhoton et al., 1993; Franzluebbbers and Stuedemann, 2008). The impact of NT on BD is highly variable, depending on the climate, soil limitations, and crop rotation and the used of other practices in conjunction with NT. The amount of biomass and organic material left on the soil surface and returned to the soil has a major effect on the decrease or increase of BD when comparing NT to CT. Soils that have a higher amount of soil organic matter and improved porosity naturally have lower BD than soils that have similar textures but have less organic matter content. Long-term NT studies by Kahlon et al. (2013) and Franzluebbbers and Stuedemann (2002) show a decrease in bulk density when additional practices, such as double cropping or applying mulch, are used in different climatic settings. Under ideal conditions, bulk density can be decreased even with short-term NT if additional practices, such as growing cover crops, are also used (Villamil et al., 2006). A decrease in bulk density immediately after tillage can be short-lived. Tillage has a negative impact on soil structure and aggregate stability, which leads to compaction and increased penetration resistance (see table 1).

Soils in a thermic soil temperature regime tend to have higher bulk density than those in a mesic soil temperature regime. This is true even after long-term use of a NT system unless additional practices (such as growing cover crops, mulching, double cropping, and including perennial crops or small grain in the rotations) are also used (Evelt et al., 1999). Warm, moist climates speed up mineralization of soil organic matter, which leads to a lower soil organic matter content and thus higher bulk density.

### **Available Water Capacity/Total Soil Water**

Hudson (1994) evaluated the impact of soil organic matter (SOM) on available water capacity (AWC) in soils that have a surface layer of sand, silt loam, or silty clay loam. A highly positive correlation was found between AWC and the content of SOM. In all texture groups, as the content of SOM increased from 0.5 to 3.0 percent, the AWC of the surface layer more than doubled. The volume of soil water held at field capacity increased at a much higher rate than that of water held at permanent wilting point. NT systems along with using high-residue crops in the crop rotation, using cover crops that provide high levels of biomass, maintaining crop residue with a high content of carbon, and avoiding excessive removal of residue, as well as climate, are key to increasing the content of SOM.

Several studies show that AWC improves when other physical soil properties, such as SOM, the infiltration rate, bulk density, soil structure, and penetration resistance, improve (Dao, 1993; Li et al., 2008; Villamil et al., 2006). Areas that had few site and soil limitations and areas where additional measures (such as including small grain in the rotation, growing cover crops, mulching, and other soil-improving practices) were implemented along with no-till had the most improvement in AWC (Villamil et al., 2006). No-till systems, as compared to conventional tillage, resulted in higher levels of soil moisture in virtually every study in which soil moisture was measured. Maintaining soil moisture is important for achieving high yields of biomass in rain-fed environments during the dry periods of the growing season.

### **Soil Organic Matter**

The extent that soil organic matter (SOM) is improved or maintained is not solely dependent on use of no-till systems (see table 1). Additional practices such as mulching (484), rotating crops (328), harvesting forage or biomass (511), and using cover crops (340); yields; climate; and length of time NT has been used can all impact SOM levels. In some long-term studies, SOM did not improve but losses were minimized. For example, in a 24-year study, NT plots on eroded soils in Southern Illinois that have a fragipan and are under a corn and soybeans rotation stored and retained 7.8 megagrams of carbon per

hectare more than CT plots (Olson et al., 2013). However, although erosion was minimized and the SOM content was higher in the NT plots, the SOM content did not increase over the 24 years. This was due to erosion, a fragipan in the soil, and the use of low-residue crops (soybeans). Even in thermic temperature regimes in the Southeast, SOM levels under mid- and long-term NT systems were higher than those under CT systems, but SOM levels are not likely to increase unless additional measures are used (Rhoton et al., 1993). Using high-residue crops and including perennial legumes, small grain, and/or high-carbon cover crops (such as cereal rye) provide the additional carbon and root mass needed to increase or maintain SOM levels. Aziz et al. (2013) demonstrated that SOM could be significantly increased with no restrictions in silt loam by adding crop diversity to traditional corn/soybeans rotations or to other rotations that include low-residue crops. Studies of long-term use of no-till systems that included additional measures, such as mulching, growing cover crops, and using diverse rotations in thermic soil temperature regimes, showed increases in SOM (Kahlon et al., 2013; So et al., 2009; Sharratt et al., 2006; Rhoton et al., 1993; Aziz et al., 2013).

### **Penetration Resistance, Compaction, Crusting/Sealing, and Infiltration**

Analyses of penetration resistance, compaction, crusting/sealing, and infiltration in studies of NT systems showed that these properties exhibit more improvement under NT systems than CT systems (see table 1). Brock (1999) summarized various several NT studies in the southeastern part of the United States and noted that long-term no-till resulted in reduced crusting/sealing and increased infiltration and significantly reduced runoff. Infiltration, penetration resistance, and/or crusting/sealing improved more under all NT systems studied, as compared to CT systems, in all areas where these properties were analyzed, except one (Villamil et al., 2006; So et al., 2009; Li et al., 2008; Dao, 1993; Franzluebbers, 2002; Sasal et al., 2010). The only study in which NT systems did not show improvements in these physical soil properties, compared to other tillage systems, was in interior subarctic Alaska. In this study, the infiltration rate was lower with NT than with a fall chisel plow system in an area where continuous small grain was grown (Sharratt et al., 2006). This was attributed to extreme climatic conditions and the limited time that the soils were not frozen.

