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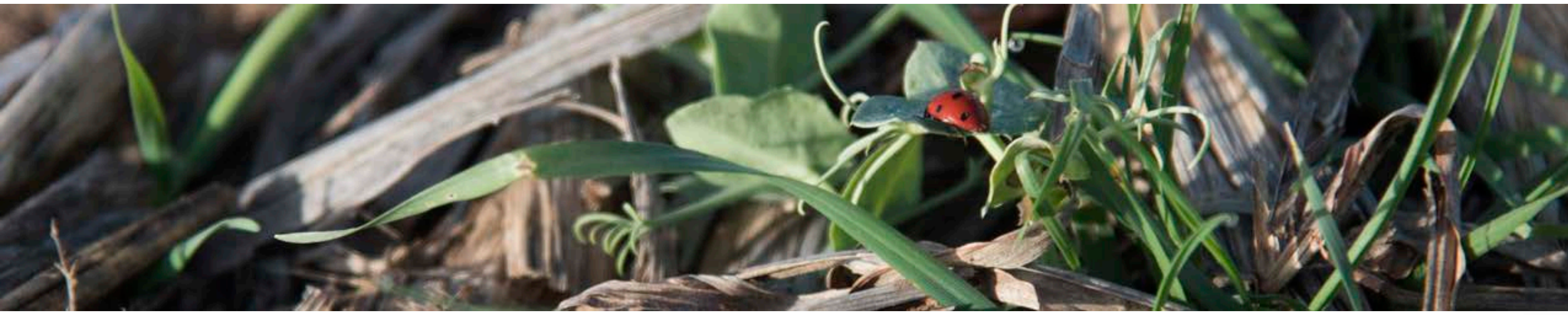

# Effects on Soil Water Holding Capacity and Soil Water Retention Resulting from Soil Health Management Practices Implementation—A Review of the Literature Posted to the NRCS Soil Health Website as of 9/2016

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# Effects on Soil Water Holding Capacity and Soil Water Retention Resulting from Soil Health Management Practices Implementation—

## A Review of the Literature Posted to the NRCS Soil Health Website as of 9/2016

**Submitted by: Christopher W. Smith, Ph.D., Soil Scientist (retired), NRCS**
**Reviewed by: Michael Kucera, Agronomist, National Soil Survey Center, Lincoln, NE**

## Executive Summary

This paper focuses on available water holding capacity and water retention as affected by soil health conservation practice implementation. **Available Water Holding Capacity** (AWC) relates to the total crop available water holding potential between wilting point and field capacity. **Water retention** (WR) relates to the actual amount of water retained in the soil for crop use. (Note: when AWC increases in the surface soil, the full benefits to crop yield and water retention may not be realized if a compaction layer exists directly below the surface that limits the ability of water to percolate below the surface.) In this case, prior to implementing continuous no till systems, subsoiling may be necessary to break the compaction layer. Improving water retention is only effective when there is adequate precipitation to recharge the crop's root zone.

## Introduction

Two major natural resource concerns of this century are climate change and water (quality and quantity). Major ground water aquifers are being depleted. Most climate models predict that average precipitation will not significantly change in most U.S. regions (exceptions are the Southwest which will be somewhat drier and the upper Midwest, Southeast/mid-Atlantic, and Northeast which will become somewhat wetter). However, temperature is expected to increase which will increase evapotranspiration making regions with similar precipitation effectively drier, exacerbating arid conditions in the Southwest and neutralizing precipitation gains in the east.

Soil Health Management Systems can serve to offset these changes by improving resiliency to drought and high rainfall events by increasing infiltration, reducing soil surface temperature and moisture loss from evaporation and runoff; improving nutrient cycling N production and nutrient uptake; and improving water holding characteristics of most soils. In addition, the potential for ground water recharge is improved where aquifers can be recharged by through-flow.

Available Water Holding Capacity (AWC) relates to the total crop available water holding potential between wilting point and field capacity. Water retention (WR) relates to the actual amount of water retained in the soil for crop use.

Conservation practices that positively affect available water holding capacity (AWC), and water retention can also increase soil organic matter (SOM), improve soil structure, bulk density, porosity, and infiltration. The impact of soil health practices on infiltration is discussed in a companion paper in the following locations:

NRCS Soil Health Literature Website:
https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/mgnt/?cid=stelprdb1257753.

USDA employees can access the Sharepoint site at:
https://ems-team.usda.gov/sites/NRCS_nssc/soilhealth/SitePages/Home.aspx.

(Note: Terms followed by an "*" are defined in the glossary)

## No Till (NT)

No till (NT) is defined in Conservation Practice Standard 329-Residue and Tillage Management, as "limiting soil disturbance to manage the amount, orientation, and distribution of crop and plant residue on the soil surface year-round" (USDA NRCS, 2017).

This section focuses on the implementation of no till (NT) alone where residues are typically present. Results of studies presented here show mixed results but tend toward increases in AWC and/or WR. Residue retention is an important component of Conservation Practice Standard 329 and Conservation Practice Standard 345. Soil moisture loss is reduced when crop residue is retained following harvest through the following growing season compared to where crop residue is removed. Soil moisture savings is typically greater in no till (NT) than conventional till (CT) systems even when residue is removed in some cases.

Increased soil moisture content under NT, where residue is retained during critical times of the growing season can provide up to 3 additional days of crop water needs (Alvarez and Steinbach, 2009). Significant increases in soil available water holding capacity (AWC) may take longer than 3 years to achieve after conversion to NT from CT. However, in a 9-year study, a NT system showed less AWC than soils under CT (Singh et al., 1996). This indicates that NT alone is not always the determining factor. Residue retention, amount, and type along with crop rotation and cover crops play a significant role in improving AWC and moisture retention. The following studies support these findings.

In one study, after 32 years, AWC increased by 23% in NT vs. CT where residue was retained under both systems. This increase was correlated to soil organic matter (SOM) increases (Mobius-Clune et al., 2008). In a southern Great Plains study, AWC was significantly higher in NT than in moldboard or stubble mulch tillage treatments. NT had greater connecting pores in the soil profile and infiltration resulting in higher water retention in the soil. After 14 years with a soybean-oat rotation on a silt loam over clay loam Ultisol*, AWC increased 19% under NT vs. CT while yields increased 28%. However, CT yields were greater than NT yields for the initial 4 years. Soil organic matter (SOM) increased 102% under NT in the surface 20 centimeters (cm) (So et al., 2009).

A study in double cropping areas of the Hebei, North China Plain, compared conservation tillage (CT) (including no till) with conventional tillage (CV) for corn-winter wheat rotation. "Winter wheat yield and water use efficiency (WUE) were improved by 6.7% and 30.1%, respectively, with CT compared to the CV treatments, and for corn, 8.9% and 6.8%, respectively." "The greatest differences were achieved by the double no till system with 100% residue cover treatment in terms of soil temperature and crop growth." "It was concluded that conservation tillage for the annual double cropping system is feasible, and the double no till with 100% residue cover is the most effective way of improving crop yields and WUE" (Jin et al., 2009). An-11-year study comparing 2-year rotations of winter wheat-canola, winter wheat-fallow, and lentil-flax; and three tillage systems (CT, reduced till and NT) showed that available water (water retention) was greatest in the spring under no till (all rotations were averaged together) (Larney and Lindwall, 1995).

However, in one 13-year study, where the impacts of management on the surface soil (0 to 10 cm depth) was studied on a clay loam soil, AWC was similar under NT or moldboard plow (MP) even though soil organic carbon (SOC) was 13% higher with NT (SOC=2.07%). NT had an AWC of ~0.12 cm/cm; while MP had ~0.13 cm/cm (Reynolds et al., 2007). On claypan silt loam soils near Centralia, Missouri, soil properties (bulk density, K-sat, water retention, pore-size distribution) were measured on Conservation Reserve Program (CRP) grassland; no till corn-soybean-wheat with clover cover crop (CC) after wheat; mulch till corn-soybean (MTCS); and hay-corn. The CRP treatment retained the most moisture and had the highest K-sat due to increased roots and bio-pores. All management systems had similar AWC values. The MTCS was the least favorable management system for the hydraulic properties studied (Jiang et al., 2007). During an 8-year field study on two southeast coastal plain sandy loams, the no till treatment developed higher bulk density, lower total porosity, and macro-porosity, but higher capillary porosity (micro-porosity) and water retention capacity (field capacity) than the conventionally tilled treatment (Raczkowski et al., 2012).

In Alberta, Canada, a barley study in a Mollisol* was conducted. After 9 years, NT with straw had 8% less AWC than CT with straw in the upper 2.5 cm. There were no differences below that depth to 10 cm (Singh et al., 1996).

