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Effects of Implementation of Soil Health Management Practices on Infiltration, Saturated Hydraulic Conductivity (K_{sat}), and Runoff

Review of the Literature Posted to the NRCS Soil Health Literature Review Library as of January 2015

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unlock the SECRETS IN THE SOIL

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Contents

Introduction

Two of the major natural resource concerns of this century are climate change and water (quality and quantity). Major aquifers are being depleted. Most climate models predict that many areas of the nation will not realize a significant change in the average amount of precipitation. Exceptions, however, are the Southwest, which is projected to become somewhat drier, and the upper Midwest and the Southeast/Mid Atlantic, which are predicted to become somewhat wetter. Nationally, increasing temperatures will increase evapotranspiration, rendering areas with unchanging amounts of precipitation effectively drier, exacerbating arid conditions in the Southwest, and neutralizing precipitation gains in the Southeast/Mid Atlantic.

"Soil health management systems"[1] are one way to try to offset the effects of these projected climate changes on crops and cropland and to improve short-term drought tolerance and, potentially, ground-water recharge. These systems can increase infiltration, reduce evaporation, moderate soil temperature changes, increase rooting depth, increase nutrient uptake, and improve the water-holding capacity for most soils. These improvements lead to better crop resilience during drought. In some circumstances, they also provide for ground-water recharge. Additionally, increased infiltration rates decrease runoff, thereby reducing sediment and nutrient loading to streams as well as reducing flood volumes.

This paper focuses on literature discussing the relationship between infiltration and saturated hydraulic conductivity (K_{sat}) and key conservation practices that improve soil health on cropland. Subsequent papers will review improvements in the available water-holding capacity and enhancements to physical soil properties within the root zone.

Note that even if increased amounts of water infiltrate into the soil, enhanced ground-water recharge may not occur. Other factors, such as restrictive layers in the soil, geologic strata above an aquifer, and high rates of evapotranspiration, can reduce a site's ability to recharge an aquifer.

Executive Summary

Conservation practices that generally increase infiltration are no-till, reduced tillage, cover crops, mulching, cropping systems with high-residue crops, solid manure applications, and compost applications. Switching from conventional tillage (CT) to no-till (NT) may increase infiltration and saturated hydraulic conductivity (K_{sat}) in the first few years, depending on site conditions, or several years (2–8) may be needed for these improvements. There are a few exceptions where infiltration is not higher under NT compared to CT. Leaving residue cover provides additional benefits, such as minimizing

[1] Soil health management systems: A suite of practices, such as crop rotations, cover crops, no-till, and mulching, that require less soil disturbance, provide living roots throughout the year, improve crop diversity, and keep the soil covered. These systems are never a single-practice approach.

crusting, improving soil aggregation, and conserving soil moisture. Although infiltration is generally greater immediately after tillage under CT compared to NT, it typically decreases throughout the year and is ultimately less. In one study, infiltration was measured to be 43 times greater under NT than CT. This magnitude of increase, however, is not typical. Traffic row compaction is significant. In an extreme case, infiltration decreased by up to 132 times in the traffic row, resulting in reduced yields. Limiting row compaction by using controlled wheel traffic patterns is essential. This generally decreases runoff (although it may increase runoff on clayey soils that have a high shrink-swell potential). In a Piedmont soil in the southeastern United States, runoff decreased by 7 times or more under NT compared to CT. Two Midwest studies of soils under no-till showed an increase in yields due to enhanced infiltration and water storage in clayey soils. In a few cases, yields may not be increased, especially when soil moisture is adequate. The lack of increase may be due to a number of factors, some of which also affect crops under CT, such as weather, compacted subsurface layers, excess wetness, and previous management of the field. The number of earthworms and the extent of their burrows increase under NT compared to CT. The burrows increase infiltration and can extend to depths of more than 45 cm.

As with switching from conventional tillage to NT, switching from conventional tillage to conservation tillage or reduced tillage (RT) can initially slow infiltration. Reduced tillage cropping systems in which root crops (sugar beets and potatoes) are grown can result in greater K_{sat} compared to conventional tillage. Differences in infiltration are more likely in non-sandy soils where soil structure can be improved. RT in the spring has shown improved infiltration and more earthworm burrows (macropores) compared to RT in the fall.

Use of cover crops (CC) commonly results in greater water infiltration because of the direct effects of improved canopy cover, improvement in soil aggregation, and the formation of macropores by cover-crop roots (which are left intact after termination). It improves porosity, infiltration, and K_{sat} from 3 percent to over 50 percent. Sandy soils show less improvement in infiltration and K_{sat} because these are already rapid; however, other physical and chemical soil properties are benefited. Use of cover crops reduced runoff in most studies. Grazing management was beneficial on fields that were wet enough to have problems with surface compaction. In one study, however, managed grazing of CC did not affect infiltration.

Use of residue and mulch moderates changes in surface temperature of the soil and results in cooler surface temperatures during hot summers. This also prevents surface crusting, thereby increasing infiltration and K_{sat}. In one extreme case, K_{sat} increased under NT by 700 to 3,100 percent. Earthworm numbers generally increase with mulch application. Infiltration may not increase if earthworms stay in the surface layer and create only shallow burrows. Mulch applied under any tillage system provides positive benefits to physical soil properties. Up to a 30 percent increase was observed in yield, infiltration rate, and moisture levels under NT where residue mulch was applied compared to where residue cover was removed. A review of studies shows that a 4 to 50 percent reduction in runoff can result where NT, mulch, and/or cover crops are used compared to where CT is used without cover crops or mulch. The reduction in runoff implies that the infiltration rate increased.

If not applied in excess, manure and other organic materials can improve soil health. In one study, the addition of solid manure increased infiltration and K_{sat} by up to 4 times in the surface layer after 1 year. The improvement was partly due to straw in the manure as well as to aggregate development. In another study, application of sludge increased the depth of water infiltration by 288, 254, and 375 percent.

Applications of manure and sludge should be incorporated in a manner that lessens movement of nutrients and pathogens via runoff. This presents a challenge in no-till operations. Using an NT drill and planting a cover crop that incorporates some manure and provides a living cover can limit off-season losses. In Maryland, low-disturbance, vertical-tillage tools are also being used to reduce the amount of ammonium needed and reduce odor.

In one study, treated wastewater containing organic solids clogged soil pores in fine textured soils until the solids decomposed while sandy soils were not as readily clogged. The potential for increasing salinity and sodicity needs to be monitored, especially in more arid climates or in soils where salts may accumulate near the surface. Adding effluent that has been treated with reverse osmosis can decrease K_{sat} and infiltration in sodic soils. Use of gypsum when this type of effluent was added prevented sealing and the formation of puddles on the soil surface.

No single research project in the review compared all conservation practices and their effects on infiltration and K_{sat}. A system approach, however, indicates that the combination of no-till and residue retention, high-residue crops, crop diversity, and cover crops should achieve the greatest increases in infiltration. Compared to using NT alone, using multiple soil health practices can improve infiltration, the amount of moisture in the root zone, and ground-water recharge and can reduce runoff.

Increased infiltration and K_{sat} also have the potential to leach nitrates and other soluble nutrients deeper into the soil profile or below the root zone. The keys to reducing nutrient leaching are the proper timing, form, and method of application; use of cover crops; and proper irrigation management.

The following studies demonstrate the importance of implementing an entire system of soil health practices, including all of the soil health planning principles. The principles are: keep the soil covered, maintain living roots, improve diversity of crops and cover crops, and minimize disturbance.

Discussion by Practice

No-Till (NT): Practice Standard 329 "Residue and Tillage Management, No Till"

Conventional tillage is switched to a no-till system typically when many soil properties need to be improved, including organic matter content, soil structure, porosity, subsurface compaction, and infiltration rate. Under no-till, bulk density can initially increase but, over time, continuous pores are established, bulk density decreases, organic matter increases in the upper few centimeters of soil (in the absence of additional practices), and infiltration increases. Bulk density is most likely to initially increase where it had been relatively low in the plow layer as a result of disking, particularly immediately following the disking operations.

Disturbance of a soil system impacts infiltration and residue, which in turn affect soil organisms. Tilling converts undisturbed soil into homogenized soil. Long-term no-till can increase bulk density. For many soil types, however, the loss of organic matter in intensively tilled or eroded areas also leads to increased bulk density. The short-term benefits of bulk density improvements from tillage are offset by the long-term benefits of no-till. The benefits of no-till include reduced erosion, increased content of organic matter, and increased number of continuous pores from earthworms and undisturbed root channels (14a).

Compacted pans, lack of aggregate stability, and surface crusting caused by conventional tillage (CT) tend to decrease infiltration and increase runoff (15). Compacted pans should be broken prior to the start of a continuous no-till system. The low aggregate stability caused by CT increases bulk density, reduces macroporosity, and slows infiltration and K_{sat} (12). When NT replaces CT, the soil reconsolidates. Over time, connective pores are established, soil structure is strengthened or re-established, and infiltration increases. This transition period may take 2 to 7 years or more.

"Soil organic carbon content may or may not increase with no-till systems alone depending on the crop rotation and other practices utilized in the central Great Plains, but other soil physical and hydraulic properties typically improve with time. In some scenarios, there may be delayed incorporation of carbon from plant residues into aggregate-stabilizing compounds because of a lack of mixing with no tillage" (2).

In a long-term study of corn grown using NT and CT in Ohio, intact channels created by earthworms and roots were shown to enhance water infiltration and reduce runoff. In a few studies, long-term near-surface infiltration remained slower under NT (alone) than under CT (11). "Water infiltration and soil moisture levels were greater under NT when residue was left on the field than when residue was removed." Note that Practice Standard 329 requires residue retention. "Higher infiltration rates and increased soil moisture under no-till supported yield increases of up to 30 percent in a fine textured Mollisol[2]" (9).

Long-term no-till has been shown to result in greater infiltration than CT in the Piedmont region of the southeastern United States (7). Several soil properties, however, were only slightly affected by various tillage treatments or no-till for a Williams loam (10). Compaction in traffic rows can reduce infiltration and K_{sat} by 40 to 132 times (1) and can reduce yields (3). It is therefore critical to use and maintain established traffic rows. Conventionally tilled fields may store less moisture than no-till fields, thereby exhibiting greater initial infiltration rates than NT fields. In one study where soil moisture content was similar under NT and CT, infiltration rates after harvest were 43 times greater under NT than under CT (4). This difference, however, is greater than normal. In some cases involving clayey soils that have a high shrink-swell potential, infiltration may be slower and runoff greater for NT soils than for CT soils (5). In one study, runoff was decreased by 7 times in a Piedmont soil (8). In a study involving 9 years of no-till following 5 years of pasture, infiltration in a silt loam was not significantly different under CT than under NT where no cover crops were planted (6). In another study, long-term records for runoff indicated that infiltration and ground-water recharge were higher under no-till (13). On a site of silt loam, NT showed a 722 percent increase in K_{sat} after 5 years. Runoff was less and yields were higher with NT than with CT (14).

Conservation or Reduced Tillage (RT): Practice Standard 345 "Residue and Tillage Management, Reduced Tillage"

Reduced-tillage cropping systems used with root crops (sugar beets and potatoes) can result in greater K_{sat} compared to CT (17). In one study, the K_{sat} values at depths of 10 to 15 cm were 23 percent greater under strip tillage than under CT at one site and 138 percent greater at a second site. It was concluded that the CT operations increased soil compaction and bulk density, thereby reducing K_{sat} (19). In another study on a different soil type, initial infiltration was also faster under sugar beet production (20). When measured in the spring following fall tillage, reduced tillage (RT) showed higher infiltration rates than CT (18). K_{sat} was higher under RT than under moldboard plowing and ripper subsoiling (21). Earthworm burrows were positively correlated with increased K_{sat} when spring-stubble-tilled plots were compared to fall-stubble-tilled plots (22). Conservation tillage management resulted in better pore connectivity and higher K_{sat} than conventional tillage. In one study, the tillage system did not affect nutrient uptake (24). Differences in hydraulic properties (K_{sat}, macroporosity) based on different tillage treatments were hardly apparent at a sandy loam site and clearly visible only at a finer textured site. This is presumably because the activity of soil fauna, which improves soil structure, was higher in the silt loam (16).

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[2] Mollisol: A soil order in U.S. Soil Taxonomy. Mollisols have generally a moderate to high base cation content (calcium, magnesium, potassium), near neutral pH (although surface layers may have been acidified by fertilization), and moderate (>1%) or higher soil organic matter content.

Cover Crops (CC): Practice Standard 340

Use of cover crops commonly results in greater water infiltration because of the direct effect of canopy coverage, additional residue cover after termination, or change in aggregation and formation of macropores by intact cover-crop roots (24a). In one study, adding a grass/legume CC improved K_{sat} by 3.6 times over corn/wheat/sunflower rotations alone (25). In a 15-year experiment in Kansas, planting sunn hemp (a cover crop with a high carbon content) increased K_{sat} by 3 times over wheat/sorghum rotations (26).