### **Aggregate Size and Stability and Soil Structure**

In studies in which aggregate size and stability and soil structure were analyzed, these properties improved more under NT systems than CT systems (see table 1). Aggregate stability improved with only 3 years of NT on sandy piedmont soils in Georgia under thermic and humid climatic conditions, which cause a more rapid breakdown of organic matter (Franzluebbers and Stuedemann, 2008). Brock (1999) reported that water-stable aggregates cannot be sustained with CT since the residue cover is not sufficient to protect against surface crusting and that long-term NT is needed to increase aggregate stability. This emphasizes the importance of limiting soil disturbance, especially for soils with inherent limitations, such as a claypan or sandy texture (Blanco-Canqui et al., 2004). Aggregate stability and size are very important in maintaining soil structure and minimizing erosion. Brock also noted that aggregate stability was increased by 50 percent in sandy southern piedmont soils under long-term NT. Karlen et al. (1994) demonstrated that there was a significant increase in aggregate size after 10 years of growing corn under a NT system on highly erodible silt loam with slopes of 10 to 13 percent, near Lancaster, Wisconsin. Rhoton et al. (1993) conducted a 15-year study on four soils with different textures in four different southeastern States. Aggregate stability was higher under NT than CT in all soils. These studies and others listed in table 1 indicate that these physical soil properties are improved with NT, regardless of the temperature and moisture region.

### **Pore-Size Distribution and Its Effects on Bulk Density and Earthworms**

Studies showed that macropore connectivity increased under NT, which allowed for increased water infiltration. There were inconsistent responses in total porosity and soil bulk density as compared with conventional tillage practices (Stubbs et al., 2004).

Macropores typically are associated with root channels, earthworm holes, and other uninterrupted channels. Full-width tillage destroys these channels, reducing macropores. Earthworm populations generally are higher under NT systems than under full-width tillage systems (Francis and Knight, 1993; Karlen et al., 1994; Blanco-Canqui and Lal, 2007 and 2008). Karlen et al. also indicated that the

earthworm populations were significantly lower in areas where corn stover was removed after harvesting grain than in areas where it was not removed.

Total porosity, which is directly linked to bulk density, tends to be lower under NT, at least initially. Studies by Jiang et al. (2007) showed that micropores (<10 micrometers) will increase under NT, even in soils that have a claypan. Annual tillage temporarily reduces bulk density, but tilled soil gradually settles and bulk density gradually increases before the soil is tilled again. In areas being converting from CT to NT, bulk density will increase and typically will not decrease unless there is an increase in soil organic matter or macropores. Practices such as adding residue mulch, growing winter cover crops with fibrous rooting systems, and including small grain in the rotation along with no-till increase porosity (Villamil et al., 2006; Blanco-Canqui and Lal, 2007; Jemai et al., 2013). Raczkowski et al. (2012) conducted an 8-year NT study in North Carolina on sandy soils under a rotation of low-residue cotton, soybeans, and peanuts along with high-residue corn and sorghum. This study showed that NT resulted in higher bulk density, lower macroporosity, and higher microporosity compared to CT. These results were expected because low-residue crops were used and the area was in a thermic soil temperature regime under a humid climate, in which residue decomposes quickly.

### **Conservation Practice 340—Cover Crop**

**Definition:** Planting crops, including grasses, legumes, and forbs, for seasonal cover and other conservation purposes (NRCS National Handbook of Conservation Practices, 2014)

**Purpose:** Plan and apply practice to support one or more of the following—

- Reduce erosion from wind and water
- Increase soil organic matter content
- Capture and recycle or redistribute nutrients in the soil profile
- Promote biological nitrogen fixation
- Increase biodiversity
- Suppress weeds
- Provide supplemental forage
- Manage soil moisture
- Reduce particulate emissions into the atmosphere
- Minimize or reduce soil compaction

Hartwig and Ammon (2002) provide a comprehensive overview of cover crops (and living mulches) and an extensive literature citation section. They define a cover crop as any living ground cover that is planted into or after a cash crop and then commonly destroyed before the next crop is planted. They state that the primary benefit of cover crops is reduction of runoff and soil erosion, which results in improved soil productivity.

Hartwig and Ammon also indicate that the integration of cover crops may provide and help to conserve nitrogen for grain crops, reduce weed pressure, and increase soil organic matter content. For example, they found that the use of hairy vetch increased the availability of nitrogen to succeeding crops, increased soil organic matter content, improved soil structure and water infiltration, decreased runoff, reduced the temperature and water evaporation in the surface layer, improved weed control, and increased soil productivity. Villamil et al. (2006) found that use of hairy vetch in the Midwest Corn Belt (Illinois) increased soil organic matter content, water aggregate stability, porosity, and available water for plants and reduced bulk density and penetration resistance.

Replacing fallow with cover crops in no-till wheat–fallow rotations after 5 years in a semiarid area in the central Great Plains generally reduced the potential for wind and water erosion, improved soil aggregation, and increased the content of soil organic carbon (Blanco-Canqui et al., 2013).

Different cover crops, both cereal and legumes, were shown to improve soil aggregation (Kladivko, 2003; Stipesevic and Kladivko, 2002; McVay et al., 1989; Kabir and Koide, 2000). Cover crops also decreased soil bulk density and compaction (Ess et al., 1998; Raper et al., 2000). Higher water retention (Scott et al.,

1990) and soil water content as a result of the use of cover crop mulching (Teasdale and Mohler, 1993) can provide soil moisture for the cash crop during periods of water stress in summer.

High-residue fall and winter cover crops are important in adding carbon, retaining plant-available nitrogen in organic matter, increasing the efficiency of fertilizer, and improving physical soil properties in the sandy soils of the southeastern Coastal Plain region of the United States (Hubbard et al., 2013).