Controlled traffic is important in improving soil physical properties (bulk density [BD], penetration resistance, water retention, AWC, root penetration, and porosity) (Blanco-Canqui et al., 2010). In one 20-year study however, AWC and water retention were unaffected by controlled traffic although infiltration decreased in traffic rows (Blanco-Canqui and Lal, 2008).

In a cold humid climate, no till (NT) had a finer pore-size distribution which may cause yield reductions in clayey soils in wet years. NT may not be as well suited in cold, humid climates (e.g., Alaska) where SOC surface build up can occur affecting spring warming even though NT increases water retention (Sharratt et al., 2006). Cold soil temperatures in NT systems appears to be more of an issue in cryic soil temperature regimes (e.g., Alaska, Manitoba) than in frigid regimes (e.g., upper Midwest).

The conclusion is that NT with residue present showed improved AWC in two studies but similar AWC to CT in five studies. Water retention (WR) was improved in these studies. Any improvements in AWC and/or WR may not occur in the first few years after implementation of NT. One study noted that CRP showed the greatest WR but similar AWC compared to NT and CT treatments. Controlled traffic may or may not improve AWC and WR.

## Reduced Till (RT)

Residue and Tillage Management, Reduced Till is defined in Conservation Practice Standard 345 as "managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting" (USDA NRCS, 2017).

Reduced tillage (RT), as the cited literature here refers to, includes strip tillage, NT with concurrent chiseling, disk plow, ridge tillage (harrow disk), stubble mulch, chisel plow, spring disk, and no till with periodic subsoiling. Root crops do not lend themselves to no till and reduced tillage may be the best option. The review below focusses on water present for plant growth vs. AWC.

Reduced tillage (RT) in the form of strip tillage (ST) vs. conventional tillage (CT) for irrigated sugar beets to determine gravimetric water content (θw), and other properties on "the soil surface and at 10 to 15 cm depth" was studied at two sites, "one in North Dakota (Lihen sandy loam) and one in Montana (Savage clay loam)." Findings showed "θw was significantly greater in the clay loam soil under the ST site" while "θw did not significantly differ between CT and ST in the sandy loam" site (Jabro et al., 2009).

In two Iowa loess hill watersheds, surface-soil water content varied between landscape positions and in ridge tilled (RT) vs. conventionally tilled (CT) watersheds. Both watersheds had been under CT or RT for 23 years. It is important to note that the CT site was converted to NT (no cover crop) 6 years before sampling. "Significantly greater water contents were found in the ridge-tilled watershed." "(After accounting for landscape-position effects, the RT watershed had more soil organic carbon (2.1% versus 1.7%)" than the CT/NT watershed. Results indicate prior long-term CT affected water-holding characteristics and other soil properties resulting in decreased water retention compared to the RT plots (Tomer et al., 2006).

The effects of moldboard plowing, reduced tillage (chisel plow, disk plow, or harrow disk) and no till were compared on soils of the Pampas (generally Mollisols*) where adequate rainfall normally occurs for rain-fed farming. Soil water content during the critical periods of planting and flowering was generally greater under reduced tillage (Alliaumea et al., 2013).

“Double cropping that includes soybean has progressed less rapidly in the U.S. southeastern coastal plains in an area that is ideal for double-cropping because of ample rainfall and long growing season.” Through the use of post-emergence herbicides, high levels of crop residue and other water conserving measures reduce water use by cover crops. The use of no till planting along with subsoiling to reduce compaction have facilitated double cropping with soybeans. In a 4-year study, full season soybeans were planted following a grazed rye cover crop, and late season soybeans were planted after winter wheat harvest on a Typic Paleudult* soil. In both cases, a special planter with a subsoil shank ahead of the furrow opener was used. Full-season soybean yields under conservation tillage were equal to or better than conventional/clean tillage. In a dry summer, soybean yields under conservation tillage exceeded conventional tillage because early growth was suppressed which conserved moisture that was available later during the critical reproduction phase. “Late-season soybean yields were favorable” following “wheat with conservation tillage using an in-row subsoil-planting into stubble. “However, planting soybeans into burned-off wheat stubble produced the highest yields in this study. In a dry spring, the cover crop depleted soil moisture resulting in lower soybean yields under conservation tillage. Yield comparisons of 76 vs. 97 cm row spacing were inconclusive, but the trend suggests that” (in the presence of a cover crop - ed.) “wider rows conserve water under periods of drought and that the narrower-row-configuration favors adequate water regimes” (Campbell et al., 1984).

The computer simulation model PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) is one of the soil-crop models that integrate the dynamics of soil, tillage, and crop processes at a daily resolution. This study had two major objectives. The first was to calibrate the use of the PERFECT soil-crop simulation model to simulate soil and crop responses to changes of traffic and tillage management. Data was obtained from research plots on a Vertisol* soil in Southeast Queensland, Australia with controlled traffic and tillage treatments in place for 5 years. Input data for the model included daily weather, runoff, water available for plant growth, available water holding capacity, soil hydraulic properties, cropping systems, controlled traffic and tillage management. The results for benefits for runoff, available soil water, and crop yield from best to worst were: (1) controlled traffic zero tillage, (2) controlled traffic stubble mulch, (3) wheeled (without controlled traffic) zero tillage, and (4) wheeled (without controlled traffic) stubble mulch. The assumption is when there is less infiltration, there is less soil moisture available for crops and more runoff (Li et al., 2008).

Reduced tillage however may or may not increase soil water at saturation or available soil moisture where fallow is practiced. An 11-year study in Lethbridge, Canada “of a 2-year rotation of winter wheat with canola vs. fallow vs. lentil/flax showed little difference in available water for the subsequent wheat crop under no till, reduced till, or conventional tillage.” In this study, the greatest amount of water was present after fallow regardless of tillage system (Larney and Lindwall, 1995). A study of 18 silt loam soils in 18 fields studied over different time spans showed that reduced tillage for tuber crops such as beets and potatoes may or may not increase soil water at saturation or available water holding capacity over conventionally tilled fields (D’Haene et al., 2008).

In a Luvic Chernozem* soil near Krakow, Poland, both, AWC and “productive water content … (water retained) … were not affected by RT or CT tillage systems or mulching in the 0 to 10 cm and 10 to 20 cm depths.” Conventional tillage with and without mulch and reduced till with mulch had similar yields. RT without mulch had lower yields than the other three treatments. The main conclusion is that applying mulch along with reduced tillage can mitigate yield losses in wheat production. (The conclusion was that more soil moisture was available for plant use when mulch was applied) (Glab and Kulig, 2008).

A 2-year study was carried out to compare effects of conventional till (CT) and strip till (ST) practices for sugar beet on a Lihen sandy loam. Soil water did not differ significantly between CT and ST plots in either year (Jabro et al., 2011).

“Twenty years after establishing tillage and straw management treatments in interior Alaska, … no tillage resulted in greater saturated hydraulic conductivity and more soil water was retained than other tillage treatments. However, infiltration was greater in fall chisel plow than other tillage treatments and was likely less without tillage because of the remaining organic surface layer restricting infiltration. Infiltration was enhanced by retaining straw rather than removing it from the soil surface after harvest. Use of no till for continuous small grain production is not sustainable in this region due to lack of weed control strategies. In addition, in no till systems, an organic layer reduced infiltration and lowered soil temperature too much for optimum production. Therefore, minimum tillage (i.e., autumn chisel plow or spring disk) appears to be the best option to maximize infiltration in interior Alaska.” However, there was no difference in soil moisture retention between chisel till and disk tilled treatments and significantly less soil moisture retention in chisel till vs. no till plots (Sharratt et al., 2006).

Generally, RT, especially with mulch, provides increased water for plant growth vs. CT. In the cold, moist environment of many parts of Alaska, RT allows greater infiltration than NT and therefore greater stored water. In two studies, there was no significant difference in stored water between RT (without mulch), NT, and CT.

## Cover Crop (CC)

Cover Crop (CC) is defined in Conservation Practice Standard 340 as “crops including grasses, legumes, and forbs for seasonal cover and other conservation purposes” (USDA NRCS, 2017).

Cover crops (CC) can have positive, neutral, or negative effects on the soil water retention for the next crop. The effect is negative in certain climates when not enough time is available after termination to recharge soil water before the next crop or when the greater infiltration and reduced evaporation aggravate an overly-wet soil condition. In general, “CC’s are more suited for use in sub-humid to humid regions than in semi-arid regions” but may provide benefits in semi-arid areas (discussed in the following paragraph). “In sub-humid to humid regions, cover crops can be terminated or removed (by haying or grazing) to provide time to recharge or retain the soil water supply for the next crop” (Unger and Vigil, 1998).