The morphology of grass roots also affects infiltration (27). A study conducted in a claypan soil in Missouri showed that the "use of perennial grasses in rotation (or permanently) benefited soil hydraulic properties" (29). In a 3-year study on two Coastal Plain soils in Georgia, an increase in infiltration of about 58 percent was observed where cover crops were grown compared to fallow areas (31). In a long-term study of corn and soybeans, the use of vetch or rye as a cover crop increased K_{sat}. These increases were related to legume plantings. It was suggested that the legumes encouraged greater faunal activity (34). In another study, managed grazing of cover crops did not significantly reduce infiltration in the Piedmont area of the southeastern United States after 2.5 years of grazing (8).

Perennial vegetation may be more effective than annually cropped systems at improving physical soil conditions. Areas of perennial vegetation are not subject to the surface compaction caused by planting operations, and perennial root systems appear to create a more stable, continuous pore network. For a claypan soil, hydraulic properties were compared between an area of long-term (>100 years), continuous row-crop cultivation and an area of native prairie that had never been tilled. K_{sat} in the upper 10 cm of soil was 57 times higher at the native prairie site. The difference was partly explained by the significant difference in pore-size distribution (32). This difference in K_{sat} implies the magnitude of the effect cultivation has on soils. Use of cover crops accelerates improvements in physical soil properties, which become more similar to those that existed historically under native grass systems. In an area of a fine-silty Mollisol[3] in the U.S. Midwest, K_{sat} after 10 years of growing switchgrass as a hedgerow was 6 times greater than that in the cultivated field (33). This further demonstrated that runoff is reduced where biomass is grown as a permanent cover.

Managing wheel compaction in traffic rows is important for increasing K_{sat}. In a review paper that summarized cover-crop studies, runoff was reduced by between 4 and 50 percent for no-till with residue mulch or no-till with cover crops as compared to conventional till alone (30). In sandy soils, cover crops may not increase the infiltration rate, which is already high (28).

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[3] Mollisol: A soil order in U.S. Soil Taxonomy. Mollisols have generally moderate to high base cation content (calcium, magnesium, potassium), near neutral pH (although surface layers may have been acidified by fertilization), and moderate (>1%) or higher soil organic matter content.

Mulching: Practice Standard 484

Practice Standard 484 applies to locations where mulch is imported onto a field. The objective of the following discussion is to highlight the effects of mulch and residue cover on soil infiltration and K_{sat} regardless of the source of the mulch or cover. Addition of residue and mulch to the soil surface also provides significant protection against the formation of surface crusts, moderates the soil surface temperature, and creates habitat for organisms. Retention of residue is a component of Practice Standards 329 and 345.

Soil crusting reduces infiltration and thereby increases runoff and erosion. In a 1-year study of a no-till system, retention of stover increased K_{sat} from 700 to 3,100 percent, depending on soil type, compared to removal of stover (35). In another study, 10 years of straw mulching appeared to be a viable practice to improve near-surface (0-3 cm) K_{sat} in long-term NT soils. Residues may not, however, increase overall rates of water infiltration deeper in the soil profile because burrowing of earthworms is shallow (36). An eight-season study was conducted on Cecil sandy loam in the southeastern United States. Soils managed by soybean and grain sorghum/sorghum crop sequences following winter wheat were sampled after harvest in the eighth season. Comparisons were made for winter wheat under conventional tillage (CT), in-row chisel (MT), and no-till (NT). Infiltration was significantly greater under the MT system than the CT and NT systems (but only at the least-significant-difference level of 0.20). Maintenance of wheat straw on the soil surface exhibited an effect to a depth of 75 mm under both the MT and NT treatments and affected infiltration under the MT treatment. Effects of crop rotations on physical properties can be erased or modified by tillage and may only be observed under NT (37).

A 12-year study was conducted on a fine textured Mollisol[4] that included 4 rotations (monocropping and rotations of corn and wheat) under rainfed conventional tillage, no-till, residue retention, and residue removal. Infiltration increased soil moisture by up to 30 percent under NT when residue was left in the field compared to being removed after harvest (38). A paper that reviewed several studies cited a 4 to 50 percent reduction in runoff for no-till with mulch or cover crops, or both, as compared to conventional till alone (39).

All tillage systems can benefit from mulching and from limiting removal of stover after harvest. A long-term field study of no-till, ridge-till, and plow-till at three mulching rates on a silt loam in Ohio showed water infiltration rates ranging from 1.2 cm h^{-1} (plow-till) to 4.6 cm h^{-1} (no-till). Increasing mulch application rates by 0, 8, and 16 Mg ha^{-1} increased K_{sat} in soil under maize and wheat (for the highest mulch rate). The increases were 189, 188, and 166 percent under no-till, ridge-till, and plow-till,

[4] Mollisol: A soil order in U.S. Soil Taxonomy. Mollisols have generally moderate to high base cation content (calcium, magnesium, potassium), near neutral pH (although surface layers may have been acidified by fertilization), and moderate (>1%) or higher soil organic matter content.

respectively. Under no-till, the soil also showed greater structural stability than under plow-till and significantly lower compaction values (40).

Eroded Ultisols[5] occupy more than 40 percent of the Southern Piedmont region of the United States. In a 5-year study on double-crop NT, residue ranged from 10 to 14 Mg $ha^{-1}y^{-1}$. Soil carbon increased significantly under NT. Average soil carbon for slight, moderate, and severe soil erosion classes ranged from 0.97 to 2.37 percent at soil depths of 0 to 1.5 cm. Accompanying the soil-carbon responses were increases in soil nitrogen, water-stable aggregation, and infiltration. Runoff decreased from 35 to 37 percent under conventional tillage to 6 percent under NT (41).

In another study, however, there were no significant differences in K_{sat} between treatments. This study was conducted on Raynham silt loam (a coarse-silty Epiaquept[6]) in Chazy, New York. The study examined the effects of 32 years of corn-stover harvest vs. stover returned in a plow-till (PT) and no-till (NT) system. Results of this study suggest that, on a silt loam soil in a temperate climate, long-term stover harvest had lower adverse impacts on soil quality than long-term tillage. Stover harvest appears to be sustainable when practiced under NT management (42).

Crop-residue cover is commonly used to reduce surface sealing. One study used numerical simulations for combinations of (i) soil type, either a clay loam or loamy sand; (ii) percent residue cover; (iii) K_{sat} of the surface seal relative to bulk soil K_{sat}; (iv) residue-patch size; and (v) rainfall intensity. More residue cover was needed to produce the same increase in infiltration for the clay loam than for the loamy sand (44).

However, a study of residue (burning, baling and hauling, incorporation, and incorporation of twice the amount of residue produced by the crop) for winter wheat and grain sorghum in an area of Richfield silty clay loam (a fine, montmorillonitic, Argiustoll[7]) showed that most of the soil physical properties measured were not influenced by either grain sorghum or wheat residue management treatments but did differ between crops. However, pore-size distribution within the Ap horizon of the sorghum plots

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[5] Ultisols: A soil order in U.S. Soil Taxonomy. Ultisols have a low base saturation and an argillic horizon, which is a horizon that has a higher clay content than the overlying horizon and that formed partially from the movement of clay from the overlying horizon.

[6] Coarse-silty Epiaquept: In this case, a soil that has a surface layer and subsoil of silt loam and that, in an undrained condition, has a perched high water table near the surface at some period during the year. More information about this soil can be obtained at https://soilseries.sc.egov.usda.gov/OSD_Docs/R/RAYNHAM.html.

[7] Fine, montmorillonitic, Argiustoll: In this case, a soil that has a topsoil of silty clay loam, a high shrink-swell potential, and soil moisture during some part of the growing season. The content of soil organic matter is more than 1 percent, and surface structure is not both hard and massive. The pH is near neutral (unless acidified by fertilization), and base cation content (calcium, magnesium, potassium) is naturally moderate to high. More information about this soil can be obtained at https://soilseries.sc.egov.usda.gov/OSD_Docs/R/RICHFIELD.html.

was more conducive to water infiltration. The K_{sat} was several times greater in the soil cores obtained from the sorghum plots than from those obtained from the wheat plots (46).

A review chapter discussed the control of runoff through the management of crop residue. Reduced tillage systems were examined, and residue management in irrigated systems was compared to dryland systems. Cropping intensity was also examined. Surface crop residues generally increased infiltration and decreased evaporation. Overall, the amount of residue (biomass) left on the soil surface is more important to the improvement of water conservation than the specific tillage type or management system (47).

NT systems may not provide benefits in all environments, such as where a freeze-thaw cycle does not occur after the soil is frozen. A study was conducted to characterize infiltration, water retention, and saturated hydraulic conductivity in a silt loam in interior Alaska after 20 years of tillage and straw management treatments and continuous barley. The study examined no-till, autumn chisel plow, spring disk, intensive tillage (autumn and spring disk), and retention or removal of stubble and loose straw from the soil surface after harvest. No-till resulted in greater saturated hydraulic conductivity. Infiltration was greater for soil under autumn chisel-plow than under other tillage treatments and was presumably suppressed in no-till areas by an organic layer overlying the mineral soil. Infiltration was also enhanced by retaining (rather than removing) straw from the soil surface after harvest. “No-till is not yet a sustainable management practice in this region due to a lack of weed-control strategies. In addition, the formation of an organic layer in no-till has important ramifications for the hydrological and thermal environment of the soil. Therefore, minimum tillage (i.e., autumn chisel-plow or spring disk) appears to be a viable management option for maximizing infiltration in interior Alaska” where a freeze-thaw cycle does not occur (45).

Other Additions of Organic Matter (Wastewater, Sludge, Effluent, and Solid Manure)

Chicken and dairy manure were incorporated to a depth of 15 cm in a Waialua gravelly clay variant (an isohyperthermic Pachic Haplustoll[8]). The initial K_{sat} was 0.34 to 1.21 m d^{-1}. K_{sat} values increased by approximately 4 times, partly due to the effects of straw in the manure, aggregate development, or both. The trial fields were not farmed during the experiment (48).

An 8-year experiment using a wheat-soybean rotation was conducted on silty clay loam to determine the influence of NPK fertilizer compared to NPK fertilizer plus farmyard-manure (FYM) on soil properties. The steady-state infiltration rate was higher under NPK + FYM than under the unfertilized and NPK-alone

[8] Isohyperthermic Pachic Haplustolls: Soils in the hot tropics that are moist in some part of the growing season. The content of soil organic matter is more than 1 percent to a depth of greater than 50 cm, and surface structure is not both hard and massive. The pH is near neutral (unless acidified by fertilization), and base cation content (calcium, magnesium, potassium) is naturally moderate to high.

treatments. There were marked improvements in soil water transmission properties (infiltration, sorptivity, and K_{sat}) for FYM-treated plots over no-FYM plots and for N-treated plots over no-N plots (49a).

A study was conducted on the influence of manure incorporation and length of incubation period on the structural stability of three tropical soils with different clay contents and mineralogies. Samples were treated with farmyard manure (FYM) at three rates, brought to field capacity, and incubated. Water-stable aggregates (WSA) for the sample with the largest treatment combination (12% FYM and 56-day incubation) increased by 23 to 27 percent compared to the natural sample with no treatment. The higher the load of FYM incorporation, the more stable the soil became with incubation. Greater improvement was found in K_{sat}, where values increased between 50 and 700 percent. Both WSA and K_{sat} increased as duration of incubation increased, regardless of FYM level, clay content, or clay mineralogy. "These increases suggest that soil incubation by itself at field capacity after structural disturbance, with or without FYM incorporation, is a desirable practice that encourages particle bonding and structural improvement" (53).

A calcareous soil was studied for the effects of sludge application on physical soil properties and transport of zinc, copper, and lead. Anaerobically digested secondary sewage sludge was applied at four rates and mixed (top 20 cm of soil) during 4 consecutive years. Corn was planted as a spring crop, followed by wheat as a winter crop. Sludge application increased the content of dissolved organic matter, modified the soil structure, increased the saturated hydraulic conductivity, and increased the rate and depth of water infiltration. On average, sludge application increased the depth of water infiltration by 288, 254, and 375 percent (54).