Studies by Delgado et al. (2008) showed that use of winter cover crops, summer cover crops with limited irrigation, and rotations that include deeply rooted small grain helped to minimize wind erosion, increase cycling of macronutrients and micronutrients, increase efficient use of nutrients, and reduce nitrate leaching into ground water in coarse-textured soils in southern Colorado. Use of summer cover crops with limited irrigation can also increase the efficiency of water use.

Use of cover crops can also have potential negative effects. Particularly in more arid regions, cover crops may use soil water that would otherwise be available to the following crop. This can be especially crucial in dry years. Pest problems can also be an issue. In addition, a high carbon to nitrogen ratio in mature grass and cereal cover crop residue may tie up nitrogen and thus reduce the amount available to the following crop (Oklahoma State University, 1998; Snapp et al., 2005).

Unger and Vigil (1998) point out that although cover crops help to control erosion, fix nitrogen, reduce nutrient leaching, improve soil conditions, and protect seedlings they also use soil water. This may not result in a water shortage for the next crop in areas where precipitation is adequate, such as humid regions, but it may reduce yields in areas where precipitation is low, such as semi-arid regions. Because of this, cover crops are better suited to humid and subhumid regions than to semi-arid regions. Residue management systems that retain crop residue on the soil surface can be used in areas that are not suited to cover crops (Unger and Vigil, 1998).

In some areas, living mulch can be used to provide a ground cover throughout the growing season. This commonly is used in vineyards and orchards (Hartwig and Ammon, 2002).

## Conservation Practice 484—Mulching

**Definition:** Applying plant residue, or other suitable material produced offsite, to the land surface (NRCS National Handbook of Conservation Practices, 2014)

**Purpose:** Plan and apply practice to support one or more of the following—

- Conserve soil moisture
- Reduce energy use associated with irrigation
- Control erosion
- Facilitate the establishment of plant cover
- Improve soil health
- Reduce airborne particulates

For this review, the effects of both adding mulch and removing residue are considered (i.e., is less residue bad and more residue good?). Most available studies on mulching and residue removal have been conducted on medium-textured soils in the Midwest (silt loam, clay loam, and loam). Some studies have been conducted on sandier soils and soils in more semi-arid areas, and much international research has also been conducted.

Mulching generally has a positive impact on physical soil properties. For example, ongoing studies in Ohio have found that mulching improves bulk density (Kahlon et al., 2013) and porosity (Glab and Kulig, 2008). Kahlon et al. found that saturated hydraulic conductivity ( $K_{sat}$ ) and mean aggregate size in the surface layer increased under ridge-till, no-till, and plow-till systems. Blanco-Canqui and Lal (2007) found that mulched soils in Ohio had higher  $K_{sat}$ , porosity and water content. The aggregate stability of soils in Wisconsin was impacted by residue treatment (Karlen et al., 1994). Similar results were found in China. Zhang et al. (2008) reported that soils under straw cover had increased macro-aggregate stability and  $K_{sat}$ .

Biological soil properties can also be improved by mulching. Blanco-Canqui and Lal found earthworms under wheat straw mulch but not in unmulched areas. They also found that removing corn stover

decreased the population of earthworm middens. Karlon et al. (2013) found that ergostol (biochemical measure of fungal biomass), earthworm populations, and total carbon content increased with increased mulching. In addition, mulching increased the total carbon in bulk soil and macro-aggregates.

Generally, it was reported that mulching enhanced the effects of no-till management systems (Kahlon et al., 2013; Zhang et al., 2008). In Wisconsin, Karlen et al. (1994) found that the soil quality index increased as the amount of residue increased (residue removal, normal residue level, and double residue level were compared). Results from a Polish study showed that the observed improvements to physical soil properties as a result of mulching correlated to improved wheat yields (Glab and Kulig, 2008). While the studies showed that mulching generally improved physical soil properties, results commonly were reported only for the surface layer. The results of the studies by Blanco-Canqui and Lal (2007) applied only to the upper 0 to 3 centimeters of the soil; results were not observed in the deeper layers. Furthermore, the results are not universal. For example, tillage practices had more impact on physical soil properties than mulching on a sandy soil in Nigeria (Obalum and Obi, 2010).

## Conservation Practice 590—Nutrient Management

**Definition:** Managing the amount (rate), source, placement (method of application), and timing of plant nutrients and soil amendments

**Purpose:** Plan and apply practice to support one or more of the following—

- Budget, supply, and conserve nutrients for plant production
- Minimize agricultural nonpoint source pollution of surface water and groundwater resources
- Properly use manure or organic by-products as a source of plant nutrients
- Protect air quality by reducing odor, nitrogen emission (ammonia and oxides of nitrogen), and formation of atmospheric particulates
- Maintain or improve the physical, chemical, and biological condition of soil

Good soil health (SH) includes the proper amount of nutrients for plant growth. Deficient amounts result in insufficient plant cover and excessive erosion, and excessive amounts result in runoff of surface water and leaching of contaminants into ground water. Salts, sodium, pH, and excessive trace elements are also important to soil health and need to be managed for optimum soil function.

Conservation practices that promote good SH can provide positive results regarding nutrient addition, retention, and recycling and plant uptake of nutrients. SH practices such as no-till (Conservation Practice 329) should be used in conjunction with other SH practices such as growing cover crops (Conservation Practice 340) to minimize runoff, leaching, and volatilization. Gregory (2004) discussed common agronomic practices, including applying fertilizer, and their ability to increase water use efficiency (WUE). Hatfield et al. (2001) noted that modifying nutrient management practices can increase WUE by 15 to 25 percent. Hartwig and Ammon (2002) discussed that the inclusion of cover crops in a cropping system may provide and conserve nitrogen for grain.