In semi-arid regions, CC’s may capture snow during fallow periods allowing moisture infiltration. Higher soil moisture can result in the spring if the CC is killed before too much soil water is used by the CC via evapotranspiration. However, CC’s can reduce yields of subsequent crops if they deplete too much soil moisture. “Use of conservation tillage with residue maintenance has improved water conservation and crop yields, and has provided benefits similar to those obtained with CC’s, except for N fixation with legumes, uptake of soil nutrients (nitrates) to prevent their leaching, and provision of additional organic matter to improve soil conditions” (Unger and Vigil, 1998). Cover crop stubble height is important for snow retention. Also, a higher C:N ratio allows the CC to decompose more slowly providing better cover, longer.

Cover provided by winter wheat can retain more soil moisture when it is desiccated early enough reducing crop moisture use while maintaining protective cover. Maintaining cover crop residue after termination can increase the amount of soil moisture retained for use through short drought periods but moist conditions may favor weed growth (Teasdale and Mohler, 1993).

High carbon cover crops (CC) can increase soil organic matter (SOM) and AWC. A study conducted in Illinois of a Mollisol with a silt loam surface layer, using winter CC sequences (vetch and/or cereal rye), showed increased AWC 8.6% with cereal rye CC followed by vetch/cereal rye CC along with a 11% SOM increase over winter fallow (Villamil et al., 2006).

A long-term experiment of cover crops (CC) at Hesston, Kansas, was established in 1995 on a Geary silt loam soil to determine if cover crops (CC) along with no till can improve soil physical properties. Winter wheat-grain sorghum in rotation with “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" was implemented at the end of 15 years. "Across N rates, SH increased cumulative infiltration by three times relative to no-CC plots." "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." Soil water was 42 to 71% greater under sunn hemp and late maturing soybean CC, respectively, at 4 cm depth; 33% at 8 cm; and 13% at 12 cm for both cc's. "Overall, addition of CCs to no till systems improved … water retention, … and the CC-induced change in SOC concentration was correlated with soil physical properties" (Blanco-Canqui et al., 2011).

"In sandy soils of the Southeastern U.S. 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." "Greater volumetric soil moisture content at field capacity for these soils (0.126 vs. 0.113 cm3/cm3) was 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 sunn hemp and 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 bulk density (BD) and increases in saturated hydraulic conductivity 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 (Hubbard et al., 2013).

"In a 5-year study, in the Southeastern U.S. region, cover crops were planted on slightly, moderately, and severely eroded classes of soils (clayey, kaolinitic, thermic Typic Kanhapludults). Cover crops used in this study were "soybean (S) and grain sorghum (G). Each CC was planted into a disk-harrowed seedbed (CT) following winter fallow in each year of the 5-year study. Grain sorghum was also no till (NT) planted into a crimson clover (CL) cover crop." Each crop was grown with and without irrigation. "Infiltration rate after 1 hour from a simulated rainfall was 47% greater for (NT + CL) G than for CTS and CTG with residues in place, and about 100% greater with residues removed. Consequently, soil water available for crop use in the surface 0.5 m was greater for (NT + CL) G than for CTG" (Bruce et al., 1992).

Winter wheat cover crops were studied for 3 years in two Indiana soils in corn-soybean rotation with NT and CT (spring disking) systems. Plots were split into "early (E) desiccated (3 to 4 weeks before planting), and standard (S) desiccated (within the week before planting). CC treatments had higher soil moisture content in spring than the control, with S wetter than E, except … where E conserved soil water during early spring drought better than the other treatments. Both S and E CC … promoted better early corn growth than the control in 5 of 6 site-years." Early CC desiccation should be performed, gaining soil physical improvements over no CC, and avoiding too much soil moisture use (Stipešević and Kladivko, 2002).

"Winter cover cropping may improve rainfall infiltration and enhance soil water storage in areas such as California's Sacramento Valley, where the majority of precipitation occurs in the fall through spring. Enhanced soil water storage within the root zone on cover-cropped fields may reduce demand for irrigation of subsequent crops." "Rainfall, runoff, and soil water content data were collected on two treatments: one with a winter cover crop (common vetch-ed.) and one treatment maintained fallow during the winter." Winter soil moisture content was measured from 0 to 1.05 meters (m) depth and was significantly higher where CCs were used than in fallow. "The study indicated that cover cropping can improve soil water storage for subsequent crops if the cover crop is destroyed before the additional (stored) soil water is lost as evapotranspiration." In addition, infiltration was increased, and runoff reduced (Joyce et al., 2002).

In another study conducted in a Mediterranean climate (California), under rain-fed cropping, evaporation may or may not decrease using cover crops, but decreased directly after rain events when the CC was rolled, and residue left on the soil surface. Cover crop use in semi-arid areas may or may not be appropriate depending on whether soil moisture is adequate for the subsequent crop. Conservation tillage with residue retained provides for moisture retention, erosion control, and limited organic matter retention (Ward et al., 2012).

In north-central Montana, no till legume green manure (LGM) treatments, terminated at first flower, reduced soil water content for the subsequent no till wheat crop 17% (30 mm [1.2 in]) compared to fallow. However, “near-record high rainfall during the wheat growing season (280 to 380 mm [11 to 14 in]) suggest that LGMs likely did not limit soil water available to wheat in this study” (O’Dea et al., 2013)

In a 14-year study on claypan silt loam soils near Centralia Missouri, “bulk density, K-Sat, water retention, and pore-size distribution were measured on Conservation Reserve Program (CRP) grassland planting; no till corn/soybean/wheat with clover cover crop (NTCSWCC) after wheat; mulch till corn/soybean (MTCS); and hay/corn” rotations. Management effects were limited to the 0 to 10 cm depth. “CRP retained the most moisture, followed by NTCSWCC then MTCS, and had the highest K-Sat due to roots and bio-pores while MTCS showed the lowest K-Sat.” All management systems had similar AWC values. (Jiang et al., 2007).

In nearly all instances, no till with a winter cover crop exhibited an increase in stored moisture for the subsequent crop over conventional tillage and/or without a cover crop. Early desiccation of the cover crop is a typical recommendation to lessen water usage by the CC. In two papers, AWC was addressed and was shown to increase along with SOC in one paper but showed no difference between CRP and NT with clover CC (comparison to mulch till not provided).

It was noted in a few papers that CC lessened runoff and increased infiltration. These factors go hand in hand with increased water stored in the soil profile.

## Mulching

Mulching is defined in Conservation Practice Standard 484 as “applying plant residues or other suitable materials produced off site, to the land surface” (USDA NRCS, 2017).

In this discussion, it is the effects of mulch that are important, not the source. In some studies, the mulch may have been produced in the field being studied.

Mulching with straw increased the soil’s capacity to retain soil water. In one study, “16 Mg $ha^{-1}yr^{-1}$ of straw retained about 40% more water between 0 and -6 kPa and 45 to 60% more water between -6 and -1,500 kPa” (available water is between -0.33 and -1,500 kPa) than the unmulched treatment in the 0- to 3-cm depth.” “The greater water retention capacity of mulched treatments is probably explained by the high-water adsorption capacity of straw-derived organic materials.” “Decomposed organic materials possess greater specific surface area and thus adsorb more water than inorganic soil particles” (Blanco-Canqui and Lal, 2007).

A study in central Ohio on long term field plots showed “mulch rates increased AWC by 18 to 35%, total porosity by 35 to 46% and soil moisture retention at low suctions (near field capacity) from 29 to 70%. At high suctions (near wilting point), no differences in soil moisture content were observed between mulch levels. Optimum mulch rates were 4 Mg/ha for increased porosity and 8 Mg/ha for enhanced available water capacity, moisture retention, and aggregate stability.” “Maintaining a mulch cover has been shown to retain soil moisture in the surface few centimeters significantly more than in non-mulched sites. Retaining cover on the soil surface has similar positive effects” (Mulumba and Lal, 2008).

“The hydraulic properties of an Orthic Black Chemozem (Typic Cryoboroll*) were studied under three tillage-residue systems in central Alberta, Canada” for 2 years. “Tillage after 9 years with straw incorporated (till + straw) (T+S) or removed (till - straw) (T-S); and no tillage with straw on the surface (no till + straw) (NT+S)” were studied.”

“Measurements began in the 9th year of continuous barley. Plant-available water capacity (AWC) (-10 to -1,500 kPa) differed among treatments only in the 0 to 2.5 cm layer”, significantly less AWC under NT+S than T+S or T-S due to differences in water retention at -1,500 kPa. “The influence of straw on soil hydraulic properties does not appear to depend on whether it was incorporated or not” (Singh et al., 1996).