Irrigation of semiarid, clayey and sandy soils with secondary effluent increased salinity and sodicity. The K_{sat} of a loamy soil and a clayey soil were decreased by leaching with secondary effluent because the pores became plugged by suspended solids. The K_{sat} of a sandy soil was not affected because of its large average pore size. The K_{sat} of high-sodicity, arid soils was decreased by irrigation of effluent that had undergone reverse osmosis treatment (to remove salts). The low electrolyte concentration of the effluent enhanced soil swelling and clay dispersion. The K_{sat} of a clayey soil leached with water of low electrolyte concentration was decreased as the sodicity was increased by the effluent irrigation. The soil had enhanced swelling and dispersion of clay. In a noncalcareous, sandy soil, the higher sodicity in the effluent-irrigated soil caused enhanced clay dispersion that led to surface soil sealing, reduced infiltration, and increased runoff. In contrast, calcareous soils under similar conditions showed no effects on runoff and soil loss due to effluent irrigation. Because of the interaction between effluent irrigation and soil properties, it is necessary to identify sensitive regions and soils prior to irrigation with effluents. Such identification can be used to prevent possible negative effects on soil structure and hydraulic properties (50). Clayey, loamy, and sandy soils were sampled from experimental plots irrigated with fresh water or secondary effluent for more than 3 years. Leaching the loamy and clay soils with reverse osmosis (RO) effluent (which had low concentrations of electrolytes) led to swelling and dispersion of clay and decreased K_{sat}. The high concentration of suspended solid particles and dissolved organic matter (DOM) in oxidation pond (OP) effluent caused significant pore clogging and reduction of K_{sat}. Leaching the soils with ultra-filtered effluent maintained high K_{sat} values because of the low concentration and small sizes of suspended solid particles and DOM and the relatively high electrical conductivity of the effluent. When the sandy soil was leached with RO and OP effluent, the relatively large average pore size prevented pore clogging and reduction in K_{sat}. Secondary effluent irrigation increased the soil exchangeable-sodium percentage (ESP) compared with freshwater irrigation (51). The effect of applications of fresh water and differently treated wastewater on K_{sat} in the surface and subsurface layers of sandy loam, loam, and clay loam was studied by investigating the ratio of K_{sat} after wastewater applications to K_{sat} after freshwater applications. "The ratios were examined in the surface horizon (Kr1) and subsurface horizon (Kr2). Reduction in K_{sat} in Kr1 mainly occurred at depths of 0–50 mm because of application of wastewater. The reduction was greater in clay loam than in loam and sandy loam. The reduction in Kr1 of greater than 50 percent occurred in different soil textures where application of wastewater with total suspended solids was ≥ 40 mg L^{-1}. The reduction in K_{sat} in Kr2 resulting from application of wastewater for different soil textures was not great at depths of 100–300 mm. Less purified wastewater can be used in light textured soils, resulting in less reduction in K_{sat}." (52).

Detailed Summaries of Cited Literature

The summaries below were initially copied from the paper's abstract. In some of the summaries, information was added that is important to soil health but was not included in the abstract. Scientific terms were replaced where possible by terms better understood by the general public, and sentences and phrases were removed that were not necessary to describe the basic content. Scientific names and statistical terminology were also replaced with common terms to aid in readability. Verbatum text from the original paper is presented in quotes.

No-Till

1.—Blanco-Canqui et al. (2010). This study "assessed the 8-y impacts of intensive cropping systems and wheel traffic on soil physical and hydraulic properties and their relationships under NT on a Ladysmith silty clay loam (a fine, smectitic, mesic Udertic Argiustoll) near Hesston, KS. Winter wheat (W), grain sorghum (S), double-crop grain sorghum (*S), soybean (B), and double-crop soybean (*B) arranged in S-S-S, W*S-S-B, W-S-B, and W*B-S-B rotations were studied. In doubled crops, sorghum or soybean was planted immediately after wheat harvest. Cropping systems had less of an effect on soil properties than wheel traffic. Wheel traffic increased bulk density (ρb) from 1.16 ± 0.06 (mean ± SD) to 1.38 ± 0.03 Mg m^{-3}, cone index (CI) from 1.78 ± 0.29 to 3.10 ± 0.15 MPa, shear strength (SHEAR) from 23 ± 2.2 to 61 ± 5.2 kPa, and aggregate tensile strength from 377 ± 80 to 955 ± 148 kPa over nontrafficked rows in the 0- to 7.5-cm depth. Wheel compaction reduced cumulative infiltration by 40 to 120 times except in S-S-S. It also reduced the logarithm of the saturated hydraulic conductivity (log K_{sat}), soil water retention at 0 kPa, plant-available water, effective porosity (ϕe), and the volume of >50-µm pores. An increase in ρb, CI, and SHEAR linearly reduced ϕe (r > −0.74), which, in turn, reduced cumulative infiltration and log K_{sat} (r > 0.74). Data strongly supports the need for using controlled traffic to reduce the adverse impacts of wheel traffic on soil physical quality."

2.—Benjamin et al. (2008) concluded "soil OC content with no-till systems in the central Great Plains may not immediately lead to beneficial changes in other soil physical and hydraulic properties. There may be delayed incorporation of carbon from plant residues into aggregate-stabilizing compounds because of a lack of mixing with no tillage. Another factor that may delay beneficial effects of increasing OC on physical and hydraulic properties is the dry soil-surface conditions that occur for extended periods of time in this climate. Dry conditions minimize the microbial activity necessary for the oxidation of organic compounds into agents needed for soil aggregation. It may be helpful to concentrate efforts on identifying the constituents of soil OC that improve water stable macro aggregates and other soil physical properties to help design rotations that will improve soil productivity for long-term sustainable agricultural use." Using the core method, K_{sat} had a mean value of 10.8 mm h^{-1} for grass plots and 3.0-3.2 mm h^{-1} for no till wheat/fallow and wheat/corn/millet, an approximate increase of 3.5 times for the grass plots.

3.—Blanco-Canqui and Lal (2008) found in a 20-year study on a silt loam and a clay loam that wheel-traffic-induced compaction reduced NT grain and stover yields by 13 and 23 percent, respectively, in the clay loam soil but not the silt loam soil. Axle loads of 10 and 20 Mg were applied. Yield reductions were also correlated to earthworm population reduction. Infiltration was significantly reduced by 3 to 5 times under 10 Mg loads and by up to 30 times under 20 Mg loads in the silt loam soil and by 5 to 40 times under 20 Mg loads in the clay loam soil. Cumulative infiltration was reduced by about 6 to 50 times. By inference, increases in runoff are probable. Plant available water was not significantly affected. Maintaining traffic in the same path will isolate negative effects of equipment loads. This study also points out that wheel-traffic impacts vary by soil type.

4.—Dao (1993). An 8-year study was conducted to determine the effects of three tillage and residue management practices (no-till, stubble mulch, and moldboard) on soil water storage in Bethany (fine, mixed, thermic Pachic Paleustoll) and Renfrow (fine, mixed, thermic Udertic Paleustoll) silt loams on a 2% slope near El Reno, OK. Soil management cumulative effects on soil bulk density and water infiltration during and after the growing season were measured. Water content was also determined in the 3 managements. "No-till soil consistently had higher volumetric water content in the 0- to 1.2-m depth, except in late fall or early spring when root-zone recharge took place for both soils." Increased water-holding capacity and decreased bulk density of no-till soils were also measured. "Seasonal variability of field infiltration was more evident in plowed soil than in no-till soil. Such temporal dependence would affect surface distribution and flow of precipitation to explain differences in runoff, soil erosion, and environmental impacts of tillage systems between October and June. Water infiltration into no-till soil was significantly higher than into plowed soil at similar water contents. Under ponding, recharge occurred through macropores, directly wetting depths of 0.4 to 0.6 m of no-till soil, in contrast to a layered pattern in plowed soil." "Elimination of inversion tillage enhanced precipitation storage, thereby alleviating detrimental effects of climate variability in annual winter wheat cultivation."

4a.—Edwards, W.M., et al. (1992). "Long-term watershed studies at the North Appalachian Experimental Watershed, Coshocton, Ohio have shown that when corn is planted in soil covered by the residue of the previous crop (i.e. no-tillage management), surface runoff from summer storms is greatly reduced. In addition, the residue cover provides a favorable environment for various soil invertebrates, especially earthworms. During high-intensity rainstorms, some of the water that infiltrates in no-till corn fields moves rapidly downward in burrows made by the earthworms." Samplers were developed for collecting infiltrating rain water flowing in L. *ferrestris* burrows at a depth of 45 cm below the soil surface. With annual surface applications of 175 kg N ha^{-1} as NH_4NO_3, concentrations of NO3-N in water flowing in individual burrows during growing season storms ranged up to 152 mg l^{-1}. Concentrations of NO3-N tended to be lowest after prolonged wet soil conditions and highest after intermittent warm, dry periods. Distilled water poured directly into the surface openings of burrows and immediately collected as it drained into samplers, contained up to 40 mg of NO3-N l^{-1}, a value greater than that measured in many of the samples resulting from natural rain storms. Water and herbicide mixtures poured through burrows showed that the linings of the burrow, or drilosphere, may contribute nitrogen to the infiltrating water while greatly reducing the concentrations of atrazine and alachior.

5.—Evett et al. (1999). This study measured surface soil hydraulic properties on no-till (NT) and conventional (stubble mulch) tillage (CT) plots, each of which was farmed with either a wheat-sorghum-fallow (WSF) or a wheat-fallow (WF) rotation on a Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) in Bushland, TX. The plots had been in the same treatments for 12 years. Tension infiltrometers were used to measure steady state infiltration rates at four heads, h (nominally -2.0, -1.5, -1.0, and -0.5 kPa. "The fitted water retention curves showed marked differences between NT and CT treatments. The more dense NT soils exhibited a more gradual reduction in water content as tension increased." "The saturated water content was significantly lower for NT than for CT. Bulk density was significantly greater for NT than for CT, and significantly greater for WSF than for WF." "For WSF rotations, saturated K was significantly greater for CT than for NT, but not in WF rotations. The overall fitted K(h) curves showed that K was greater in CT than in NT for both WF and WSF rotations over most of the water content range from 0.1 to 0.5 m^3 m^{-3}. These results indicate that greater runoff would be expected under no tillage."

6.—Francis and Knight (1993). In New Zealand, a rapid-draining Lismore stony silt loam (Umbric Dystochrept) and a slow-draining Wakanui silt loam (Udic Ustochrept) under an average precipitation of 750 mm at both sites were studied for changes in earthworm populations, bulk density, SOC, N including mineralizable, porosity and water content and infiltration and crop yields were compared under conventional tillage (CT) and no-tillage (NT) using rotations but no cover crops. Trials were conducted for 9 consecutive years at two sites. The Lismore site had been under long-term pasture (5y) prior to initiation of the experiment, whilst the Wakanui site had been under long-term (10y) arable cropping.

“At the Lismore site, organic C and total N contents in the top 150 mm of soil declined under both treatments during the trial, although the decrease was relatively greater under CT. Tillage treatment had little effect on soil organic matter content at the Wakanui site. At both sites, organic matter was more evenly distributed in the top 150 mm of soil under CT than NT. Bulk density was largely unaffected by tillage treatment on the Lismore soil, but on the Wakanui soil it was greater under NT at 0-150 mm depth throughout most of the trial. For both the Lismore and Wakanui soils, macroporosity was generally less in the surface (0-75 mm) layers of uncultivated soil. At both sites, earthworm populations were greater under NT than CT. Yields of wheat tended to be greater under NT at both sites, with crops grown under CT requiring an additional 15-45 kg N ha^{-1} to obtain yields similar to those under NT. At the Wakanui site, by contrast, spring barley yields were greater under CT with an additional 10-20 kg N ha^{-1} required under NT to provide yields similar to those under CT. Under CT there is a flush of mineralization following cultivation, whilst under NT mineralization is more evenly distributed over the growing season. Crops grown following cultivation in autumn/winter have a more adequate N supply during the growing season under NT than CT, as much of the N which is mineralized after cultivation of CT soil is susceptible to leaching before the spring. Crops grown following cultivation in the spring have a more adequate N-supply than those under NT, as the flush of N mineralization under CT occurs immediately prior to the onset of rapid crop growth.”

7.—Franzlubbers (2002). “Two soils (Typic Kanhapludults), one under long-term management of conventional tillage (CT) and one under long-term management of no tillage (NT), were sampled to a depth of 12 cm. Soil cores (15 cm diameter) were either left intact or sieved and repacked to differentiate between short-term (sieving) and long-term (tillage management) effects of soil disturbance on water infiltration, penetration resistance, soil bulk density, macroaggregate stability, and soil organic carbon (SOC). Mean weekly water infiltration was not different between sieved and intact cores from long-term CT (22 cm h^{-1}), but was significantly greater in intact (72 cm h^{-1}) than in sieved (28 cm h-1) soil from long-term NT. The stratification ratio of SOC (i.e., of 0–3 cm depth divided by that of 6–12 cm depth) was predictive of water infiltration rate, irrespective of short- or long-term history of disturbance. Although tillage is used to increase soil porosity, it is a short-term solution that has negative consequences on surface soil structural stability, surface residue accumulation, and surface-SOC, which are critical features that control water infiltration and subsequent water transmission and storage in soil. The stratification ratio of SOC could be used as a simple diagnostic tool to identify land management strategies that improve soil water properties (e.g., infiltration, water-holding capacity, and plant-available water).” “Short-term soil disturbance (i.e., sieving as a simulation of tillage) of previously stratified soil led to uniform distribution of SOC, reduced soil bulk density, and increased water retention, at least initially. Greater total SOC content (i.e., sieved NT vs. sieved CT) reduced soil bulk density by 12% and improved water infiltration by 27%. Greater stratification of SOC content (i.e., long-term intact NT vs. intact CT) reduced soil bulk density by 10% and improved water infiltration nearly threefold. This greenhouse experiment suggests that stratification ratio of SOC could be used as a simple diagnostic tool to identify land management strategies that restore critical soil functions, such as water infiltration. Detailed field studies under a wide range of conditions will need to be investigated to support these findings."