Nitrogen and phosphorus are important because certain amounts of them are needed to produce most crops and they have the potential to contaminate surface water and ground water. In a well-functioning healthy soil system, other nutrients are also conserved, recycled, and made available for plant uptake. Doran and Zeiss (2000) discussed how micro-organisms are correlated to beneficial soil and ecosystem functions, including water storage, decomposition, nutrient cycling, detoxification of toxicants, and suppression of noxious and pathogenic organisms.

Nutrients that apply to Conservation Practice 590 discussed in the following paragraphs.

### Nitrogen

Regardless of the form of nitrogen (N) applied, mineralization renders N into nitrate within 1 to 2 weeks after application during the growing season; however, only a fraction of organic N from manure or green manure is mineralized at one time. Nitrate is an anion that is not sorbed to negatively charged sites on clay or soil organic matter, but it is sorbed to positively charged kaolinite, iron, and aluminum oxyhydroxide and less crystalline clay in an acid environment. Therefore, nitrate can readily leach below

the root zone in most soils if a living plant is not present to take up the N and retain it. In areas where a no-till system is used, N is injected into the soil at the time of planting. If carefully calculated amounts are applied at the proper time, crops take up much of the applied N. Residual N after harvest can run off the field or be leached unless a cover crop is planted to use much of the remaining N. Proper timing of destruction of the cover crop in spring allows for timely mineralization of organic N for crop uptake. Legume cover crops also provide additional N. These practices can reduce the amount of N fertilizer needed, thus reducing costs and carbon emissions by minimizing the demand for commercially produced N.

No-till farming in areas where tile drains are used can increase the amount of nitrogen and phosphorus reaching drain tiles and surface water because of the increased number of conductive pores in the soil. Owens (1994) stated that increases in the infiltration rate under no-till systems lead to a potential for greater movement of soluble nutrients, such as nitrate leachate, into tile drains or ground water at a shallow depth.

Use of winter cover crops, diverse crops in the rotation, and perennial grasses can help to reduce nitrate losses from leaching. Managing for soil health results in increased infiltration by water and air and increased root penetration and rooting depth. This increases the drought resistance of crops and can assist in groundwater recharge, depending on the geologic conditions. Leaching is minimized in areas where the amount and timing of fertilizer are optimal and the N uptake by the cash crop and cover crop is maximized. The benefits of a healthy soil in carbon sequestration, reducing the carbon footprint, cost savings, and erosion control should also be considered in areas where tile drains are used. Good fertilizer management is key in all areas.

Langdale et al. (1992) found during a 5-year study in restoring eroded Ultisols in the southeastern part of the United States that decomposition of residue significantly increased soil carbon. Restoration processes were initiated by increasing the average soil carbon content, representing slight, moderate, and severe soil erosion classes, from 0.97 to 2.37 percent in the upper 1.5 centimeters of the soil. Accompanying the soil carbon responses were increases in soil N, water-stable aggregation, and infiltration. Restoring Ultisols with varying levels of soil erosion requires differential fertilization. All fertilizer requirements for severely eroded plots were 1.43 to 2.30 times higher than those for moderately eroded plots. Because biological N fixation by the crimson clover cover crop appeared to be retarded on the severely eroded soils, plant N stress developed in irrigated areas under conservation tillage.

Liebig and Doran (1999) studied the impact of organic production practices versus conventional production practices on the soil quality indicators of Mollisols on selected farms in Nebraska and North Dakota. A site under a Conservation Reserve Program was included. On average, the organic farms had 22 percent more organic carbon (12,571 kilograms per hectare) and 20 percent more total N (970 kilograms per hectare) in the upper 30.5 centimeters than did the conventional farms. On four out of five organic farms, the pH of the soils was closer to neutral, the bulk density was lower, and the AWC, microbial biomass carbon and nitrogen, and soil respiration were higher as compared to the conventional farms. Nutrient levels higher than crop needs were observed on both the organic and conventional farms and indicate a potential for negative environmental impact.

A study by Rhoades et al. (1998) was conducted to determine whether use of no-till with Albizia hedgerow alley cropping would result in higher nutrient availability than use of treeless agriculture. Data revealed that intercropping of Albizia hedgerows improves N and organic matter content, which can minimize the need for chemical N fertilizer. Albizia mulch directly influenced the amount of nitrate available to plants in the short term; however, there was no evidence that including Albizia hedgerows generated more long-term changes in soil properties than a no-till system alone. The authors concluded that alley cropping on the Georgia Piedmont can dramatically increase the amount of N available to plants, and they suggested that it might be beneficial for organic farmers producing high-value horticultural crops on small acreages. Jose and Nairr (2003) discussed the importance of tree-crop interaction in designing alley cropping agroforestry that would result in better use of N and the potential for pecans in a pecan-cotton intercropping (site at University of Florida) to extract excess nitrogen that the cotton is unable to use.

## Phosphorus

It has long been thought that phosphorus (P) is in surface water as a result of being attached to sediment eroded from fields. There is a growing awareness that in areas where soil P levels are high or very high, P can move off of the surface of fields in clear runoff as well. P can also be moved vertically downward with percolating water, particularly in areas where soil P is high or very high. P retention in the root zone depends on proper placement, amount, and timing (as discussed under Conservation Practice 590) in combination with crop uptake, including cover crops, and erosion control.