In a study of the effect of cover crop residue thickness on weed suppression, soil temperature and moisture, it was shown that residue conserved soil moisture during droughty periods. “Reductions in light transmittance and daily soil temperature amplitude by cover crop residue were sufficient to reduce emergence of weeds but that maintenance of soil moisture could increase weed emergence” (Teasdale and Mohler, 1993).

In another study in an area of Luvic Chernozem* soils, “both, storage and residual pores were not affected by RT or CT tillage systems or mulching in the 0 to 10 and 10 to 20 cm depths.” AWC and productive water capacity were not different for all treatments. Yields under conventional tillage with and without mulch and reduced till with mulch were similar. Yields under RT without mulch was less than the other three treatments. “The main conclusion is that the mulching can help to avoid yield reduction in wheat production when reduced tillage is used” (Glab and Kulig, 2008). Although soil moisture was not measured, the inference is that more water was retained for crop use with mulch applied that sustained yields.

It has been a long term understanding that mulch is beneficial in reducing evaporation from the soil surface. Only five studies are included in this review from the on-line soil health literature posted to date. The three studies addressing retained water agree that mulch increases water available for plant growth. Between 8 and 19 Mg/ha were reported as needed to increase water retention. Three papers address the effects of mulch on AWC. Two papers show porosity and the increase of AWC when measured in the upper 2.5 and 10 cm depths respectively. The third paper shows no AWC increase with mulch additions for reduced till or continuous till.

## Other Organic Matter Additions

This section includes reviews of findings of SOC increases through waste water, manure, or other organic waste applications as well as the biomass addition via cover crop and/or mulch application.

Additions of SOC included under Conservation Practice Standard 590 are defined as “managing the amount (rate), source, placement (method of application), and timing of plant nutrients and soil amendments” which includes additions of manures and plant residues (USDA NRCS, 2017).

In one study, “for all textural groups studied (sand, silt loam, and silty clay loam), increasing soil organic matter (SOM) increased AWC significantly. For every percent increase in SOM by weight between 1 and 4% SOM studied, AWC increased 0.022, 0.037, and 0.028 cm/cm for S, SiL, and SiCL, respectively” (Hudson, 1994).

In another study another study, “because of the changing nature of the soil matrix (mineral-dominated to organic carbon dominated surfaces), the change in AWC ranges from about 2.5 to 5% per 1.0% change in organic carbon in soils containing less than 2.5% organic carbon and less than 40% clay” (Olness and Archer, 2005).

The U.S. National Soil Characterization database and the database from pilot studies on soil quality as affected by long-term management was used to study the effects of soil organic carbon (SOC) on water retention (1/3 and 15 bar). “At low organic carbon contents, the sensitivity of the water retention to changes in organic matter content was highest in sandy soils. Increase in organic matter content led to an increase of water retention in sandy soils, and to a decrease in fine-textured soils. At high organic carbon values, all soils showed an increase in water retention. The largest increase was in sandy and silty soils” (Rawls et al., 2003).

Soil physical properties, as affected by a long-term (~40y) fertilizer use experiment “in a maize-wheat system on sandy loam soils of India, was characterized.” “Treatments were 100% and 150% of recommended nitrogen, phosphorus, and potassium (NPK); 100% NPK + farmyard manure; 100% NPK + sulfur; and control (no fertilizer or manure). Most of the effects were pronounced in the surface soil (0 to 15 cm).” “Field capacity moisture content, plant-available water content, and saturated hydraulic conductivity were significantly higher in manure plots.” “(AWC was 58% greater in Manure + NPK plots than control and SOC was 51% greater after 40-year treatments” (Chakraborty et al., 2010).

“Soil degradation caused by intensive vegetable farming, and its reversibility after 2 to 5 years of drastic changes in soil management, was studied on 16 commercial vegetable farms in southern Uruguay. Changes in soil management included the addition of green manures and pastures in rotations with vegetable crops, use of animal manure, and erosion control support measures (terracing, reducing slope length, re-orientation of ridges).” “Available water capacity increased significantly with SOC particularly due to more moisture at field capacity, resulting in an average increase in available water capacity in the first 20 cm of soil of 8.4 mm (or 0.042 cm H2O/cm soil) for every 10 g $kg^{-1}$ (1%) of SOC increase” (Alliaumea et al., 2013).

The effects of soil organic carbon (SOC) additions from manures and crop residues on selected soil “properties were measured at seven experimental sites” (cropped to grass, or conventionally tilled cereal rye or sugar beet), on contrasting soil types. Each site had a “history of repeated applications of farm manure or differential rates of inorganic fertilizer nitrogen (N). Repeated (> 7 years annual additions) and relatively large OC inputs (up to 65 t SOC/ha) were needed to produce measurable changes in soil properties.” In “all the study sites, there was a positive relationship between SOC inputs and changes in total SOC and ‘light’ fraction SOC (LFOC), with LFOC providing a more sensitive indicator of changes in SOM status. Total SOC increased by an average of 3% for every 10 tons/ha manure OC applied, whereas LFOC increased by 14%. The measured SOC increases were equivalent to 23% of the manure OC applied (up to 65 t OC/ ha applied over 9 years) and 22% of the crop residue OC applied (up to 32 t OC/ha over 23 years). The manure OC inputs (but not crop residue OC inputs) increased plant available water capacity (14.3 to 28.9%) and topsoil porosity.” Use of only crop residues had a negative affect on AWC in some cases (Bhogal et al., 2009).

Increasing SOM generally results in increased AWC especially in sandy soils. Studies provide mixed results as clay content increases with one study showing no increase in soils with over 40% clay.

## Forage and Biomass Planting

Forage and Biomass Planting is defined in Conservation Practice Standard 512 as “establishing adapted and/or compatible species, varieties, or cultivars of herbaceous species suitable for pasture, hay, or biomass production” (USDA NRCS, 2017).

Included in this discussion are native prairie, CRP, pasture, grass, and grass-legume crops as part of a rotation.

Pasture sites typically have greater available water capacity (AWC) than cultivated sites. This is attributed to greater SOM, and more favorable structure and porosity (Mugdal et al., 2010).

A 1938 paper summarizes a northern U.S. study on how sod rotations impact how much rainfall is accumulated in the soil profile. “Grass crops absorbed 87.4 percent of the rainfall, a 3-year rotation with one sod crop absorbed 85.5 percent, while continuous corn absorbed only 69.6 percent, according to trials extending over 14 years” (Albrecht, 1938).

“On claypan silt loam soils near Centralia, Missouri, bulk density, K-Sat, water retention, and 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 0-10 cm. CRP retained the most moisture and had the highest K-Sat due to roots and bio-pores while MTCS showed the lowest K-Sat. All management systems had similar AWC values. CRP had the most porosity in all but the micropore (<10 µm) range. Results show that soil hydraulic properties are further degraded on the backslope position, where topsoil is the shallowest when row cropping and mulch tillage are used. Results suggest that the use of perennial grasses in rotation (or permanent grass) will benefit soil hydraulic properties, particularly on slope positions most vulnerable to degradation where soil conditions cannot be improved by row-crop conservation systems" (Jiang et al., 2007).

Various properties were studied between a native prairie and a field that had been under cultivation for 132 years, the last 18 years in mulch till corn-soybean-grain sorghum. On a volume basis (data adjusted for bulk density differences), the upper 20 cm (similar clay contents) showed the prairie site had 42% more SOM and 27% higher AWC than the cultivated site (Mugdal et al., 2010).

"In a loamy soil in a Mediterranean climate (Tehran Province, Iran), after 50 years, AWC at dryland wheat farming sites were 29 to 33% lower than pasture sites at the 0 to 15 cm depth. AWC in pasture sites was higher due to high SOM, better soil structure, and higher porosity" (Haghighi et al., 2010).

However, ARS compared long term (15-year) non-irrigated continuous grass-legume mixture (not grazed or hayed) vs. no till treatments of wheat/corn/ millet vs. wheat/fallow rotation at the semi-arid ARS Central Great Plains Research Station, Akron, Colorado on a Weld soil series (deep smectitic silt loam over silty clay loam). Significant increases in SOC in the grass-legume and the wheat/corn/millet treatments occurred compared to the wheat/fallow in the surface soil (95 mm) grading to no differences below 295 mm, but there were no differences in water storage porosity (Benjamin et al., 2008). (Note: Initial conditions were not stated.)

Long term permanent cover generally results in greater AWC. One study states that retained water was greater under CRP than cropped sites. One study showed no significant difference in AWC between 15 years of grass-legume cover vs. NT cropping in a semi-arid climate.