8.—Franzluebbers and Stuedemann (2008). A multiple-year research was conducted on a Typic Kanhapludult soil in Georgia to study how cover crop management affected bulk density, aggregation, infiltration, and penetration resistance. The managements included grazed and ungrazed cover crop and tillage system—conventional (CT; initial moldboard plowing and thereafter disk tillage) and no tillage (NT). The objective was to evaluate how integrated crop-livestock systems with cattle grazing of cover crops would affect soil physical properties, especially those related to soil compaction and surface soil degradation, under both conventional and no tillage management. "Soil bulk density was reduced with CT compared with NT to a depth of 30 cm at the end of 0.5 year, but only to a depth of 12 cm at the end of 2, 2.5, and 4.5 years. Grazing of cover crops had little effect on soil bulk density, except eventually with 4.5 years of management. Water stable macroaggregation was reduced with CT compared with NT to a depth of 12 cm at all sampling times during the first 2.5 years of evaluation. Stability of macroaggregates in water was unaffected by grazing of cover crops in both tillage systems. Across 7 sampling events during the first 4 years, there was a tendency for water infiltration rate to be lower with grazing of cover crops than when ungrazed, irrespective of tillage system. Across 10 sampling events, soil penetration resistance was greater under NT than under CT at a depth of 0–10 cm and the difference was greater in ungrazed than in grazed systems. Biannual CT operations may have alleviated any surface degradation with animal traffic, but the initially high level of soil organic matter following long-term pasture and conversion to cropland with NT may have buffered the soil from any detrimental effects of animal traffic." Overall, "conversion of long-term perennial pasture to cropland resulted in changes in soil physical properties that were dependent upon subsequent tillage system. Initial moldboard plowing followed by disk tillage (CT) resulted in lower soil bulk density to a depth of 0–30 cm than undisturbed soil managed with no tillage (NT) at the end of 0.5 year. Thereafter, differences in bulk density between tillage systems disappeared below a depth of 12 cm with disk tillage only to 15–20 cm. Grazing of cover crops had little effect on soil bulk density, perhaps because of the high surface-soil organic C concentration following perennial pasture that mitigated compaction. Soil aggregation was degraded with CT compared with NT management. Stability of aggregates was unaffected by grazing of cover crops in both tillage systems. Water infiltration was variably affected by tillage and cover crop management, but was reduced with grazing of cover crops compared with ungrazed cover crops when soil water content was high at the time of measurement. Soil penetration resistance was often greater under NT than under CT, despite soil under NT was generally wetter than under CT. Soil penetration resistance was greater under grazed than ungrazed cover crops with CT, but not different between cover crop systems with NT. Overall, the introduction of cattle to consume the high quality cover crop forages (*Secale cereale* and *Pennisetum glaucum*) did not cause substantial physical damage to the soil. Additional long-term research is warranted to verify these short-term (initial 2.5 years) results."

9.—Govaerts et al. (2007). This study assessed practices that would sustain higher and stable yields for wheat and maize in the non-equatorial, subtropical highlands of Central Mexico. The soil is a Cumulic

Phaeozem (FAO, 1998) (fine, mixed, thermic Cumulic Haplustoll). A long-term experiment (randomized complete block) was started in 1991 under rainfed conditions in the volcanic highlands of central Mexico (2240 m a.s.l.; 19.318N, 98.508W). Soils were evaluated after "12 years of 16 management treatments from a factorial arrangement of: (1) four rotations (monocropping and rotation of maize and wheat), (2) two tillage (conventional tillage [CT] and zero tillage [ZT]) and (3) two crop residue management practices (residue retention and removal). Water infiltration and soil moisture levels were greater under ZT when residue was left in the field then when residue was removed. Higher infiltration rates and favorable moisture dynamics supported up to 30% yield increase. A significantly higher incidence of root rot was found in monoculture of maize under ZT than CT. Residue retention significantly increased maize root rot incidence compared to residue removal. Rotation of maize and wheat decreased the incidence of maize root rot up to 30%. In general, the incidence of root disease was lower in wheat (up to 3 on a scale of 7) than in maize (up to 3.93 on a scale of 4) for all treatment. In maize, both non-parasitic and parasitic nematodes increased under ZT; however, in wheat no effect of tillage was seen. Incidence of root rot and parasitic nematode populations were not correlated with yield. Although root diseases may have affected crop performance, they affected yield less than other critical plant growth factors such as infiltration and water availability. Both environmental conditions and microflora played a key role in the biology and expression of soil pathogens. In the semi-arid and rainfed subtropical highlands of central Mexico, positive effects were observed with zero tillage, crop rotations and crop residue retention, compared with common farming practices."

10.—Jabro et al. (2011) (2). This was a short-term study that "evaluated the effect of one year of no tillage (NT) versus conventional tillage (CT) on soil penetration resistance (PR), bulk density (BD), gravimetric moisture content (MC), and saturated hydraulic conductivity (Ks) during the fallow phase of a spring wheat–fallow rotation. The study was conducted on two soils mapped as Williams loam at the Froid and Sidney sites." Soil measurements were made between May and August. Results for PR, BD, and moisture content showed that no soil properties differed significantly between NT and CT tillage practices, except for soil PR at the Sidney site. Initially PR was lower in CT than in NT at depths of 0–5 and 5–10 cm in June but was greater under CT than under NT at 0-5 cm deep in August at the Sidney site. At Froid, PR increased from May to August regardless of tillage treatment and soil depth. Greater soil PR values in August were attributed to lower moisture contents in the soil, due to small amount of precipitation at the end of the growing season in northeastern Montana." Since this was only a 1 year study, no correlation to the no-till conservation (Practice Standard 329) can be made. The only conclusion that can be drawn from this study is that PR is likely to initially be less following CT compared to NT for a short term, but within a few months PR was equal to or greater on CT sites versus NT sites.

11.—Lipiec et al. (2006). "The effect of long-term use of various tillage systems on pore size distribution, areal porosity, stained (flow-active) porosity and infiltration of silt loam Eutric Fluvisol" was assessed. "Tillage treatments were: (1) ploughing to the depth of 20 cm (conventional tillage (CT)); (2) ploughing to 20 cm every 6 years and to 5 cm in the remaining years (S/CT); (3) harrowing to 5 cm each year (S); (4) sowing to the uncultivated soil (no tillage (NT)), all in a micro-plot experiment." "The differences among the tillage treatments were more pronounced at depth 0–10 cm than 10–20 cm." "CT soil had the greatest areal porosity and stained porosity." "Cumulative infiltration (steady state) as measured by the double ring infiltrometer method was the highest under CT (94.5 cm) and it was reduced by 62, 36 and 61% in S/CT, S and NT soil, respectively. Irrespective of tillage method, cumulative infiltration rates throughout 3 h most closely correlated with stained porosity in top layers (0–6 cm). Overall, the results indicate that soil pore system under CT with higher contribution of large flow-active pores compared to reduced and no tillage treatments enhanced infiltration and water storage capacity."

12.—Obalum and Obi (2010). This paper evaluates the impact of tillage and mulching practices in Nigerian Ultisols under no till and conventional till sorghum, soybean, or sorghum-soybean production. The experiment was conducted on a sandy loam soil with the tillage systems as the main plots and the mulch practices as the sub-plots with 4 replications. Earthworm activity was higher with no-till and an intercrop system. Total porosity was higher under conventional tillage in sorghum. Hydraulic conductivity was higher under conventional tillage under sorghum and intercrop sorghum-soybeans. The cropping system had more pronounced effect on physical properties than the tillage-mulch management practices.

13.—Owens (1994). This chapter contains a section on impact of tillage practices on subsurface water quality. The review demonstrates that macropores are destroyed by tillage, causing water to flow as a front through the soil rather than through preferential paths. Long-term runoff records indicate that infiltration and ground-water recharge may be higher under no-till. Leachate measured vs. leachate plus runoff reported show a 29 to 80% increase in leachate under no-till corn and soybean with corn facilitating greater infiltration. Soil moisture is greater under residue management systems as well. Increases in infiltration under no-till, also lead to the potential for greater movement of soluble nutrients, such as nitrate leachate, into tile drains or shallow ground water. The use of winter cover crops, diverse crops in rotation, and perennial grasses has shown benefits for their potential to reduce nitrate leaching losses as well. This chapter was based on various research papers across the United States and South America.

14.—So et al. (2009). The impact of 14 years of continuous conventional (CT) or no-till (NT) cultivation on surface soil structure and crop yields was examined on a weakly structured silty loam soil at Grafton in N.S.W. The annual soybean yields of the NT treatment between 1981 and 1985 were consistently less than or equal to those resulting from CT with an average of 2.46 t ha^{-1} and 2.82 t ha^{-1}, respectively, for the two treatments. However, CT was unable to sustain the greater yield, and from 1987 onwards the yields of the NT treatments have typically been greater than those of the CT (with averages of 2.14 t ha^{-1} and 1.67 t ha^{-1}, respectively). During the earlier years of the trial, soil porosity and crop yields were not greatly affected by the different tillage techniques. During later years and at the end of the trial, however, soil porosity and structural stability were greater under NT. Increased soil macroporosity (saturated water content of 0.61 for NT vs. 0.40 for CT) and structural stability (dispersed silt + clay contents of 10% for NT vs. 30% for CT) under long-term no-till cultivation were consistent with higher saturated hydraulic conductivity (189 for NT vs. 23 mm h^{-1} for CT, an 722% increase), higher infiltration and lower runoff under rainfall, increased plant available water (12.5% for NT vs. 10.5% for CT), water use efficiency, and crop yields. The improvement in soil structure observed under NT is associated with the significant increase in surface soil organic carbon contents (3.37% for NT vs. 1.67% for CT) and is shown to be the major contributor to the sustained improvement of crop yields.

14a.—Stubbs et al. (2004). “Soil biota is critical to the functioning of any agro-ecosystem, but studying soil biota is difficult due to the diversity and challenges associated with isolating and identifying these organisms. Soil disturbance or lack of disturbance can have a profound effect on biotic populations, processes and community structure. This contribution examines changes that occur in soil during the transition to no till cropping. Interrelations occur among organisms in the soil food web, and between organisms and soil physical and chemical properties in their environment. As interest grows in sustainable cropping systems that mimic natural process and soil organic matter cycling is imperative to understand how to transition to no-till and its effect on an organism’s niche or functional role. Ecosystem investigations will enhance the understanding of changes that occur with the adoption of reduced tillage and no-till cropping so that these systems become increasingly viable.” “Physical parameters of soil altered by tillage have a great influence on the soil ecology. Disturbance of the soil system, intact undisturbed soil versus tilled homogenized soil will impact infiltration and residue placement which are some of the changes that will affect soil organisms.” Soil under long-term no-till can increase in bulk density. However, these fears may be unfounded for many soil types because the loss of OM from intensively tilled or eroded soils leads to increased bulk density and the benefits of short-term bulk density improvements from tillage are offset by long-term benefits of no-till that reduce erosion, maintain organic matter, and increase continuous pores from earthworms and undisturbed root channels.

15.—Verbist et al. (2007). “Subsoil compaction due to conventional tillage techniques and its relation to subsurface flow and runoff was investigated on a sloped field. The presence of a plow sole was confirmed by significantly higher penetration resistances between 20 and 40 cm depth, a significantly higher soil bulk density and a 14% decrease in drainage pore space compared to the top layer. Ring infiltrometer measurements also confirmed a significant reduction of the saturated hydraulic conductivity at 30 cm depth, indicating limited permeability. With the use of an extensive grid of tensiometers, matric heads were monitored and the occurrence of a temporary water table on top of the plow pan was confirmed in a number of cases.” Subsurface flow parallel to the slope surface in a downward direction was confirmed. “For the whole measuring period, when a perched water table was observed, 91% of the rainfall events caused runoff and this number increased with increasing rainfall intensity. For low and medium rainfall intensities (<10 mm h^{-1}), 66% and 63% of the runoff events were related to saturation of the top soil.” “Over a period of 20 months saturation in the surface layer as a result of subsoil compaction resulted in surface runoff and soil loss.”

Conservation Tillage

16.—Buczko et al. (2006). “The objective of this study was to characterize macroporosity and surface soil hydraulic properties in two soils of different texture (Lietzen sandy loam (Humic Dystrudept) and Adenstedt silt loam (Typic Hapludoll) under conventional (CT) and conservation tillage systems.” Mean values of macroporosity were 0.005% for Lietzen and 0.018% for Adenstedt. For Adenstedt, RT showed higher macroporosity than CT. “Such treatment-induced differences were less developed for Lietzen. The Ks values measured with the ponded ring infiltrometer (RIF) at the sandy Lietzen site were higher than the corresponding values measured with the tension infiltrometer. These differences may be caused by subcritical soil water repellency (i.e., contact angles of the soil-water-air interface below 90°), although further factors could also be important (e.g., air entrapment, differences in water saturation, geometry of infiltration devices).” The finer textured Adenstedt soil showed differences in hydraulic properties due to tillage treatments, with little apparent differences for the sandy Lietzen site. This is presumed to be due to higher soil fauna activity and better structure at the Adenstedt site. Values are one order of magnitude higher than values estimated from soil texture. This implies that soil structure has a dominant influence on hydraulic conductivity.