Some soils, such as those high in calcium carbonate and particularly those high in iron oxyhydroxides or x-ray amorphous clay, have a substantial proportion of soil P fixed by these constituents. If these soils are eroded, they contribute higher amounts of sorbed P to surface water than noncalcareous, "oxidic" or amorphous clay soils do. By improving soil health and increasing the soil organic matter content, a higher proportion of soil P is associated with the organic fraction and therefore more available to plants. Soil P can also be lost through runoff if the concentrations are high. Monitoring soil P levels and fertilizing accordingly will minimize losses.

Vogeler et al. (2009) studied data from a long-term fertilization trial in Braunschweig, Germany, on a silty loam (Dystric Cambisol/Orthic Luvisol [FAO]) where mean annual precipitation was 620 millimeters and average air temperature was 8 degrees C. The data was used to evaluate the effects of P fertilization on bulk density, porosity, water retention, soil organic matter,  $K_{sat}$ , P accumulation in soils, yields of various crops, and P uptake. Conventional tillage and conservation tillage were evaluated under three fertilizer regimes—nitrogen and potassium; nitrogen, potassium, and farmyard manure; and nitrogen, potassium, phosphorus, and farmyard manure. The results 6 and 8 years after implementation showed that the soils under conservation tillage had better pore connectivity and higher saturated hydraulic conductivity than those under conventional tillage. Generally, the soil organic matter content increased under all three fertilizer regimes in areas where conservation tillage was used. Yields were not significantly affected by the tillage system. Mineral P fertilization resulted in more buildup of P available for plant use in the upper part of the soils as compared to unfertilized areas, but P uptake generally did not increase. A reduction in tillage intensity affected soil properties, but it had a very limited effect on yields and nutrient uptake.

## Manure and Municipal Waste Application

Manure application is not only a beneficial use of resources, but the organic matter, nitrogen, phosphorus, potassium, and other nutrients in manure also improve soil health. Continued manure application to meet the requirements for N leads to excessive amounts of P in the soil; therefore, it should be applied to meet the requirements for P. Additionally, salts may build up and should be monitored and managed. Metals such as zinc may also be a concern unless application rates are well managed.

Although municipal waste applied as effluent may provide little organic solids to the soil, it can be a good source of N and P. There is a tendency to apply wastewater beyond agronomic rates because the primary purpose of waste application is to dispose of waste. This can lead to excessive leaching of N. A buildup of pharmaceuticals, which can reduce soil health, may be a concern as well.

Abbas and Fares (2009) applied increasing amounts of chicken or dairy manure to a clayey Haplustoll. The results were increased aggregation and  $K_{sat}$  and decreased bulk density. As expected, carbon dioxide evolution rates increased as manure application rates, and therefore N rates, increased.

Bhattacharyya et al. (2007) studied the use of commercial fertilizer with farmyard manure (FYM) to enhance soil carbon levels. Results of an 8-year study showed that manure increased soil organic carbon (SOC) content in the upper 45 centimeters of the soils for which nitrogen (N), phosphorus (P), and potassium (K) treatments were used with FYM treatments as compared to NPK treatments with control treatments. Applications of FYM significantly reduced soil bulk density and increased mean weight diameter and SOC in different aggregate-size fractions. The response of SOC to FYM application was dependent on inorganic fertilization and was even more dependent on the balanced application of NPK than on the application of N only. The steady-state infiltration rate under NPK + FYM application was higher than under NPK application alone. An increase in SOC concentration in almost all size fractions was dependent on use of inorganic fertilizer, but it was independent of the type of inorganic fertilization. Soil water transmission properties (infiltration, soil water sorptivity, and  $K_{sat}$ ) markedly improved with FYM

and N applications. The effects of FYM application in increasing SOC and improving water transmission properties were not dependent on inorganic fertilization or the type of inorganic fertilizer.

Buildup of P, salts, and trace elements can be a concern. Organically bound P, particularly where manure has been applied to the surface, is especially prone to removal from the field in surface runoff if the infiltration rate is at or above the precipitation or irrigation rate and if adequate cover (cash crop, cover crop, and/or mulch) is not maintained.

Edmeades (2003) showed that manured soils had a higher content of organic matter and higher populations of microfauna than fertilized soils and that they had more P, potassium (K), calcium (Ca), and magnesium (Mg) in the surface layer and more nitrate N, Ca, and Mg in the subsoil. Manured soils also had lower bulk density and higher porosity, hydraulic conductivity, and aggregate stability as compared to fertilized soils. However, there was no significant difference between fertilized and manured soils in the long-term effects on crop production. Because the ratio of nutrients in manure is different than the ratio of nutrients removed by common crops, these studies also show that excessive accumulation of some nutrients, particularly P and N, can result from the long-term use of manure. Under these conditions, higher runoff of P or leaching of N may result. In soils that have low P retention and/or leached organic P, a greater loss of P from leaching may occur.

Fraser et al. (1988) studied the changes in the soil microbial environment that resulted from conventional and organic nutrient management under a grain and legume crop rotation. Overall, soil bacteria and fungi populations, enzyme activity (microbial activity), and microbial biomass were significantly higher in soils amended with manure. Soil chemical properties were influenced significantly by chemical management, particularly by application of beef feedlot manure under an organic management system. Total organic carbon, Kjeldahl N, and potentially mineralizable N in the surface layer (0 to 7.5 centimeters) in manure-amended soils were 22 to 40 percent higher than in soils amended with conventional fertilizer and/or herbicide. Soluble P levels were eight times higher in the manure-amended soils, and soil nitrate levels after harvest in 1981 were two to three times higher to a depth of 30 centimeters. Soil microbial biomass, bacteria and fungi populations, dehydrogenase activity, and carbon dioxide evolution were higher in soils planted to oat and clover and amended with manure. Increases in microbial populations and activity paralleled increases in soil organic C content, Kjeldahl N, and water-filled pore space.