## Conservation Crop Rotation

Conservation Crop Rotation is defined in Conservation Practice Standard 328 as "growing crops in a recurring sequence on the same field" (USDA NRCS, 2017).

Crop rotation generally affects the amount of water stored in the soil profile rather than affecting available water capacity (AWC). Including grass/legume crops is typically required to affect retained water but a fallow period may be more effective where precipitation is inadequate.

In a 3-year study in the southeastern U.S., where the use of sunn hemp was included in the NT rotation (vs. fallow or crimson clover CC), volumetric soil water was increased. In general, the soil in the row had lower BD and greater water content than that of the inter-row. Overall the study indicated that land managers should consider the inclusion of a late summer cover crop following sweet corn and that sunn hemp provides substantial benefit (Hubbard et al., 2013).

The objective of a study in Iowa and Indiana "was to quantify potential differences in soil moisture due to the presence of a cereal rye cover crop in a corn-soybean rotation." "During the drought of 2012, soil volumetric water content (θ) and soil water storage (SWS) were monitored daily at three sites. Measurements of soil θ were taken at depths of 10, 20, 40, and 60 cm, and SWS was estimated to an 80-cm depth. Soil water during the drought of 2012 was affected by a rye cover crop in comparison to without a rye cover crop for one (located in Iowa) of the three sites monitored. At the Iowa site, soil θ was on average 0.041 and 0.033 cm3/cm3 … greater at the 10 and 20 cm depths, respectively, following termination of a rye cover crop than crops without a rye cover crop." Overall, the use of a cereal rye cover crop in a corn-soybean rotation did not significantly lower soil moisture, because there was only a small amount of rye cover crop growth/biomass before the rye was terminated (Daigh et al., 2014).

"In an unusually dry farming season on mainly Lester loam soils in Minnesota: conventional (continuous corn and deep tillage), rotation (5-year corn-soybean-oats/alfalfa-alfalfa-alfalfa rotation with (mulch) tillage 2/5 years), and no till (corn-soybean with no cultivation) were studied for several soil property changes. Soil organic matter content was highest on the rotation farm, followed by the no till farm, and lowest on the conventional till farm. Soil moisture was higher in the no till and rotation systems compared to the conventional till farm. The conventional till farm had the highest runoff volume per cm rain compared to the rotation and no till farms. These results indicate that perennial close-seeded crops (such as alfalfa) used in crop rotations, as well as plant residue left on the surface of no till fields, can enhance soil organic content and decrease runoff thereby increasing water infiltrated into the soil. The lower soil penetrometer resistance and higher level of soil moisture in soils with a crop rotation and with no till show that these practices can increase soil aggregation and water infiltration, both of which prevent erosion. In an unusually dry year, a crop rotation, and particularly no till' … provided superior corn and soybean yields, most likely due to higher soil moisture as the result of greater water infiltration and retention associated with cover crops (rotation till farm) and crop residue (no till farm)" (Gregory et al., 2005).

Use of "winter cover crops may improve rainfall infiltration and enhance soil moisture content in areas such as California's Sacramento Valley, where the majority of precipitation occurs in the winter over a relatively short period of time in a series of heavy rainfall events. Enhanced soil moisture within the root zone on cover-cropped fields may reduce the amount of irrigation needed for subsequent crops. A study was conducted in the winters of 1998-1999 and 1999-2000 to determine if enough soil moisture is conserved to benefit subsequent crops and to evaluate the effects of soil physical conditions on the soil-water balance for three 4-year rotation farming systems within the Sustainable Agriculture Farming Systems (SAFS) Project at the University of California, Davis. Rainfall, runoff, and soil water content data was collected on two treatments using a winter cover crop and one treatment maintained fallow during the winter. Runoff and soil water content measurements were significantly affected by management systems. During the winter of 1999-2000, soil water content measurements from 0 to 1.05 m depth were significantly higher in the cover-cropped systems than in the fallow treatment after field capacity had been reached." The study indicated that rotations including cover cropping can improve total soil water available for subsequent crops if the cover crop is terminated prior to the soil water loss through evapotranspiration (Joyce et al., 2002).

In a Missouri field trial under no till, there were no AWC differences between CRP; NT c/s/w/clover CC; mulch till c/s; and hay-corn. However, CRP retained the most moisture. In Illinois, the use of winter cover crops (red clover) in the rotation increased total and water storage porosity along with plant available water (Jiang et al., 2007).

"Soil degradation caused by intensive vegetable farming and tillage, and its reversibility after 2 to 5 years of drastic changes in soil management on 16 commercial vegetable farms in south Uruguay was studied. Changes in soil management included the addition of green manures and pastures in rotations with vegetable crops, use of animal manure, and erosion control support measures (terracing, reducing slope length, re-orientation of ridges). Soil degradation was assessed by comparing soil properties in 69 vegetable fields with values at reference sites located close to the cropped fields. Effects of the changes in soil management were assessed by comparing soil properties at the start and the end of the project. Compared to reference sites, the vegetable fields contained 36% less soil organic carbon (SOC), and 11% lower plant-available soil water capacity. After 2 to 5 years of improved soil management, SOC concentration in the upper 20 cm increased by on average 1.53 g/kg (12%) in the Phaeozems (Abruptic)* and 1.42 g/kg (9%) in the Phaeozems (Pachic)*. SOC in Vertisols* increased only by 0.87 g/kg, most likely due to their greater initial SOC concentration. Available water capacity increased significantly with SOC particularly due to more water retention at field capacity, resulting in an increase in available water capacity in the first 20 cm of soil of 8.4 mm for every 10 g/kg of SOC increase" (Alliaumea et al., 2013).

“The use of annual legume green manure cover crop (LGM) as a partial-fallow replacement in western Canada to protect the soil against erosion and increase N fertility, particularly when combined with tall wheat stubble left to trap snow to replenish soil water to offset soil moisture used by the LGM was studied. Yields, N use efficiency, water use efficiency, and economic returns for hard red spring wheat (W) grown in rotation with Indianhead black lentil a green manure legume (LGM-W-W) vs. a traditional fallow-wheat-wheat (F-W-W) system were compared.” “The study was conducted over 12 years (1988-99) on a medium-textured soil near Swift Current, Saskatchewan.” “Wheat stubble was left tall to trap snow, tillage kept to a minimum, and the wheat was fertilized based on NO3 soil tests. After 6 years, it was concluded that waiting until full bloom to turn down (moldboard plow) the legume (usually late July or early August) to maximize N2 fixation was too late and the LGM utilized too much soil water hurting wheat yields. After 1993, LGM turndown was changed to an earlier date resulting in equal wheat yields following a LGM to those after fallow (due to improved water use efficiency). Results suggest that the use of LGM cover crops to replace fallow can be a viable option in this region” (Zentner et al., 2003.

However, in a 14-year Missouri (humid region) trial under no till, there were no AWC differences between CRP; NT corn/soybean/wheat/clover CC; mulch till corn-soybean; and hay (Est. for 4 years)-corn. CRP retained the most moisture (Jiang et al., 2007). In another 15-year study, in the central Great Plains, no differences in water storage porosity was shown between grass vs. wheat-corn-millet, and wheat-fallow treatments (Benjamin et al., 2008).

In semi-arid Alberta, Canada “performance of winter wheat under conventional, minimum, and zero tillage in a wheat monoculture and in 2-year rotations with fallow/ canola, or lentils/flax” were studied. “Continuous cropping greatly depleted soil water reserves, resulting in some crop failures. Averaged over 10 years, available water for establishment of winter wheat in fall was least after canola (45 mm), followed by continuous winter wheat (59 mm), lentils/flax (74 mm), and fallow (137 mm).” “The effect of rotation on soil water was much greater than that of tillage. Zero tillage had little impact on available water to 1.5 m depth.” “However, after 6 to 7 years, available water in the 0 to 15 cm depth under winter wheat in spring was greatest under zero tillage. Precipitation storage efficiency during the fallow year was generally unaffected by tillage system.” Possible reasons for the lack of a tillage effect on soil water status in the fall: “(i) similar water extraction by the preceding canola, lentils/flax and wheat crops, and similar water storage on the fallow plots, irrespective of tillage system; (ii) a narrow window between harvest of the preceding crops and seeding of the winter wheat crop (especially on the W-C and W-L/Fx rotations, … which allowed insufficient time for tillage system to significantly affect soil water regime; and (iii) the nature of the CT treatment, which would be considered minimum tillage in more humid climates due to the shallow working depth of the heavy-duty cultivator (10 cm) and non-inversion of the soil” (Larney and Lindwall, 1995).