17.—D’Haene et al. (2008). “Reduced tillage (RT) agriculture is growing more important in today’s agriculture in Western Europe. However, crop rotations often include beets and potatoes, crops that are generally assumed to be less suitable under RT agriculture because they result in a high disturbance of the soil at the formation of the ridges and at harvest. Therefore, the short- and long-term effect of RT agriculture on bulk density (BD), water retention curve (WRC), aggregate stability and field-saturated hydraulic conductivity of silt loam soils” (average 780 mm/y and temperature of 9.8 C) “with crop rotations including root crops was evaluated. At each location (10 RT and 7 CT) with similar soils and rotations, BD of the 5–10 cm layer was mostly lower (but only with very small differences) in the RT fields (average of 1.42 +-0.05 Mg m^{-3} standard deviation) compared to the CT fields (1.44 +-0.09 Mg m^{-3}) and the water content at saturation was mostly higher (0.394 +-0.027 m^3 m^{-3} and 0.382 +-0.021 m^3 m^{-3} for RT and CT fields, respectively). No differences in BD (1.53 +-0.03 Mg m^{-3}) or WRC could be found in the 25–30 cm soil layer when comparing the RT with the CT fields. Determination of aggregate stability by the change in mean weight diameter was 40% higher under RT than CT agriculture.” “The mean weight diameter (MWD), aggregate stability and assessment of soil crustability and erodibility was significantly higher even after short-term RT compared to CT.” “The MWD after a heavy shower, a slow wetting of the soil and stirring the soil after prewetting was 19%, 38% and 34% higher for RT than CT fields, respectively. The field-saturated hydraulic conductivity tended to be higher under RT compared to the CT fields. Despite the high disturbance of the soil every 2 or 3 years of crop rotations including sugar beets or potatoes, RT agriculture had a positive effect on the investigated physical soil properties.”

18.—Liebig et al. (2004). “This paper summarizes the interactive effects of tillage, crop sequence, and cropping intensity on soil quality indicators for two long-term cropping system experiments in the northern Great Plains. The experiments, located in central North Dakota, were established in 1984 and 1993 on a Wilton silt loam (fine-silty, frigid Pachic Haplustoll). Soil physical, chemical, and biological properties considered as indicators of soil quality were evaluated in spring 2001 in both experiments at depths of 0-7.5, 7.5-15, and 15-30 cm. Management effects on soil properties were largely limited to the surface 7.5 cm in both experiments. For the experiment established in 1984, differences in soil condition between a continuous crop, no-till system and a crop–fallow, conventional tillage (CT) system were substantial." "The continuous crop, no-till (NT) system possessed significantly more soil organic C (by 7.28 Mg ha^{-1}), particulate organic matter C (POM-C) (by 4.98 Mg ha^{-1}), potentially mineralizable N (PMN) (by 32.4 kg ha^{-1}), and microbial biomass C (by 586 kg ha^{-1}), as well as greater aggregate stability (by 33.4%) and faster infiltration rates (by 55.6cm h^{-1}) relative to the" CT system. Soil from the NT system was improved with respect to its ability to provide a source for plant nutrients, withstand erosion, and facilitate water transfer. Properties were affected less by management practices in the experiment established in 1993, although SOM-related properties tended to be greater under continuous cropping or minimum tillage than crop sequences with fallow or NT. In particular, PMN and microbial biomass C were greatest in continuous spring wheat (with residue removed) as compared to sequences with fallow (SW–S–F and SW–F). Results from both experiments "confirm that farmers in the northern Great Plains of North America can improve soil quality and agricultural sustainability by adopting production systems that employ intensive cropping practices with reduced tillage management."

19.—Jabro et al. (2009) studied the effects of conventional (CT) and strip (ST) tillage practices on bulk density (ρb), gravimetric water content (θw), and saturated hydraulic conductivity (Ks) at the soil surface and at 10 to 15cm depth at two sites, one in North Dakota (Lihen sandy loam) and one in Montana (Savage clay loam). "Measurements were made in the center of crop rows within CT and ST plots of irrigated sugarbeet. Tillage treatments significantly affected soil ρb and θw in clay loam soil at the EARC site, while pb and θw did not differ between CT and ST in sandy loam." Ks at the soil surface did not differ significantly between CT and ST practices at either site but the effect of tillage on Ks at the 10- to 15-cm depth was significant in both sandy loam and clay loam soils. The Ks values at 10- to 15-cm depth were 23% and 138% greater for ST than for CT at ND and MT, respectively. "Differences in soil compaction as evaluated through ρb at 10- to 20-cm depth explain Ks variations between the CT and ST systems at both sites. It was concluded that the CT increased soil compaction, which consequently altered ρb, thereby reducing Ks in the soil." "Soil ρb was generally lower in ST plots than in CT plots while θw was greater for ST than for CT regardless of soil type." "The ST plots likely had better volume of macropores than CT plots, producing greater water flow through the ST soil profile and consequently enhanced water storage capability as reflected by wetter soil conditions under ST system."

20.—Jabro et al. (2011) (1). "A 2-year study was carried out to compare effects of conventional (CT) and strip (ST) tillage practices on soil bulk density (Pb), water content (w), final infiltration rate (Infil) and saturated hydraulic conductivity (Ks) for a Lihen sandy loam where sugarbeet was grown during the 2007 and 2008 growing seasons." Under each tillage system, Pb and θw were measured in all plots at soil surface (0 to 10 cm) and 10-to 30-cm depths. At both depths under each tillage system, in-situ Infil was measured using a pressure ring infiltrometer (PI) and in-situ Ks was measured using a constant head well permeameter (CHWP). Although, the authors noted a significant difference in Pb between CT and ST plots at 10- to 30-cm depth in 2007, soil w did not differ significantly between CT and ST plots in 2007. In 2008, soil Pb and θw did not differ significantly between CT and ST plots at both depths. The Infil was affected by tillage practice in 2007 but was not significantly affected in 2008. The effects of tillage on Ks were significant in 2007 and in 2008. Soil Ks values were 68% and 56% greater for ST than for CT in 2007 and 2008, respectively. It was concluded that ST reduced soil compaction in the row, consequently increased total porosity, reduced Pb, and thereby increased Infil and Ks in the soil.

21.—Pagliai et al. (2004). "Soil structure conditions were evaluated by characterizing porosity using a combination of mercury intrusion porosimetry, image analysis and micromorphological observations. Saturated hydraulic conductivity and aggregate stability were also analyzed. In soils tilled by alternative tillage systems, like ripper subsoiling, the macroporosity was generally higher and homogeneously distributed through the profile while the conventional tillage systems, like the moldboard ploughing, showed a significant reduction of porosity both in the surface layer (0–100 mm) and at the lower cultivation depth (400–500 mm). The higher macroporosity in soils under alternative tillage systems was due to a larger number of elongated transmission pores. Also, the microporosity within the aggregates, measured by mercury intrusion porosimetry, increased in the soil tilled by ripper subsoiling and disc harrow (minimum tillage). The resulting soil structure was more open and more homogeneous, thus allowing better water movement, as confirmed by the higher K_{sat} in the soil tilled by ripper subsoiling. Aggregates were less stable in ploughed soils and this resulted in a more pronounced tendency to form surface crust compared with soils under minimum tillage and ripper subsoiling. The application of compost and manure improved the soil porosity and the soil aggregation. A better aggregation indicated that the addition of organic materials plays an important role in preventing soil crust formation. These results confirm that it is possible to adopt alternative tillage systems to prevent soil physical degradation and that the application of organic materials is essential to improve the soil structure quality."

22.—Pitkanen and Nuutinen (1998). "The contribution of earthworm burrows to infiltration and surface runoff was investigated in a 15-year-old tillage experiment in Finland. The tillage treatments included fall moldboard plowing, fall stubble cultivation and spring stubble cultivation, each replicated four times. At the time of the study, all treatments had been left untilled following harvest. Earthworms were sampled by combined formalin extraction and hand-sorting. Undisturbed soil samples taken from formalin-sampled areas were subjected to simulated rainfall treatments in the laboratory, and percolating water and surface runoff were collected. After the rainfall treatments the saturated hydraulic conductivity (K_{sat}) of each sample was measured, and a dye was applied to study the preferential pathways of soil water. The earthworm fauna consisted of the dominant *Aporrectodea caliginosa* and clearly less abundant *Lumbricus terrestris* and *L. rubellus*. The only discernible difference between the tillage treatments was that L. terrestris was present only in un-plowed soils, although in very low numbers. During the rains, there were no significant differences between the treatments in volumes of percolated water, but there was significantly less runoff from spring stubble-cultivated soil than from fall-tilled soils. K_{sat} was also significantly higher in the spring stubble-cultivated soil. K_{sat} was positively related to the volume of percolation, and negatively to the volume of surface runoff collected during the second rain. Total areas of stained earthworm burrows at the depths of 20 and 30 cm were correlated positively with K_{sat}."

23.—Schwartz et al. (2010). This study evaluated the effects of sweep tillage (ST) on near surface soil water dynamics as compared with an untilled (UT) soil during a 7-month period in a fallow field on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) that was previously under stubble–mulch tillage management. "During a 114-day period from April through July, tillage with a sweep (0.07–0.1 m) significantly decreased net water storage above 0.3 m soil depth by an average of 12 mm as compared with UT plots. After tillage, soil water contents at 0.05 and 0.1 m were significantly lower in ST plots, even following repeated precipitation events. Water contents at soil depths deeper than 0.2 m were not influenced by tillage. Cumulative 3-day evaporation following precipitation events averaged 3.1 mm greater under ST compared with UT. After extended dry periods, evaporation rates were similar among both treatments despite the greater near-surface water contents of UT plots." This resulted in great cumulative evaporation in ST plots (19 mm) from July through October; however, "this was offset by 26 mm greater infiltration compared with UT. A more advanced surface crust development and greater initial water contents were likely responsible for lower cumulative infiltration of UT compared with ST plots. Immediately after tillage, cumulative daily net radiation averaged 22% greater for ST compared with UT surfaces and these differences diminished with time. Increased evaporation under tillage was likely a result of enhanced vapor flow near the surface and greater absorption of radiation by a tilled surface with reduced albedo."

24.—Vogeler et al. (2009). Data from a long-term fertilization trial in Braunschweig, Germany on a silty loam (Dystric Cambisol/Orthic Luvisol (FAO)) with a mean annual precipitation of 620 mm and average air temperature of 8C, were used to evaluate phosphorus (P) fertilization on bulk density, porosity, water retention, soil organic matter, K_{sat}, P accumulation in the soil, yield of various crops, and P uptake. "Conventional (CT) and conservation tillage (Con till) vs. three fertilizer regimes (i) nitrogen and potassium, (ii) nitrogen, potassium and farmyard manure, and (iii) nitrogen, potassium, phosphorus and farmyard manure were evaluated. Six and 8 years after implementing, Con till resulted in a better pore connectivity and a higher saturated hydraulic conductivity than the CT system. Generally, soil organic matter (SOM) increased in all treatments" under Con till. "Yield was not significantly affected by the tillage system. Mineral P-fertilization" "resulted in a build-up of plant-available P in the top soil compared with non-fertilized plots, but in general did not increase P uptake. While the reduction in tillage intensity affected soil properties, it had very limited effects on yield and nutrient uptake."

Cover Crops and Permanent Grass/Legumes

A major component in this rejuvenation is the increase in soil organic matter (SOM) due to the reduction in disturbance and root and residue decomposition. Ideally, a perennial grass/legume cover provides the greatest opportunity for increasing SOM, connective pores, and infiltration.

8.—Franzluebbers and Stuedemann (2008). A multiple-year research was conducted on a Typic Kanhapludult in Georgia to study how cover crop management affected bulk density, aggregation, infiltration, and penetration resistance. The managements included grazed and ungrazed cover crop and tillage system [conventional (CT; initial moldboard plowing and thereafter disk tillage) and no tillage (NT)]. The objective was to evaluate how integrated crop-livestock systems with cattle grazing of cover crops would affect soil physical properties, especially those related to soil compaction and surface soil degradation, under both conventional and no tillage management. "Soil bulk density was reduced with CT compared with NT to a depth of 30 cm at the end of 0.5 year, but only to a depth of 12 cm at the end of 2, 2.5, and 4.5 years. Grazing of cover crops had little effect on soil bulk density, except eventually with 4.5 years of management. Water stable macroaggregation was reduced with CT compared with NT to a depth of 12 cm at all sampling times during the first 2.5 years of evaluation. Stability of macroaggregates in water was unaffected by grazing of cover crops in both tillage systems. Across 7 sampling events during the first 4 years, there was a tendency for water infiltration rate to be lower with grazing of cover crops than when ungrazed, irrespective of tillage system. Across 10 sampling events, soil penetration resistance was greater under NT than under CT at a depth of 0–10 cm and the difference was greater in ungrazed than in grazed systems. Biannual CT operations may have alleviated any surface degradation with animal traffic, but the initially high level of soil organic matter following long-term pasture and conversion to cropland with NT may have buffered the soil from any detrimental effects of animal traffic." Overall, "conversion of long-term perennial pasture to cropland resulted in changes in soil physical properties that were dependent upon subsequent tillage system. Initial moldboard plowing followed by disk tillage (CT) resulted in lower soil bulk density to a depth of 0–30 cm than undisturbed soil managed with no tillage (NT) at the end of 0.5 year. Thereafter, differences in bulk density between tillage systems disappeared below a depth of 12 cm with disk tillage only to 15–20 cm. Grazing of cover crops had little effect on soil bulk density, perhaps because of the high surface-soil organic C concentration following perennial pasture that mitigated compaction. Soil aggregation was degraded with CT compared with NT management. Stability of aggregates was unaffected by grazing of cover crops in both tillage systems. Water infiltration was variably affected by tillage and cover crop management, but was reduced with grazing of cover crops compared with ungrazed cover crops when soil water content was high at the time of measurement. Soil penetration resistance was often greater under NT than under CT, despite soil under NT was generally wetter than under CT. Soil penetration resistance was greater under grazed than ungrazed cover crops with CT, but not different between cover crop systems with NT. Overall, the introduction of cattle to consume the high quality cover crop forages (*Secale cereale* and *Pennisetum glaucum*) did not cause substantial physical damage to the soil. Additional long-term research is warranted to verify these short-term (initial 2.5 years) results."