Jokela et al. (2009) concluded that additions of manure and starter fertilizer have a significant effect on extractable P and K in areas under cover and companion crops. Use of liquid dairy manure alone did not improve any soil quality indicators.

Pagliai et al. (2004) found that the macroporosity of soils tilled with a ripper or subsoiler was generally higher and homogeneously distributed throughout the profile and that the porosity of soils tilled with a moldboard plow was significantly reduced both in the surface layer (0 to 100 millimeters) and at the lower depth of cultivation (400 to 500 millimeters). The application of compost and manure improved the soil porosity and aggregation. The improved aggregation indicated that additions of organic material were important for preventing the formation of a soil crust.

Pease et al. (1998) examined dairy and dairy/poultry farms to estimate potential N and P losses at the edge of fields and below the root zone. They simulated farm income effects under current practices and three other possible nutrient management systems: 1) systems requiring manure incorporation, 2) systems restricting N applications to agronomic recommendation levels, and 3) systems restricting P applications to the amount taken up by crops harvested. Results indicated very different environmental and economic impacts.

Manure incorporation had only marginal impacts on potential nutrient losses and farm income and is very difficult to implement on most dairies.

Restricting N application is consistent with current nutrient management and results in a win-win outcome for many dairies. Potential N losses were reduced by 18 to 50 percent, and income increased by as much as 5 percent. However, one drawback of restricting N application was that concurrent potential P losses were reduced by only 3 to 15 percent.

Restricting P application has the potential to cause the most significant decrease in nutrient losses and the most serious negative impact to dairy and dairy/poultry farm income. Potential N losses decreased by

21 to 56 percent, and potential P losses decreased by 28 to 43 percent. However, the cost is too high to be sustainable for most dairies (incomes reduced by 11 to 23 percent). Poultry litter could not be applied under this nutrient management system, which likely would impose additional costs on producers.

Reeve et al. (2012) reported that significant acreages of certified organic dryland wheat are in the semi-arid western United States. Yields are severely restricted by the lack of precipitation. Many dryland organic wheat farmers do not grow cover crops or apply fertilizer because of the application costs. Composts, however, have a strong carryover effect. Also, the long-term benefits of infrequent application to soil quality, yields, and economics in areas under dryland wheat and fallow systems have not been evaluated. Soils were sampled in 2008 and 2010 on the site of a previous compost response trial on a commercial dryland wheat farm in Snowville, Utah. Dairy manure compost was applied in 1994 at the rate of 50 megagrams dry matter per hectare in a randomized complete block design with three replicates. Sixteen years later, soils from the compost-amended plots contained 1.6 times more total organic C; higher microbial biomass, dehydrogenase, and acid and alkaline phosphatase activity; and higher amounts of P, K, and Zn available for plant use in the upper 5 centimeters than soils from the control plots. In 2010, the upper 5 to 10 centimeters contained 1.6 times more total organic C, higher amounts of P and K available for plant use, and higher dehydrogenase and acid and alkaline phosphatase activity. The 2-year average yield increased from 0.5 megagram per hectare on the control plots to 1.0 megagram per hectare on the compost-amended plots. When compared with an increase in yield of 2.3 megagrams per hectare measured in 1995 to 1997, the estimated half-life of the compost effect was 6 years. Despite the long-term benefits measured in this study, the viability of using compost for dryland wheat production depends on the proximity of growers to sources of compost and on its availability.

Russelle et al. (2007) determined that, under multiple scenarios, allowing cattle in areas under a mixed crop rotation increases soil C accumulation as compared to annual cropping alone.

Schneider et al. (2009) applied municipal solid waste compost (MSW) and a co-compost of green waste and sewage sludge (SGW) every other year for 6 years to cultivated plots of silt loam Glossic Luvisols. These soils, located in the Parisian Basin, France, were under a winter wheat and corn rotation. Compost addition decreased  $K_{sat}$  in the interfurrow area after plowing by almost one order of magnitude; the average value was  $5.6 \times 10^{-5}$  meters per second ( $ms^{-1}$ ) in the MSW plot and  $4.1 \times 10^{-5} ms^{-1}$  in the SGW plot as compared to  $2.2 \times 10^{-4} ms^{-1}$  in the control plot. This effect had disappeared 6 months after plowing; the average  $K_{sat}$  in the control plot had decreased to  $1.9 \times 10^{-5} ms^{-1}$  and that of the compost-amended plots had remained stable.

Tobert et al. (2008) examined the potential impact of limiting the time of poultry litter application according to nutrient movement, which is important for water quality. The WinEPIC model was used to simulate poultry litter applications in winter and chemical fertilizer application on both cool-season and warm-season grass pastures in the major soil regions of Alabama. On pastures under warm-season grasses, soluble N losses could be reduced if poultry litter was applied after December 30. On pastures under cool-season grasses, the date of application did not affect soluble N losses in any of the regions and no improvement was observed by limiting applications in northern Alabama as compared to southern Alabama. No significant differences in soluble P losses were observed according to the date of application for either warm-season or cool-season grasses. This indicates that factors other than P uptake by plants during the growing season were the dominant regulators of the amount of soluble P lost through runoff. The results indicate that best management practices, such as those that are administered according to the P index, are more important than plant growth factors in determining N and P losses.