Retained water can be greater where a grass or legume cover is planted after other crops depending on the species and the timing of termination. In certain semi-arid areas, fallow may store more moisture than where a cover crop is included in the rotation. No till has also been shown to result in increased retained water compared to conventional tillage. AWC was shown in Uruguay to be increased across 26 sites after 2 to 5 years where green manure or pasture was included in the rotation vs. continuous vegetable plantings. Two other studies showed no increases in AWC where grass was included.

## Subsoiling or Deep Tillage

Deep Tillage is defined in Conservation Practice Standard 324 as “performing tillage operations below the normal tillage depth to modify adverse physical or chemical properties of a soil” (USDA NRCS, 2017).

Subsoiling or deep tillage is not currently a conservation practice listed as a component of typical Soil Health Management Systems (SHMS). Deep tillage is used where tillage pans (compaction layers) exist to enhance crop rooting, deeper water movement, water retention, and soil moisture availability. It may apply to SHMS’s when it is conducted prior to implementing a continuous no till system. Use of tillage radish or other cover crops with tap roots as a means of disrupting tillage pans applicable to Conservation Practice Standard 324, but may be substituted for deep tillage to alleviate compaction layers in some cases.

Compaction is facilitated by a lack of microbial activity that provides biologic glues that stabilize structure and aggregates so that the soil can better withstand equipment traffic and tillage. By exercising no till and maintaining a cover and living root system, these glues can persist and be increased.

Subsoiling prior to implementation of continuous no till systems has met with mixed results. Proper soil moisture content is very important to shatter the tillage pan and only when severe compaction is present does it appear to be a benefit. Adequate soil moisture must be present deeper in the crop's root zone for the crop to take advantage of it. In years with adequate precipitation, the effects of subsoiling and deeper root exploration may not be seen. Benefits are mainly temporary (2 to 3 years), especially where equipment traffic is not controlled. No till coupled with cover crops and controlled traffic are probably the best long-term solution to alleviating compaction although subsoiling prior to switching to no till when a severe compaction layer is present may be beneficial until improvements in compaction from implementing a SHMS take effect (Hoorman et al., 2011).

In New Zealand's poorly drained, easily compacted soils. Moutoa silty clay (Typic Haplaquoll*) where animal and crop production are integrated, soil properties were studied for the impact on forage oat establishment after 15 years of conventional tillage (CT). Treatments were "paraplowed (P), deep subsoiled (V), shallow subsoiled (S), or were left as non-subsoiled controls (C). The surface 15 cm was surface-tilled (T) or not tilled (N). Subsoiling greatly reduced soil strength." Subsoiling without T continued to show improved profile cone index (a measure of compaction) cumulative frequency 233 days after subsoiling. T (vs. N) reduced emergence from 142 to 113 plants per square meter and reduced yield from 5,318 to 3,679 kg/ha. Forage yield increased from 3,974 to 4,674 kg/ha with subsoiling. Generally, subsoiling without T (N treatment) produced better soil conditions and oat crop performance than the prevailing practice of T without subsoiling (Sojka et al., 1997).

In the U.S. southern coastal plain soils, strip tillage and subsoiled beneath each row "decreased cone index (penetration resistance) directly beneath the row, decreased surface bulk density, increased surface moisture content, decreased energy usage, and increased yields. Controlled traffic was beneficial only when in-row subsoiling was not used as an annual tillage treatment" (Raper et al., 1994).

Case-studies of the impact of tillage, and other factors on soybean yield and root rot severity show that "soil-borne diseases are most damaging with wet/low oxygen soil conditions as a result of inadequate drainage, poor soil structure, low organic matter, low soil fertility, and high soil compaction." Subsoiling increased yield, but pathogens were not lowered, indicating greater root mass and root penetration depth overcame the effects of pathogens (Abawi and Widmer, 2000).

In another 3-year trial in a Norfolk loamy sand (Typic Kanduidult*) known for tillage pan development, no till, subsoiling, and subsoiling using an implement that creates a shank opening of approximately 0.1 inch otherwise known as slit treatments, showed no differences in yield despite 1-trial-year of inadequate moisture (Vepraskas, 1995). In Ohio, subsoiling showed significantly lower yields in corn and soybean plots for both 10-ton and 20-ton compaction treatments compared to no till without subsoiling. (Sundermeier and Reeder, 2011). Subsoiling to correct tillage pans prior to implementing no till was not studied.

The perception that tap-rooted species may penetrate compacted soils better than fibrous-rooted species for biological tillage was studied. "Forage radish (FR) and rapeseed were evaluated against cereal rye. In addition, three different levels of compaction (high, medium, and no compaction) were created by wheel trafficking. Cover crop roots were counted by the core-break method. At 15 to 50 cm depth under high compaction, FR had more than twice as many roots and rapeseed had about twice as many roots as rye in experiment 1; FR had 1.5 times as many roots as rye in experiment 2. Under no compaction, little difference in root vertical penetration among three cover crops existed. Rapeseed and cereal rye root counts were negatively related to soil strength, while FR roots showed either no (experiment 1) or positive (experiment 2) relationship with soil strength. Soil penetration capabilities of three cover crops were: FR greatest; rapeseed next; and cereal rye least" (Chen and Weil, 2010).

The papers reviewed show in three out of five studies that subsoiling then implementing NT result in increased yields over non-subsoiled treatments. Cover crop roots, especially where forage radish is included, can also alleviate the effects of the presence of tillage pans.

## Conclusion

This review covers both water retained (RW) for crop use and available water holding capacity (AWC) of the soil. Retained water is a temporal value and AWC is an intrinsic soil property providing an estimate of the ability of the soil to hold water between gravitational loss and the permanent wilting point moisture content for most plants.

The focus is to summarize the literature in the NRCS Soil Health database as of 9/2016 with respect to RW and AWC sorted by the effects of Soil Health Management System conservation practices.

Retained water is shown to be increased as a result of conducting no tillage or reduced tillage over conventional tillage; applying mulch; and/or rotating crops (with early termination) where precipitation amount is sufficient. Subsoiling allows improved access to moist soil layers and probably allows moisture to penetrate deeper in the soil profile. Tap rooted cover crop species are also shown to be beneficial.

Retained water was not addressed for the sections covering Other Organic Matter Additions and Forage and Biomass Plantings.

Available Water Holding Capacity is shown to be increased in some cases under no till, with cover crops, use of mulch, organic matter increases, and under pasture. Sandy soils' AWC increases most as SOM increases but AWC may not be affected in high clay containing soils. NT appears to increase the proportion of plant available moisture containing pores. AWC was not addressed under the Reduced Tillage, the Conservation Crop Rotation, and the Subsoiling or Deep Tillage sections.

Although no studies here addressed combinations of these practices, it is intuitive that incorporating a selection of the subject practices, as appropriate, should maximize water retained for plant growth and the possibility of increasing AWC.

## Glossary

**Aeric Ochraqualf:** A somewhat poorly to poorly drained soil with a light-colored surface layer and an increase in clay in the subsoil. Taxa is no longer in use. Updated taxa for the Crosby soil series is fine, mixed, mesic, Aeric Epiaqualf. From this, it can also be noted that this soil has a clayey subsoil and the shallow water table is perched on this subsoil in a mesic climate (e.g., Indiana) fine, smectitic, mesic Aquic Argiudoll: soils with loamy, silty or clayey surface horizons and clayey subsoils that have high shrink-swell potential. Mean annual soil temperature is between 8 and 15 degrees C. The soil is in a humid climate with a short dry season however, has a water table within the soil profile as shallow as 50 cm part of the year. These soils have 1% SOM or more in the surface layers and high base (Ca, Mg, K) status.

**Luvic Chernozem:** Blackish soils rich in organic matter with high base status and CEC, and containing a subsoil with more clay content than the surface layers (if un-eroded).

**Mollisol:** Soils with 1% SOM or more in the surface layers and high base (Ca, Mg, K) status.

**Phaeozems (Abruptic):** Dark topsoil, no secondary carbonates (unless very deep), high base status. The clay increase in the subsoil is double the percent clay in the surface horizon if the surface horizon has <20% clay; or there is an absolute 20% increase if the surface horizon has >=20% clay content.

**Phaeozems (Pachic):** Topsoil dark to >=50cm, no secondary carbonates (unless very deep), high base status.

**Smectitic:** A clay mineralogy family consisting on 2:1 alumino-silicate clays exhibiting high CEC values and high shrink swell potential.