24a.—Reeves, D.W. (1994) stated in a review chapter that "cover crops frequently result in greater infiltration of water due to the direct effect of residue coverage or in change in aggregation and formation of macropores by roots."

25.—Benjamin et al. (2007). An investigation at Akron, CO, on a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls) compared soil conditions in winter wheat–summer fallow (WF) plots with soil conditions in wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), wheat–corn–millet (WCM), and a perennial grass/legume mix. "Bulk density, pore size distribution, and saturated hydraulic conductivity were measured 7, 11, and 15 yr after inception. Bulk density in the grass plots decreased from 1.39 to 1.25 Mg m^{-3} in 15 yr. Bulk density in the annually cropped plots decreased from 1.38 to 1.30 Mg m^{-3} during the same time period. The pore size distribution became more uniform among the cropped treatments 15 yr after the start of the experiment." "K_{sat} increased in the grass plots from 27 mm h^{-1} to 98 mm h^{-1} in 15 yr." "K_{sat} in the annually cropped plots increased from about 14 to about 35 mm h^{-1} during the same period. The results from this study show that improving soil physical properties by cropping system alone may take many years. Perennial vegetation may be more effective than annually cropped systems at improving soil physical conditions because of less surface compaction from planting operations and the apparent ability of perennial root systems to create a more stable, continuous pore network."

26.—Blanco-Canqui et al. (2011). This study was a long-term experiment of cover crops (CCs) at Hesston, KS, that was established in 1995 on a Geary silt loam soil to determine if inclusion of CCs may be a potential strategy to boost no-till performance by improving soil physical properties. To assess this potential, they "utilized a winter wheat grain sorghum rotation, four N rates, and a hairy vetch (HV) CC after wheat during the first rotation cycles, which was replaced in subsequent cycles with sunn hemp (SH) and late-maturing soybean (LMS) CCs in no-till on a silt loam soil." At the end of 15 years, they "studied the cumulative impacts of CCs on soil physical properties and assessed relationships between soil properties and soil organic C (SOC) concentration. Across N rates, SH reduced near-surface bulk density by 4% and increased cumulative infiltration by three times relative to no-CC plots. Without N application, SH and LMS reduced Proctor maximum ρb, a parameter of soil compactibility, by 5%, indicating that soils under CCs may be less susceptible to compaction. Cover crops also increased mean weight diameter of aggregates (MWDA) by 80% in the 0- to 7.5-cm depth. The SOC concentration was 30% greater for SH and 20% greater for LMS than for no-CC plots in the 0- to 7.5-cm depth. The CC-induced increase in SOC concentration was negatively correlated with bulk density and positively with MWDA and cumulative infiltration. Overall, addition of CCs to no-till systems improved soil physical properties, and the CC-induced change in SOC concentration was correlated with soil physical properties."

27.—Greggory et al. (2010). This study explored the effect of the roots of different forage grasses on soil hydraulic properties. Six different grass cultivars were grown on replicated field plots at North Wyke, UK. Tension infiltration measurements were used to assess soil hydraulic properties and structure over two consecutive seasons. Measurements of shrinkage, water repellence, and the water release characteristic on soil samples taken from the North Wyke site were also made. Greggory et al. also compared the effects of different grasses on soil structure with the effects of differences in soil management. Tension infiltration measurements were made on fallow soil, permanent grassland, and arable land on a long term experiment at Rothamsted, Harpenden, UK. The “data showed that the saturated hydraulic conductivity of the capillary matrix of the soil sown with grass depended on the grass species. Grass species affected the characteristic pore size estimated from tension infiltration data. At the Rothamsted site,” it was inferred “that the development of macropore structure can be ranked grassland > arable > fallow (from the greatest to the least amount of macropores). In the North Wyke site, all the grass plots showed evidence of a macropore structure, consistent with the grassland site at Rothamsted, but there did not appear to be any variation between grass species.” It was “concluded that changes to soil structure were probably due to physical rearrangement of soil particles by shrinkage.”

28.—Hubbard et al. (2013). This 3-year study assessed the effects of cover crops on soil physical properties and C/N relationships in sandy soils of the southeastern (SE) USA coastal plain region. Five cropping systems/cover crop combinations were evaluated “(A) sunn hemp-crimson clover-sweet corn; (B) sunn hemp-fallow- sweet corn; (C) fallow-crimson clover-sweet corn; (D) fallow-fallow- sweet corn; and (E) fallow-fallow-fallow. Three N rates (0, 67, and 133 kg/ha) were tested on the corn for cropping systems A, B, and C, while N rates of 0, 67, 133, 200, and 267 kg/ha were used for cropping system D. No N was applied to cropping system E.” “Bulk density (BD), saturated hydraulic conductivity (Ks), and volumetric soil moisture content were evaluated in the top 7.6 cm; and carbon/nitrogen levels in the top 2.5 cm.” “ Biomass added to the soil from sunn hemp ranged from 6.9 to 9.8 Mg/ha, while crimson clover ranged from 3.3 to 5.0 Mg/ha.” This increased soil C (0.3–4.7 mg/g) and N (0.1–0.5 mg/g), improving soil structure and fertility. “Significantly greater C (2.2 mg/g vs. 1.8 mg/g, lower BD (1.71 Mg/m^3 vs. 1.73 Mg/m^3) and greater volumetric soil moisture content at field capacity for these soils (0.126 vs. 0.113 cm^3/cm^3) were found in the rotations with sunn hemp as the first crop compared to rotations with fallow as the first crop.” “This study showed that cover crops using no-till planting systems increased C and N levels in the top 2.5 cm of soil” leading “to improvements in soil structure as shown by decreased BD and increases in Ks and volumetric water content.” Sunn hemp (higher C:N ratio) was particularly effective as a late summer cover crop compared to crimson clover (lower C:N ratio) as a winter cover crop. In general “the study indicated that high residue input from cover crops is important for adding C, retaining plant-available N in organic matter, increasing fertilizer use efficiency, and improving soil physical properties in the very sandy soils of the southeastern (SE) USA coastal plain region.” (However, cover crops can increase SOM to some degree as well as CEC and the nutrient-holding capacity in general significantly where acidity is minimized. CWS – ed.)

29.—Jiang et al. (2007). On a claypan soil (Mexico silt loam and Adco silt loam) near Centralia Missouri, soil properties (bulk density, K_{sat}, water retention, pore size distribution) were measured on CRP; no-till corn/soybean/wheat with clover cover crop after wheat; mulch till corn/soybean (MTCS); and hay/corn. CRP land was not fertilized. Management effects were limited to the 0-10 cm depth. CRP retained the most moisture and had the highest K_{sat} due to roots and biopores while MTCS showed the lowest K_{sat}. The hay/corn treatment received 5 fertilizer and lime passes and was intermediate in K_{sat}. All management systems had similar AWC values. CRP had the most porosity in all but the micropore (<10 um) range. The results show that at the backslope position, where topsoil is the shallowest, even row cropping with conservation tillage (such as mulch tillage) may further degrade soil hydraulic properties. “Results suggest that the use of perennial grasses in rotation (or permanently) will benefit soil hydraulic properties, particularly at slope positions most vulnerable to degradation where soil conditions cannot be improved by row-crop conservation systems.”

30.—Hartwig and Ammon (2002). In this review paper, studies are cited showing a reduction in runoff of between 4 and 50% by the use of no-till with mulch and/or cover crops when compared to conventional till without cover. (The implication is that infiltration is increased. CWS – ed.)

31.—McVay et al. (1989). A 3-year field study at two Georgia sites “was begun in 1985 to measure the equivalent fertilizer N supplied by winter annual legumes and to monitor changes in soil physical and chemical properties. Corn was grown on a Rome gravelly clay loam soil (fine-loamy, mixed, thermic Typic Hapludult) at the Limestone Valley location, and grain sorghum on a Greenville sandy clay loam soil (clayey, kaolinitic, thermic Rhodic Paleudult) in the Coastal Plain.” “Main plots were cover crops of hairy vetch, crimson clover, berseem clover, winter pea, wheat , and fallow.” “Hairy vetch and crimson clover replaced the greatest amount of fertilizer N.” More water-stable aggregates were found following cover crops than fallow at the Coastal Plain location. “Higher infiltration rates were found following cover crops than fallow at both locations and infiltration rates were greater following hairy vetch than following wheat at the Coastal Plain site. An adapted winter legume cover crop can replace all of the fertilizer N necessary for optimum rain-fed grain sorghum and up to two-thirds of that required for corn production, and improve soil physical properties.”

32.—Mugdal et al. (2010). This study was conducted in “the summer of 2008 to test the hypothesis that for claypan soils, hydraulic properties can be significantly affected by long-term soil and crop management” from two fields with Mexico silt loam (Vertic Epiaqualfs) in central Missouri. “One field has been under continuous row crop cultivation for over 100 years (Field), while the other field is a native prairie that has never been tilled (Tucker Prairie). Soil cores from six replicate locations from each field were sampled to a 60 cm (24 in) depth at 10 cm (3.9 in) intervals. Samples were analyzed for bulk density, saturated hydraulic conductivity (K_{sat}), soil water retention, and pore-size distributions. Values of coarse” and fine pores “for the Field site were almost half those values from the Tucker Prairie site.” “The geometric mean value of K_{sat} was 57 times higher in the native prairie site (12.4 in hr^{-1}) than in the cropped field (0.219 in hr^{-1}) for the first 10 cm interval. Differences in K_{sat} values were partly explained by the significant differences in pore-size distributions. The bulk density of the surface layer at the Tucker Prairie site (0.81 g cm^{-3}) was two-thirds of the value at the Field site (1.44 g cm^{-3}), and was significantly different throughout the soil profile, except for the 20 to 30 cm depth. Results show that row crop management and its effect on soil loss have significantly altered the hydraulic properties for this soil.”

33.—Rachman et al. (2004). “This study evaluated soil hydraulic properties within a grass hedge system 10 yr after establishment. The study was conducted at the USDA-ARS research station near Treynor, IA in a field managed with switchgrass hedges” on the contour. The soil was classified as Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls). “Three positions were sampled: within the grass hedges, within the deposition zone 0.5 m upslope from the grass hedges, and within the row crop area 7 m upslope from the hedges. Intact soil samples (76 by 76 mm) were taken from the three positions at four depths (100-mm increments) to determine saturated soil hydraulic conductivity (K_{sat}), bulk density (pb), and soil water retention. The grass hedge position had significantly greater macroporosity than the row crop and deposition positions in the first two depths and greater than the deposition position in the last two depths. The K_{sat} within the grass hedge (668 mm/h) was six times greater than in the row crop position (115 mm/h) and 18 times greater than in the deposition position (37 mm/h) for the surface 10 cm. Bulk density and macroporosity were found to provide the best two-parameter regression model for predicting K_{sat}. These results indicate that grass hedges significantly affected soil hydraulic properties in the area under the hedges for this loess soil” but not in the area above the hedges. Note that this practice is not a current conservation practice but is most similar to Contour Buffer Strips (332). (This study can serve as a relative indicator of K_{sat} improvement under switchgrass production for biomass; however, controlled traffic row reduction in K_{sat} needs to be considered. CWS – ed.)

34.—Villamil et al. (2006). Winter cover crops (WCC) (hairy vetch and cereal rye) in a no-till corn–soybean rotation effects on soil physical and chemical properties were studied in a deep Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) at Urbana, IL. Corn-fallow/soybean-fallow (CS); corn-rye/soybean-rye (C-R/S-R); corn-rye/soybean-vetch (C-R/S-V); and, corn-rye/soybean-vetch and rye (C-R/S-VR) (all under no-till) effects on several soil physical and chemical properties were analyzed. Properties included soil organic matter (SOM), pH, total nitrogen (TN), nitrates (NO3–N), and available phosphorus (P), water-aggregate stability (WAS), bulk density (Db), penetration resistance (PR), total porosity (TP), pore-size distribution, water retention properties, and saturated hydraulic conductivity (K_{sat}). “Compared with winter fallow, crop sequences that included WCC provided substantial benefits from the soil productivity standpoint.” “C-R/S-V or C-R/SVR increased SOM down to 30 cm. All WCC sequences improved WAS with increases of 9, 13, and 17% for C-R/S-R, C-R/S-V, and C-R/S-VR, respectively. WCC sequences reduced Db and PR of the soil surface and increased total and storage porosity along with plant available water. While the C-R/S-V sequence was the most effective in reducing soil NO3–N, the C-R/S-R sequence was the most effective in fixing soil P.” The difference in SOM between C-R/SV and C/S was an increase of about 10 kg ha^{-1} SOM for the C-R/S-V sequence. An even larger increase was shown with C-R/S-VR (15 kg SOM).