Ugarte and Wander (2013) stated that soil testing strategies that include biologically based indicators in organic and alternative farming systems are needed to improve the balance of production and environmental goals. In their study, soil samples were collected before and after soils were transitioned from conventional row crop production to organic management systems that included rotations with varied input and tillage intensity. Pasture, row crop, and vegetable farming systems were implemented using specific local production practices. Subplots within each system were used for comparison of farming systems with and without dairy manure and compost amendments. Soil analyses included standard chemical tests (upper 15 centimeters) for available P, exchangeable K, Ca, Mg, pH, total organic carbon (SOC), and total N. Biological assays (upper 15 centimeters and depths of 15 to 30 centimeters) included particulate organic matter-C (POM-C) and particulate organic matter-N (POM-N),

soil and POM-C to POM-N ratios, fluorescein diacetate (FDA) hydrolysis, potentially mineralizable N (PMN), and hydrolysable amino-N + NH<sub>4</sub> (IL-N). Even though cropping and tillage intensity varied among systems, organic matter and nutrient reserves were not statistically different. Nutrient concentrations were medium to high, even without applications of compost or manure. POM content increased by an average of 20 percent between depths of 15 and 30 centimeters whereas it increased by only about 6 percent in the upper 15 centimeters. This increase and the changes in other properties demonstrate the multiple benefits of growing annual or perennial crops in winter. Results from the analyses suggest that PMN and POM have particular potential for use in commercial soil testing needed to determine recommendations for amendment applications that balance production and environmental goals.

Wortmann and Walters (2006) observed that repeated manure application can lead to excessive soil test P (STP) levels and increased P concentration in runoff but that it can also improve water infiltration and help to minimize runoff. The research evaluated soil P tests for predicting P concentration in runoff to determine the residual effects of composted manure on P loss through runoff and leaching. Because phosphorus is conserved during the composting process, compost commonly has a much lower N to P ratio. If compost or fresh manure is applied as an N fertilizer, over-application of P will result. The research was conducted from 2001 to 2004 under natural runoff conditions on plots 11 meters long. Low-P and high-P compost had been applied during the previous 3 years, with a total application of 750 and 1,150 kilograms of P per hectare, respectively. Bray-P1 in the upper 5 centimeters was increased from 16 to 780 milligrams per kilogram with application of high-P compost. Runoff and sediment losses were 69 and 120 percent higher with no compost than with residual compost treatments. Phosphorus concentrations in runoff increased as STP increased, but a high amount of P loss also occurred with the no-compost treatment. Agronomic soil tests predicted mean P concentrations in runoff, but increases in STP resulted in relatively small increases in the concentration. Downward movement of P was not detected below a depth of 0.3 meter. Agronomic soil tests are useful in predicting long-term P concentrations in runoff. The potential for P loss may be a concern even where levels of P in the soil are moderate. The residual effect of compost application in minimizing loss from sedimentation and runoff was evident more than 3 years after application.

Wuddivira and Ekwue (2009) examined the influence of manure incorporation and the incubation period on the structural stability of three tropical soils in the Republic of Trinidad and Tobago that had different clay content and mineralogy. Samples were treated with farmyard manure (FYM) at a rate of 0, 6, and 12 percent per dry mass of soil, brought to field capacity (FC), and incubated for 56 days at an average temperature of 26 degrees C and an average humidity of 67.5 percent. Subsamples were taken at 14, 28, and 56 days to determine water-stable aggregation (WSA) and K<sub>sat</sub>. WSA increased 23 to 27 percent for the three soils when comparing the sample with no treatment on up to the sample with the highest treatment combination (12 percent FYM and 56-day incubation period). The higher the amount of FYM incorporated the more stable the soil became as the incubation period increased. K<sub>sat</sub> improved even more: values increased from 50 to 700 percent. Both WSA and K<sub>sat</sub> increased as the incubation period increased, regardless of the FYM level or the clay content and mineralogy of the soil. This suggests that soil incubation at FC after structural disturbance, with or without FYM incorporation, encourages bonding of particles and improves soil structure.

Yang et al. (2011) conducted a 19-year study in the Loess Plateau of China, evaluating the effects of fertilization regimes on soil organic C (SOC) dynamics, physical soil properties, and wheat yields. The SOC content in the upper 20 centimeters of the soil remained unchanged over time in the unfertilized plot (CK), but it increased significantly in plots treated with inorganic N, P, and K fertilizers (NPK) and with a combination of manure and N, P, and K fertilizers (MNPk). After 18 years, the SOC in the plots treated with MNPk and NPK remained significantly higher in the upper 20 centimeters and upper 10 centimeters, respectively, than in the control plot. The MNPk-treated soil retained significantly more water than the CK soil at tensions of 0 to 0.25 kilopascal (kPa) and of 8 to 33 kPa for the upper 5 centimeters. The MNPk-treated soil also retained much more water than the NPK-treated and CK soils at tensions of 0 to 0.75 kPa and the CK soil at tensions of 100 to 300 kPa between depths of 10 and 15 centimeters. There were no significant differences of K<sub>sat</sub> among the three treatments in the upper 5 centimeters or between depths of 10 and 15 centimeters. In contrast, the unsaturated hydraulic conductivity in the MNPk plot was lower than that in the CK plot in the upper 5 centimeters and between depths of 10 and 15 centimeters. On average, wheat yields were similar under both the MNPk and NPK treatments but were significantly

higher than under the CK treatment. Considering conservation of soil quality and sustainable crop productivity, applications of NPK and organic manure best manage nutrients in areas of rain-fed, wheat–fallow cropping systems.