**Typic Cryoboroll:** An obsolete taxa of U.S. Soil Taxonomy that has been revised to a subgroup of Cryolls. These soils have a frigid soil temperature regime (less than 8 degrees C mean annual soil temperature). Soils have 1% SOM or more in the surface layers and high base (Ca, Mg, K) status.

**Typic Haplaquoll:** Typically deep soils with 1% SOM or more in the surface layers and high base (Ca, Mg, K) status.

**Typic Haploboroll:** An obsolete taxa of U.S. Soil Taxonomy that has been revised to Typic Haplocryolls. These soils have a frigid soil temperature regime (less than 8 degrees C mean annual soil temperature). Soils have 1% SOM or more in the surface layers and high base (Ca, Mg, K) status.

**Typic Kandiudult:** Soils that have been significantly weathered containing a subsoil with more clay content than the surface layers (if uneroded). Base (Ca, Mg, K) status and CEC is very low, and there can be toxic levels of aluminum (Al+3).

**Typic Paleudult:** Soils that have been significantly weathered containing a thick subsoil with more clay content than the surface layers (if uneroded). Base (Ca, Mg, K) status is very low, and there can be toxic levels of aluminum (Al+3).

**Ultisol:** Soils that have been significantly weathered containing a subsoil with more clay content than the surface layers (if uneroded). Base (Ca, Mg, K) status and CEC is low, and there can be toxic levels of aluminum (Al+3).

**Vertisols:** Clayey soils with a high shrink-swell potential in the surface and subsoil layers. Typically, these soils have a high base cation status (Ca, Mg, K).

## Literature Summaries

These summaries are for references cited in this review and are obtained from the Literature Review Summaries posted on the NRCS Soil Health website. They are presented here for the reader's easy reference. Summaries were initially copied from the paper's abstract and/or conclusion. Verbiage not relevant to soil health may have been removed, and additional information important to clarify the relationship to soil health management were added as needed. Scientific and statistical terms were replaced where possible by terms better understood by the reader. Sentences and phrases were removed that were not necessary to describe the basic content.

**Abawi and Widmer, 2000.** In this review paper, case-study examples are presented to illustrate the impact of tillage, and other factors on bean yield and root rot severity. The conclusions are soil borne diseases are most damaging when soil conditions are poor as a result of inadequate drainage, poor soil structure, low organic matter, low soil fertility, and high soil compaction. The aforementioned cultural practices all have an impact on these physical characteristics as well as increasing the diversity of the soil biota. Effects of subsoiling include increases in yield but not lower pathogen numbers indicating greater root mass and penetration depth overcoming the effects of the pathogens. Effects may only last one year.

**Albrecht, 1938.** The paper states that sod rotations are an important factor in accumulating moisture in the subsoil. “Grass crops absorbed 87.4 percent of the rainfall, a 3-year rotation with one sod crop absorbed 85.5 percent, while continuous corn absorbed only 69.6 percent, according to trials extending over 14 years.”

**Alliaumea et al. 2013.** “This paper reports soil degradation caused by intensive vegetable farming, and its reversibility after two to five years of drastic changes in soil management on 16 commercial vegetable farms in south Uruguay. Changes in soil management included addition of green manures and pastures in rotations of vegetable crops, use of animal manure, and erosion control support measures (terracing, reducing slope length, re-orientation of ridges). Soil degradation caused by vegetable farming was assessed by comparing soil properties in 69 vegetable fields with values at reference sites located close to the cropped fields. Effects of the changes in soil management in the 69 fields were assessed by comparing soil properties at the start and to those at the end of the project. Compared to the on-farm reference sites, the vegetable fields contained 36% less SOC, … and 11% lower plant-available soil water capacity.” “After two to five years of improved soil management, SOC concentration in the upper 20 cm increased by on average 1.53 g $kg^{-1}$ (12%) in the Phaeozems (Abruptic)* and 1.42 g $kg^{-1}$ (9%) in the Phaeozems (Pachic)*. SOC in Vertisols* increased only by 0.87 g $kg^{-1}$, most likely due to their greater initial SOC concentration. Topsoil carbon sequestration was on average 3.4 Mg $ha^{-1}$ in the Phaeozems. Multiple linear regression showed the quantity of incorporated amendments, the initial amount of SOC and the clay content to explain 77% of the variability in yearly changes of SOC.” “Available water capacity increased significantly with SOC particularly due to more water retention at field capacity, resulting in an increase in available water capacity in the first 20 cm of soil of 8.4 mm for every 10 g $kg^{-1}$ (1%) of SOC increase.”

**Alvarez and Steinbach, 2009.** Compared the effects of plow tillage (mouldboard plow), reduced tillage (chisel plow, disk plow or harrow disk), and no till. Soil water content during the critical periods of sowing and flowering was generally greater under limited tillage. Soybean yield was not affected by tillage system, meanwhile wheat and corn yields were lower under reduced tillage and no till than under plow tillage without nitrogen fertilization. The adoption of limited tillage systems in the Pampas leads to soil improvement but also generates the necessity of increase nitrogen fertilizers utilization to sustain yields of graminaceous crops. (No cover crops were used).

**Benjamin et al., 2008.** Comparisons of long term (15-year) no till treatments of non-irrigated continuous grass-legume mix vs. wheat/corn/ millet vs. wheat fallow rotation at the semi-arid ARS Central Great Plains Research Station, Akron, Colorado on a Weld Soil Series (deep smectitic* silt loam over silty clay loam). It showed significant increases in SOC in the grass and wheat/corn/millet treatments over the wheat/fallow in the surface 95 mm grading to no differences below 295 mm. K-Sat was significantly higher in the grass treatment to 370 mm but there were no differences in bulk density and water storage porosity.

**Bhogal et al., 2009.** “The effects of organic carbon (OC) additions from farm manures and crop residues on selected soil … properties were measured at seven experimental sites … (cropped to grass, and conventionally tilled rye or sugar beet), on contrasting soil types, … with a history of repeated applications of farm manure or differential rates of inorganic fertilizer nitrogen (N). Repeated (> 7 years annual additions) and relatively large OC inputs (up to 65 t OC ha-1) were needed to produce measurable changes in soil properties.” In “all the study sites, there was a positive relationship between OC inputs and changes in total soil OC and ‘light’ fraction OC (LFOC), with LFOC providing a more sensitive indicator of changes in SOM status. Total SOC increased by an average of 3% for every 10 t ha-1 manure OC applied, whereas LFOC increased by 14%. The measured SOC increases were equivalent to 23% of the manure OC applied (up to 65 t OC ha-1 applied over 9 years) and 22% of the crop residue OC applied (up to 32 t OC ha-1 over 23 years). The manure OC inputs (but not crop residue OC inputs) increased topsoil porosity and plant available water capacity.”

**Blanco-Canqui and Lal, 2007.** Straw mulching for 10 consecutive years "increased the soil's capacity to retain water at all soil water potentials (0 to −1500 kPa or saturation to wilting point) in the top 10-cm. Soil mulched with 16 Mg ha−1yr−1 of straw retained about 40% more water between 0 and −6 kPa and 45 to 60% more water between −6 and −1500 kPa than the unmulched treatment in the 0- to 3-cm depth. The unmulched treatment drained more rapidly than the mulched treatments between −300 and −1500 kPa. Differences in soil water retention (SWR) between 8 and 16 Mg ha−1yr−1 of straw mulch were small and generally nonsignificant in the 0- to 3-cm depth, although the soil mulched with 16 Mg ha−1yr−1 consistently maintained a greater water content that the other treatments. In the 3- to 10-cm depth, the unmulched treatment retained 25 to 50% less water than the low-mulch treatment and 45 to 70% less water than the high-mulch treatment, indicating greater SWR in treatments with increasing mulch rates. In the 10- to 20-cm depth, SWR was unaffected by mulching, indicating that the beneficial effects of long-term surface mulching were mostly confined to surface soil layers. The greater water retention capacity of mulched treatments is probably explained by the high-water adsorption capacity of straw-derived organic materials."

**Blanco-Canqui and Lal, 2008.** This study compared wheel traffic effects within no till fields in Ohio. "This study set out to measure the differences in soil hydraulic properties … and assess their relationships with corn grain and stover yield in NT Celina silt loam and Hoytville clay loam receiving three levels of axle loads for 20-year. Imposition of three-axle load treatments including control, 10 Mg, and 20 Mg affected water infiltration rates but not bulk density (ρb), saturated hydraulic conductivity (Ksat), soil water retention (SWR), plant available water (PAW), and pore-size distribution in both soils."