Residue and Mulch

35.—Blanco-Canqui et al. (2007) (2). “This study quantified impacts of systematic removal of corn stover on soil hydraulic parameters after 1 year of stover removal under no-till (NT) systems. These measurements were made on three soils in Ohio including Rayne silt loam at Coshocton OH, Hoytville clay loam at Hoytville OH, and Celina silt loam at South Charleston. Interrelationships among soil properties and saturated hydraulic conductivity (K_{sat}) predictions were assessed. Earthworm middens, K_{sat}, bulk density (bd), soil water retention (SWR), pore-size distribution, and air permeability (ka) were determined for six stover treatments, which consisted of removing 0%, 25%, 50%, 75%, 100% of residue left in the field and doubling corn stover by adding an equal amount where no stover was removed "corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg/ha of stover on the field. Stover removal reduced the number of earthworm middens, K_{sat}, SWR, and ka, and increased bd at all sites. Compared to leaving 100% of the stover in place, complete stover removal reduced earthworm middens 6-fold at Coshocton and about 14-fold at Hoytville and Charleston." "K_{sat} decreased from 3.1 to 0.1 mm/h at Coshocton, 4.2 to 0.3 mm/h at Hoytville, and 4.2 to 0.6 mm/h at Charleston while soil bd increased about 12% in the 0–10-cm depth at Coshocton and Hoytville." Where all residue was removed SWR was 70% of that where no residue was removed and 58% of that where residue was doubled at all sites. Where 75 percent or more of the residue was retained, air permeability was significantly higher than where 50% or less was retained at Coshocton and Charleston. Differences in the number of middens, bd, SWR, K_{sat}, and ka where no residue was removed compared to where it was doubled were generally not significant. "Measured parameters were strongly correlated, and ka was a strong K_{sat} predictor. Stover harvesting induces rapid changes in soil hydraulic properties and earthworm activity, but further monitoring to determine threshold levels of stover removal for specific conditions" is needed.

36.—Blanco-Canqui and Lal (2007) (1). The impact of crop residue on soil hydraulic properties was studied on uncropped no-tillage (NT) plots receiving three levels of wheat straw mulch (0, 8, and 16 Mg ha^{-1} yr^{-1}) application for 10 consecutive years on a Crosby silt loam in central Ohio. "Water infiltration rates, earthworm population, saturated hydraulic conductivity (K_{sat}), soil water retention (SWR), total porosity, and pore-size distribution were determined and unsaturated hydraulic conductivity estimated from SWR and K_{sat} data. Mulching significantly impacted hydraulic properties in the 0 to 3-cm soil depth, but water infiltration rate was unaffected." Earthworm were not present in the unmulched treatment, while 158 worms/m^2 ± 52 (mean ± SD) occurred in treatments with 8 Mg/ha/yr of straw and 267 worms/m^2 ± 58 occurred in treatments with 16 Mg/ha/y of straw. "Mulched treatments had a K_{sat} 123 times greater and retained 40 to 60% more water between 0 and -1500 kPa than the unmulched treatment. Soil porosity increased by 28% under 8 Mg Mg/ha/y of straw and by 44% under 16 Mg/ha/y in the 0 to 3cm depth compared with the unmulched treatment. Pore volume of macro- and mesopores was greater in mulched treatments and fine mesopores was greater in the unmulched treatment in the 0 to 3cm depth. Straw mulching appears to be a viable practice to improve near-surface hydraulic properties in long-term NT soils, although residues may not increase water infiltration rates." Overall, this study revealed that surface mulching with wheat straw in a long-term NT system on a Crosby silt loam improved soil hydraulic properties only near the surface, indicating a significant stratification of the effects of mulching. While this study provided useful insights into the independent effects on soil hydraulic properties of long-term mulching with large amounts of straw, results may have been different had crops been grown on the study plots because of crop residue–tillage–cropping system interactions and below-ground (e.g., roots) biomass input. Note that NT does not relate to NT conservation practice/planting system, it simply means that no tillage was performed on the site.

37.—Bruce et al. (1990). "This study was conducted to identify the effect of tillage intensity associated with soybean and grain sorghum crop sequences following winter wheat, and the effect of summer crop species on selected physical characteristics of a Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult) at Watkinsville, GA. Through eight seasons, soybean and grain sorghum were grown in 10 crop sequences that were imposed on three tillage treatments: conventional tillage (CT), in-row chisel (MT), and no-tillage (NT). Following summer crop harvest in the eighth season, aggregate stability, organic C, bulk density, air-filled pore space, particle-size distribution, and infiltration of water were measured. Aggregate stability at 0 to 10 mm was significantly higher for MT and NT than for CT. The CT treatment exhibited significantly lower bulk density and higher air-filled pore space than MT and NT. Infiltration was significantly greater on the MT than the CT and NT treatments. Greater aggregate stability, higher air-filled pore space, and lower bulk density were measured after two or more years of grain sorghum than after soybean. The maintenance of wheat straw on the soil surface under the MT and NT treatment exhibited an effect to a depth of 75 mm and the in-row chisel treatment affected infiltration. Crop-rotational effects on these physical properties can be erased or modified by tillage, and may only be observed under NT. Grain yield response of soybean and grain sorghum to changes in soil physical characteristics, as a consequence of crop sequence and tillage" system, may need to be further evaluated.

38.—Govaerts et al. (2007). This study assessed practices that would sustain higher and stable yields for wheat and maize in the non-equatorial, subtropical highlands of Central Mexico. The soil is a Cumulic Phaeozem (FAO, 1998) (fine, mixed, thermic Cumulic Haplustoll). A long-term experiment (randomized complete block) was started in 1991 under rainfed conditions in the volcanic highlands of central Mexico (2240 m a.s.l.; 19.318N, 98.508W). Soils were evaluated after "12 years of 16 management treatments from a factorial arrangement of: (1) four rotations (monocropping and rotation of maize and wheat), (2) two tillage (conventional tillage [CT] and zero tillage [ZT]) and (3) two crop residue management practices (residue retention and removal). Water infiltration and soil moisture levels were greater under ZT when residue was left in the field then when residue was removed. Higher infiltration rates and favorable moisture dynamics supported up to 30% yield increase. A significantly higher incidence of root rot was found in monoculture of maize under ZT than CT. Residue retention significantly increased maize root rot incidence compared to residue removal. Rotation of maize and wheat decreased the incidence of maize root rot up to 30%. In general, the incidence of root disease was lower in wheat (up to 3 on a scale of 7) than in maize (up to 3.93 on a scale of 4) for all treatment. In maize, both non-parasitic and parasitic nematodes increased under ZT; however, in wheat no effect of tillage was seen. Incidence of root rot and parasitic nematode populations were not correlated with yield. Although root diseases may have affected crop performance, they affected yield less than other critical plant growth factors such as infiltration and water availability. Both environmental conditions and microflora played a key role in the biology and expression of soil pathogens. In the semi-arid and rainfed subtropical highlands of central Mexico, positive effects were observed with zero tillage, crop rotations and crop residue retention, compared with common farming practices."

39.—In a review paper, Hartwig and Ammon (2002) studies are cited showing a reduction in runoff of between 4 and 50% by the use of no till with mulch and/or cover crops when compared to conventional till without cover. (The implication is that infiltration is increased. CWS – ed.)

40.—Kahlon et al. (2013). "A long-term on going experiment was done to evaluate the effects of three tillage treatments (NT, ridge till (RT) and plow till (PT)) and three mulch rates (0, 8 and 16 Mg ha^{-1} yr^{-1}) on soil physical properties and total C concentrations in macro and microaggregates. The experiment was initiated in 1989 on a Crosby Silt Loam (Stagnic Luvisol) in Central Ohio" (at Waterman Farm of Ohio State University). "The data show positive effects of mulch rate on soil physical attributes and total C concentration under NT. Significant variations in bulk density (rb) and penetration resistance (PR) along with their interactions were observed among tillage and mulch treatments. The water infiltration capacity (ic) ranged from 1.2 cm h^{-1} (PT) to 4.6 cm h^{-1} (NT). With increase in mulch rate from 0 to 16 Mg ha^{-1}, saturated hydraulic conductivity (Ks) for 0–10 cm depth increased from 1.78 to 3.37, 1.57 to 2.95 and 1.37 to 2.28 (_10_2 cm h^{-1}) under NT, RT and PT, respectively. ANOVA indicate significant interaction between tillage, mulch and soil depth for the Ks. Similarly, the mean weight diameter (MWD, mm) increased from 0.36 to 1.21, 0.29 to 0.84, 0.25 to 0.62 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Total C (%) increased from 1.26 to 1.50, 1.20 to 1.47 and 0.95 to 1.10 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Macro-aggregates (250–2000 mm) contained 30% more total C and N concentrations than microaggregates (<250 mm). Under NT, the soil showed a higher structural stability than PT with significantly lower compaction values. Further, with NT the soil showed a higher capacity to retain C than PT. Thus, long term use of NT along with mulch application enhances soil quality with respect to soil mechanical, hydrological properties along with carbon concentration in the soil."

41.—Langdale et al. (1992). "Eroded Kandhapludult soils occupy more than 40% of the Southern Piedmont region of the USA. The humid thermic climate associated with the Ultisols permits double crop residue production ranging from 10 to 14 Mg ha^{-1} y^{-1}. Long-term conservation (no-till) tillage into these crop residues is beneficial in ameliorating the effects of soil erosion. During the course of a five-year study, decomposition of these residues increased soil carbon significantly. Restoration processes were initiated by increasing average soil carbon, representing slight, moderate and severe soil erosion classes, from 0.97 to 2.37% in the 0 to 1.5-cm depth. Accompanying soil carbon responses were increases in soil N, water-stable aggregation and infiltration. Runoff coefficients on conservation tilled restored soils was only 6%, compared to 35% for those conventionally tilled. Rill and interrill soil loss rates were also reduced significantly with surface residue provided with conservation tillage. Restoring Ultisol landscapes with variable levels of soil erosion requires differential fertilization. All fertilizer requirements for severely eroded plots were 1.43 to 2.30-fold higher than those of moderately eroded plots. Because biological N fixation by the crimson clover cover crop appeared to be retarded on the severely eroded site, observed plant N stress developed on the irrigated/conservation tillage treatment. Cumulative grain yields of severely eroded site ranged from 15.4 to 30.3 Mg ha^{-1} $5y^{-1}$, and were statistically equal to or exceeded those of the slightly eroded site." "Conservation tillage grain yields were best optimized on the rain fed moderately eroded site, probably because of the more desirable texture-organic properties of the 13-cm thick Ap horizon."

42.—Moebius-Clune et al. (2008). This study evaluated the long-term effects of 32 years of maize, stover harvest vs. stover return on soil quality in the surface layer (5–66 mm) under plow till and no-till systems on a Raynham silt loam (coarse-silty, mixed, active, nonacid, mesic Aeric Epiaquept). It was conducted in Chazy, NY, "using physical, chemical, and biological soil properties as soil quality indicators. Twenty-five soil properties were measured, including standard chemical soil tests, aggregate stability, bulk density, penetration resistance, saturated hydraulic conductivity, infiltration, several porosity indicators (aeration pores (PO > 1000), soil water potential = $\Psi > -0.36$ kPa; air-filled pores at field capacity (PO > 30), $\Psi > -10$kPa; available water capacity, $-1500 < \Psi < -10$ kPa), total organic matter, parasitic and beneficial nematode populations, decomposition rate, potentially mineralizable N, and easily extractable and total glomalin. Only eight indicators were adversely affected by stover harvest, and most of these effects were significant only under NT. Almost all indicators affected by stover removal were affected equally or more adversely by tillage. A total of 15 indicators were adversely affected by tillage. Results of this study suggest that, on a silt loam soil in a temperate climate, long-term stover harvest had lower adverse impacts on soil quality than long-term tillage. Stover harvest appears to be sustainable when practiced under NT management."

43.—McVay et al. (1989). A 3-year field study at two Georgia sites "was begun in 1985 to measure the equivalent fertilizer N supplied by winter annual legumes and to monitor changes in soil physical and chemical properties. Corn was grown on a Rome gravelly clay loam soil (fine-loamy, mixed, thermic Typic Hapludult) at the Limestone Valley location, and grain sorghum on a Greenville sandy clay loam soil (clayey, kaolinitic, thermic Rhodic Paleudult) in the Coastal Plain." Main plots were cover crops of hairy vetch, crimson clover, berseem clover, winter pea, wheat, and fallow. Hairy vetch and crimson clover replaced the greatest amount of fertilizer N. More water-stable aggregates were found following cover crops than fallow at the Coastal Plain location. "Higher infiltration rates were found following cover crops than fallow at both locations and infiltration rates were greater following hairy vetch than following wheat at the Coastal Plain site. An adapted winter legume cover crop can replace all of the fertilizer N necessary for optimum rain-fed grain sorghum and up to two-thirds of that required for corn production, and improve soil physical properties."