McFarland et al. (2010) found that land application of bio-solids is effective in restoring forage productivity and enhancing the moisture-holding capacity of soils in disturbed areas of rangeland in Utah. By applying aerobically digested, anaerobically digested, composted, and lime-stabilized bio-solids on rangeland test plots at a rate of as high as 20 times the estimated N-based agronomic rate, forage yields were increased from 132.8 kilograms per hectare (118.2 pounds per acre) in control plots to 1182.3 kilograms per hectare (1052.8 pounds per acre). Despite the environmental benefits associated with increased forage yields (e.g., reduced soil erosion, improved drainage, and enhanced terrestrial carbon sequestration), the type of forage generated both before and after the bio-solids were applied was dominantly invasive weeds, all of which had fair to poor nutritional value.

### **Acidity and Alkalinity**

These will be addressed in a future document.

### **Salts and Sodium**

Bhardwaj et al. (2008) demonstrated that replacing saline–sodic irrigation water from sewage treatment with treated wastewater (TWW) that is considerably less saline–sodic but has a higher content of organic matter and suspended solids improves the stability of the soil structure and the hydraulic conductivity of the soil.

Lado and Ben-Hur (2009) reviewed the effects of irrigating with effluent that has undergone various treatments on the hydraulic properties of semiarid and arid soils. The direct and indirect effects are closely related to both the effluent and the soil properties. Leaching the soils with sewage effluent can reduce the soil  $K_{sat}$ , a parameter that depends on the quality of the effluent and on the soil texture. The  $K_{sat}$  of a sandy soil was not affected by the use of effluent with various qualities; the low clay content and the relatively large average pore size prevented significant clogging of the soil pores with the solids suspended in the effluent. Leaching loamy and clay soils with effluent that contained high concentrations of suspended solids resulted in a significant reduction in  $K_{sat}$  because more suspended solids were trapped in the small pores in these soils. Irrigation of arid soils, which are high in sodicity, with effluent resulted in a reduction in  $K_{sat}$  because the low concentration of electrolytes in the effluent promotes dispersion of clay.

The indirect effects of effluent irrigation on  $K_{sat}$  also depend on the properties of the soil. The changes in exchangeable sodium percentage (ESP) appear to be the main reason that  $K_{sat}$  in effluent-irrigated clay that was leached with water that had low concentrations of electrolytes (deionized water) was lower than that of freshwater-irrigated soils. The higher ESP increased the amount of swelling and dispersion of clay, which reduced  $K_{sat}$ . Studies conducted using a rainfall simulator on field plots found that the presence of a soluble Ca source determined the effects of effluent irrigation on sealing of the soil and the infiltration rate of the soil. In noncalcareous sandy soils, previous effluent irrigation led to enhanced clay dispersion during a rainstorm because of the increased sodicity of the soils. A more developed seal forms on the soil surface during periods of rainfall in areas that are irrigated with effluent rather than with freshwater. In contrast, calcareous soils were not affected by previous effluent irrigation, probably because of the presence of soluble calcium carbonate ( $CaCO_3$ ). The dissolution of  $CaCO_3$  released Ca that replaced the excess exchangeable sodium from the effluent and thereby reduced the ESP to natural levels. No differences in clay dispersion between the types of irrigation treatment were found. Sensitive areas and soils should be identified prior to application of effluent for irrigation to prevent possible deleterious effects on soil structure and  $K_{sat}$ .

Li et al. (2010) showed that raw domestic sewage water decreased the hydraulic conductivity of nonsodic soils but increased that of sodic soils as compared to distilled water. Also, gypsum application decreased leachate pH by about 0.5 pH units and increased hydraulic conductivity by as much as 180 percent, with the exception of soils that have a sodium adsorption ratio of 20. In those soils, the hydraulic conductivity decreased by about 50 percent. The adverse effects of irrigating with domestic sewage water on soil hydraulic conductivity generally can be inhibited or ameliorated by applying gypsum.

### **Trace Elements (Heavy Metals)**

Yeganeh et al. (2010) stated that the increasing use of sewage sludge on farmland has raised concerns about the potential for transport of heavy metals into food chains and ground water. The study took place at the experimental station at Isfahan University of Technology, Isfahan, Iran, which is 1,630 meters above sea level and has mean annual rainfall of 140 millimeters and mean annual temperature of 14.5 degrees C. It was conducted on a calcareous soil classified as a fine-loamy, mixed, thermic Typic Haplargid. It analyzed the effects of sludge application on physical soil properties and transport of zinc (Zn), copper (Cu), and lead (Pb). Secondary anaerobic-digested sewage sludge was applied at a rate of 0, 25, 50, and 100 tons per hectare (dried weight basis) for 4 consecutive years, and it was mixed into the upper 20 centimeters of the soil. Corn was planted as a spring crop, and wheat was planted as a winter crop. Sludge application increased the dissolved organic matter content and modified the soil structure; increased the infiltration rate, saturated hydraulic conductivity, and aggregate stability; and decreased the bulk density. Sludge application greatly increased DTPA (diethylenetriamine pentaacetic acid)-extractable soil metal concentrations to a depth of 50 centimeters and significantly to a depth of 1 meter. In the plots that received four applications of 100 tons of sewage sludge per hectare, the mean concentrations of Zn, Cu, and Pb in the subsoil increased by 1,600 times, 7 times, and 4.5 times, respectively, as compared to the control plot. Irrigation that included use of a border system as needed resulted in an irrigation application efficiency rate of about 40 percent; therefore, about 60 percent of the applied water was lost through deep percolation or evaporation. Results indicated that a combination of enhanced physical soil properties, heavy and inefficient irrigation, and high organic matter content with heavy metals cause significant metal mobility. High applications of sludge pose potential risks for ground water and food chain contamination. Application rates should reflect the nutrient needs of the crops grown (20 tons per hectare every 4 to 5 years or an average of 4 to 5 tons per hectare per year).

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