44.—Ruan et al. (2001). "Surface sealing of bare soils often reduces rain infiltration, and crop-residue cover is commonly used to reduce surface sealing." Numerical experiments were conducted "to quantify effects of the percentage and distribution of residue cover on infiltration, and to provide guide-lines for residue management." "Numerical simulations were conducted for combinations of (i) soil type, either a clay loam or loamy sand soil; (ii) percentage residue cover (Prc); (iii) saturated hydraulic conductivity of the surface seal (Kc) relative to bulk soil (Ks); (iv) residue-patch size with a constant P; and (v) rainfall intensity." "More residue cover was needed to have the same percentage of infiltration increased for the clay loam soil, less surface sealing, larger residue-patch size, and greater rainfall intensity."

45.—Sharratt et al. (2006). The objective of this study was "to characterize infiltration, water retention, and saturated hydraulic conductivity of a soil 20 years after establishing tillage and straw management treatments in interior Alaska. The strip plot experimental design, established on a silt loam and maintained in continuous barley, included tillage as the main treatment and straw management as the secondary treatment. Tillage treatments included no tillage, autumn chisel plow, spring disk, and intensive tillage (autumn and spring disk) while straw treatments included retaining or removing stubble and loose straw from the soil surface after harvest. Soil properties were measured after sowing in spring 2004; saturated hydraulic conductivity was measured by the falling-head method, infiltration was measured using a double-ring infiltrometer, and water retention was assessed by measuring the temporal variation in in-situ soil water content. No tillage resulted in greater saturated hydraulic conductivity and generally retained more water against gravitational and matric forces than other tillage treatments. Infiltration was greater in autumn chisel plow than other tillage treatments and was presumably suppressed in no tillage by an organic layer overlying mineral soil. Infiltration was also enhanced by retaining straw on rather than removing straw from the soil surface after harvest. No tillage is not yet a sustainable management practice in this region due to lack of weed control strategies. In addition, the formation of an organic layer in no tillage has important ramifications for the soil hydrological and thermal environment. Therefore, minimum tillage (i.e., autumn chisel plow or spring disk) appears to be a viable management option for maximizing infiltration in interior Alaska."

46.—Skidmore et al. (1986). "This study was conducted to determine the influence of several methods of residue management for winter wheat and grain sorghum on physical properties of Richfield silty clay loam (fine, montmorillonitic, mesic Aridic Argiustolls). Residue management treatments were: residue removed by burning, residue removed by baling and hauling, incorporation of the residue produced during the immediate past cropping season, and incorporation of twice the amount of residue produced by the crop. Most of the soil physical properties measured were not influenced by either grain sorghum or wheat residue management treatments; however, they differed between crops. The soil aggregates from the sorghum plots were smaller, more fragile, less dense, less stable dry, and more stable wet than the aggregates from the wheat plots. The pore size distribution of the soil from the Ap horizon of the sorghum plots was more conducive to water infiltration. The saturated hydraulic conductivity was several times greater in the soil cores obtained from the sorghum plots than those obtained from the wheat plots."

47.—Steiner (1994). This review chapter discusses the control of runoff through the management of crop residue. Residue management options included: reduced tillage systems, cropping intensity, and residue management in irrigated v. dryland systems. Surface crop residues generally increased infiltration and decreased evaporation. Overall, the amount of residue (biomass) left on the soil surface is more important to the improvement of water conservation than the specific tillage type or management system.

Other SOM Additions (Wastewater and Manure)

48.—Abbas and Faras (2009). "The objectives of this study were to: (i) simulate the effect of OM application rates (0, 168, 336, and 672 kg total N ha^{-1}) and types (chicken and dairy manures) on soil organic C (SOC) and CO_2 emissions from a Hawaiian tropical soil (Waialua gravelly clay variant (very-fine, mixed, superactive, isohyperthermic Pachic Haplustoll)) on 2 to 6% slopes at the Waimanalo agricultural research station (21°20′15″ N, 157°43′30″ W) ; and (ii) correlate SOC, CO_2 emissions, and two major soil properties: bulk density (ρb) and saturated hydraulic conductivity (K_{sat}). Measurements of SOC and ρb were conducted on samples collected from the top 10 cm of soil tilled before and after manure application, cultivated with sweet corn, and drip irrigated for two consecutive growing seasons. The K_{sat} values were calculated from infiltration data measured with a tension infiltrometer. The Rothamsted C turnover model was used to simulate SOC and CO_2 emissions." "Results revealed that SOC, CO_2 emissions, and K_{sat} increased while ρb decreased with increasing OM rates. There was no significant effect of OM type. There was a highly significant correlation between the measured and simulated SOC and between the measured SOC and the simulated CO_2 emissions. The K_{sat} values significantly correlated with the measured and simulated SOC and the simulated CO_2 emissions. A significant inverse relationship between ρb and K_{sat} was observed." It was concluded that "in addition to improving soil aggregation, decreasing ρb, and increasing K_{sat}, OM application to this tropical soil increases SOC pools that contribute to atmospheric CO_2 following tillage and other agricultural practices."

49a.—Bhattacharyya et al. (2007). The authors studied the use of commercial fertilizer along with farmyard manure (FYM) in the Indian Himalayas to enhance soil carbon levels. They conducted an "8-year experiment, initiated in 1995–1996 on a silty clay loam soil, to determine the influence of fertilizer and fertilizer + farmyard manure (FYM) application on soil properties" using a wheat-soybean rotation. Manure increased "soil organic C (SOC) content in the 0–45 cm soil depth in NPK + FYM treatment as compared to NPK and control treatments was 11.0 and 13.9 Mg C ha^{-1} at the end of 8 years, respectively. Application of FYM significantly reduced soil bulk density and increased mean weight diameter (MWD) and SOC contents in different aggregate size fractions. SOC content in macroaggregates was greater than in microaggregates. The response of SOC content to FYM application was dependent upon inorganic fertilization and more upon balanced application of NPK than N only. Steady state infiltration rate under NPK + FYM (1.98 cm h^{-1}) was higher than under unfertilized (0.72 cm h^{-1}) and NPK (1.2 cm h^{-1})." The response to FYM application in increasing SOC concentration in almost all size fractions was dependent upon inorganic fertilizer, but was independent of the type of inorganic fertilization. There were marked improvements in soil water transmission properties (infiltration, soil water sorptivity, and K_{sat}) under FYM treated plots over no FYM and N treated plots over no N. However, the effect of FYM application in increasing SOC content and water transmission properties was not dependent upon inorganic fertilization and the type of inorganic fertilizer.

50.—Lado and Ben-Hur (2009). "The use of effluent for irrigation could have an impact on the chemical and hydraulic properties of soils. This paper reviews the effects of irrigation with effluents that have undergone various treatments on hydraulic properties of semiarid and arid soils. Irrigation of semiarid clay and sandy soils with secondary effluent increased the salinity at depths down to ~1.5 m, and the sodicity down to ~1.5 and >4 m, respectively. The increase of the organic matter load in the effluents resulted in inconsistent effects on the organic matter content of the topsoil, but it could lead to its decrease in the subsoil because of a 'priming effect' of the effluent. Percolation of effluent through the soil profile can reduce its saturated hydraulic conductivity (Ks) to an extent that depends on the effluent quality, soil chemical properties, and the pore size distribution in the soil. Leaching a loamy and a clay soil with secondary effluent decreased the Ks because of plugging of the pores with suspended solids, whereas the Ks of a sandy soil was not affected because of its large average pore size. Irrigation of high sodicity, arid soils with effluent that had undergone reverse osmosis treatment decreased Ks because of the low electrolyte concentration of the effluent, which enhanced soil swelling and clay dispersion. An increase of soil sodicity, caused by effluent irrigation, decreased the Ks of a clay soil leached with water of low electrolyte concentration, as a result of enhanced clay swelling and dispersion. In a non-calcareous, sandy soil, the higher sodicity in the effluent-irrigated soil led, under rainfall conditions, to enhanced seal formation, reduced infiltration, and increased runoff, as a result of enhanced clay dispersion. In contrast, for calcareous soil under similar conditions, no effect of effluent irrigation on runoff and soil loss was observed. This was, probably, because of the release of Ca during the dissolution of $CaCO_3$; this Ca replaced exchangeable Na, thereby reducing the soil sodicity to its natural levels. Because of the interaction between effluent irrigation and soil properties, it is necessary to identify sensitive regions and soils prior to irrigation with effluents, to prevent possible deleterious effects on soil structure and hydraulic properties."

51.—Lado and Meni (2010). The "objective of this study was to improve the basic understanding of the effects of irrigation with various effluents on the saturated hydraulic conductivity (Ks) of arid and semiarid soils. Clay, loamy, and sandy soils from semi-arid areas of Israel were sampled from experimental plots irrigated with freshwater or secondary effluent for >3 yr, and were used in column experiments. Leaching the loamy and clay soils with reverse osmosis (RO) effluent, which contained low electrolyte concentrations, led to clay swelling and dispersion and thereby decreased the soil Ks. In these soils, the high concentration of suspended solid particles and dissolved organic matter (DOM) in oxidation pond (OP) effluent caused significant pore clogging, which reduced the Ks. Leaching the soils with ultrafiltered effluent maintained high Ks values due to the low concentration of suspended solid particles and DOM, their small sizes, and the relatively high electrical conductivity of this effluent. The relatively large average pore size in the sandy soil prevented pore clogging and Ks reduction when leached with RO and OP effluent. Secondary effluent irrigation increased the soil exchangeable Na percentage (ESP) compared with freshwater irrigation but did not change the organic matter content in the soil. In the loamy and clay soils, this higher ESP of the effluent-irrigated soils resulted in greater reductions in Ks when leached with deionized water than occurred in freshwater-irrigated soils."

52.—Sepaskhah and Sokoot (2010). "The effects of applying freshwater along with differently treated wastewater on K_{sat} in the surface and subsurface layers of sandy-loam, loam, and clay-loam soils" were studied. "This effect was studied by investigating the ratio of Ksat for wastewater to Ksat for fresh water with soil surface as Ksat1 and soil subsurface as Ksat2. The results showed that the application of freshwater did not reduce the Ksat1 considerably. However, the reduction in Ksat1 mainly occurred in soil depth of 0–50mm due to the application of wastewater. This effect is more pronounced in clay loam soil than in loam and sandy-loam soils. It is concluded that application of wastewater with TSS (total suspended solid) of ≥ 40 mg L^{-1} resulted in Ksat1 reduction of >50% in different soil textures. However, the Ksat2 reduction at soil depth of 100–300mm is not considerable by application of wastewater for different soil textures. Further, it is concluded that less purified wastewater can be used in light-texture soils resulting in less reduction in Ksat1. Empirical models were developed for predicting the value of Ksat1 as a function of amounts of wastewater application and TSS for different soil textures that can be used in management of wastewater application for preventing deterioration of soil hydraulic conductivity."

53.—Wuddivira and Ekwue (2009) examined the influence of manure incorporation and incubation duration on the structural stability of three tropical soils in the Republic of Trinidad and Tobago with different clay contents and mineralogies. "Samples were treated with farmyard manure (FYM) at the rates of 0, 6, and 12% per dry mass of soil, brought to field capacity (FC), and incubated for 56d at an average temperature and humidity of 26°C and 67.5%, respectively. Subsamples were taken at 14, 28, and 56 d for the determination of water-stable aggregation (WSA) and K_{sat}." Results showed an increase in WSA of 23 to 27% for the three soils studied when they compared the natural sample with no treatment to the largest treatment combination (12% FYM and 56-d incubation). "The higher the load of FYM incorporation, the more stable the soil became with incubation. Greater improvement was found in K_{sat}, whose values increased between 50 and 700%. Also, both WSA and K_{sat} increased with incubation duration regardless of FYM level or clay content and mineralogy. This suggests that, by itself, soil incubation at FC after structural disturbance, with or without FYM incorporation, is a desirable practice that encourages particle bonding and soil structure improvement."

54.—Yeganeh et al. (2010). "Increasing use of sewage sludge on farmland has raised concerns about the potential transport of heavy metals into food chains and groundwater." This study was located at Isfahan University of Technology, Isfahan, Iran experimental station at 1630 m above sea level, where mean annual rainfall is 140 mm and mean annual temperature is 14.5 C. The calcareous soil is a fine-loamy, mixed, thermic Typic Haplargid. "This study determined the effects of sludge application on soil physical properties and transport of zinc (Zn), copper (Cu), and lead (Pb). Secondary anaerobic digested sewage sludge was applied at rates of 0, 25, 50, and 100 t⁄ha (on a dried weight basis) for four consecutive years and mixed in the top 20-cm of soil. Corn was planted as a spring crop, followed by wheat as a winter crop. Sludge application increased the dissolved organic matter content and modified the soil structure; increased the soil 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 50 cm depth and significantly to 1 m. In the plots that received four application of 100 t⁄ha sewage sludge, the mean concentrations of Zn, Cu, and Pb in subsoil increased by 1600, 7, and 4.5 times, respectively, compared with the control." "Results indicate that a combination of enhanced soil physical properties, heavy and inefficient irrigation and high organic matter content with heavy metals cause significant metal mobility. High sludge applications pose risks of groundwater and food chain contamination and rates are best restricted to those reflecting the nutrient demand of crops (20 t⁄ha every 4 to 5 yr or an average of 4 to 5t⁄ha⁄yr)."

Citations

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