**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 … near Hesston, Kansas." "Wheel traffic increased bulk density, … cone index, shear strength, and aggregate tensile strength … over non-trafficked rows in the 0- to 7.5-cm depth. Wheel compaction reduced cumulative infiltration by 40 to 120 times … in all but one system. "It also reduced … saturated hydraulic conductivity, soil water retention at 0 kPa, plant-available water, effective porosity, and the volume of >50-μm pores." "Data strongly supports the need for using controlled traffic to reduce the adverse impacts of wheel traffic on soil physical quality."

**Blanco-Canqui et al., 2011.** Conducted 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 cover crops (CCs) may be a potential strategy to boost no till performance by improving soil physical properties. "To assess this potential, we 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, we 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." "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." Soil water was 42 to 71% greater under Sunn hemp and late maturing soybean CC respectively at 4 cm depth;33% at 8 cm; and 13% at 12 cm for both cc's. "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."

**Bruce et al., 1992.** "To determine the effectiveness of selected crop biomass inputs on soil surface characteristics that significantly impact rainfall infiltration, sites on slightly, moderately, and severely eroded classes of Cecil-Pacolet soils (clayey, kaolinitic, thermic Typic Kanhapludults) were selected. On each class of erosion, soybean (S) and grain sorghum (G) were each planted into a disk-harrowed seedbed following winter fallow in each year of the 5-year study. Grain sorghum was also no till-planted into a crimson clover cover crop. Each summer crop was grown both under irrigation and natural rainfall." "The effect of increased soil surface aggregate stability was reflected in a soil water pressure greater than -0.1 MPa in the surface 0.5 m for a significantly greater fraction of the summer growing season and in increased infiltration." "Infiltration rate of simulated rainfall after 1 hour was about

47% greater for (NT + CL) G than for CTS and CTG with residues in place, and about 100% greater with residues removed. Consequently, the soil water readily available for summer crop use in the surface 0.5 m was greater for (NT + CL) G than for CTG."

**Campbell et al., 1984.** "Double cropping of soybean has progressed less rapidly in the U.S. southeastern coastal plains than expected by the ample rainfall and long frost-free season. Post-emergence herbicides, the management of plant residues to reduce water use by cover crops, and a no till planter with a subsoiler are the innovations that have facilitated this new production. Full season soy bean was planted in a Typic Paleudult* following a grazed cover crop of winter or late-season soybean was planted following winter wheat harvest. In both cases, a special planter was used with integral subsoil shank ahead of the opener. Full-season soybean under conservation tillage produced yields equal to or better than yields in conventional clean tillage. In a summer, soy bean yields under conservation tillage exceeded conventional tillage because of suppressed early biomass production which conserved stored soil water and favored growth during the reproduction phase of the crop-cycle. Late-season soybean yields behind wheat favored the conservation tillage practice of in-row subsoil-planting into stubble. However, planting in burned-off wheat stubble produced the highest yields in this study. In a dry spring, the cover crop accelerated soil water use which resulted in lower soybean yields under conservation tillage. Comparisons of 76 vs. 97 cm rowing were inconclusive, but the trend suggests that wider rows conserve water under periods of drought and that the narrower-row configuration favors adequate water regimes."

**Chakraborty et al., 2010.** "Soil physical environment as affected by long-term … (~40 years) … fertilizer experiment application in a maize-wheat system on sandy loam soils of India was characterized." "Treatments were 100% and 150% of recommended nitrogen, phosphorus, and potassium (NPK); 100% NPK + farmyard manure; 100% NPK + sulfur; and control (no fertilizer or manure)." Most of the effects were pronounced in 0- to 15-cm layer. "The field capacity moisture content, plant-available water content, and saturated hydraulic conductivity were significantly higher in manure plots." "(AWC was 58% greater in Manure + NPK plots than control. SOC was 51% greater after 40 years of treatments)."

**Chen and Weil, 2010.** This paper reviewed the general perception that tap-rooted species may penetrate compacted soils are better than fibrous-rooted species for use in biological tillage. Forage radish (FR) and rapeseed were evaluated against cereal rye. Three different levels of compaction (high, medium and no compaction) were created by wheel trafficking. "Cover crop roots were counted by the core-break method. At 15 to 50 cm depth under high compaction, FR had more than twice as many roots and rapeseed had about twice as many roots as rye in experiment 1; FR had 1.5 times as many roots as rye in experiment 2. Under no compaction, little difference in root vertical penetration among three cover crops existed. Rapeseed and rye root counts were negatively related to soil strength by linear and power functions respectively, while FR roots showed either no (Exp.1) or positive (Exp. 2) relationship with soil strength." Soil penetration capabilities of three cover crops were: FR greatest; Rapeseed next; and Cereal rye least.

**Daigh et al., 2014.** "The objective of this study was to quantify potential differences in soil moisture due to the presence of a rye cover crop in a corn-soybean rotation at various locations … in Iowa and Indiana." "During the drought of 2012, soil volumetric water content (θ) and soil water storage (SWS) were monitored daily at three sites. Measurements of soil θ were taken at depths of 10, 20, 40, and 60 cm, and SWS was estimated to an 80-cm depth. Soil water during the drought of 2012 was affected by a rye cover crop in comparison to without a rye cover crop for one (i.e., located in Iowa) of the three sites monitored. At the Iowa site, soil θ was on average 0.041 and 0.033 cm3 cm-3 … greater at the 10 and 20 cm depths, respectively, … following termination of a rye cover crop than crops without a rye cover crop". Overall, the use of a rye cover crop in a corn-soybean rotation did not significantly lower soil water, but was expected due to low amount of rye cover crop growth/biomass.

**Dao, 1993.** AWC and other properties were studied as affected by moldboard, stubble mulch till and NT wheat on silt loam soils in the semiarid region of the southern Great Plains. The alterations in surface hydraulic properties of no till soil enhanced the conservation of stored water by reducing evaporation losses with the crop residue mulch. Decreased surface bulk density and the reduction in soil sealing and crust formation enhanced water infiltration into the no till soil, resulting in increased volumetric water-holding capacity and precipitation storage. In general, ZT (NT) with residue retained had higher soil moisture, even in the deeper layers (40 to 100 cm), than when residues were removed. The 0 to 20 cm stratum contained less water than the 20 to 40 cm layer.

**D'Haene et al., 2008.** A study of 18 silt loam soils over a variety of years showed that reduced tillage for crops such as beets and potatoes may or may not increase soil water at saturation over conventionally tilled fields.

**Glab and Kulig, 2008.** In a Luvic Chernozem* near Krakow, Poland "both, storage and residual pores were not affected by RT or CT tillage systems or mulching in the 0 to 10 and 10 to 20 cm depths." Yields under conventional tillage with and without mulch and reduced till with mulch were similar. Yields under RT without mulch was less than the other 3 treatments. "The main conclusion is that the mulching can help to avoid yield reduction in wheat production when reduced tillage is used." (Although not measured, the inference is that more water was retained for plant use with mulch applied).

**Gregory et al., 2005.** "In an unusually dry farming season on mainly Lester loams in Minnesota: conventional (continuous corn and deep tillage), rotation (5-year corn-soybean-oats/alfalfa-alfalfa-alfalfa rotation with tillage 2/5 years) and no till (corn-soybean with no cultivation) were studied for several soil property changes. Soil organic matter content was highest on the rotation farm, followed by the no till farm, and lowest on the conventional farm. Soil penetrometer resistance was lower and percent soil moisture was higher in the no till and rotation systems compared to the conventional farm. The conventional farm had the highest runoff volume per cm rain and higher nitrogen (N) loss in runoff when compared to the rotation and no till farms, as well as a higher phosphorus (P) flux in comparison to the no till farm. These results indicate that perennial close-seeded crops (such as alfalfa) used in crop rotations, as well as plant residue left on the surface of no till fields, can enhance soil organic content and decrease runoff thereby increasing water infiltrated into the soil. The lower soil penetrometer resistance and higher soil moisture on the rotation and no till farms show that conservation tillage can increase soil aggregation and water infiltration, both of which prevent erosion. In this unusually dry year crop rotation, and particularly no till … provided superior corn and soybean yields, most likely due to higher soil moisture as a result of greater water infiltration and retention associated with cover crops (rotation farm) and crop residue (no till farm)."

**Hubbard et al., 2013.** This 3-year study "assessed the effects of cover crops (and rotations) on soil physical properties and C/N relationships in sandy soils … of the southeastern (SE) U.S. 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." "Bulk density (BD), saturated hydraulic conductivity (Ks), and volumetric soil moisture content (WC) were evaluated in the top 7.6 cm." "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 WC." 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) U.S. coastal plain region." "Significant differences were observed in soil physical properties between the row and interrow. In general, the soil in the row had lower BD and greater WC than that of the interrow. Overall the study indicated that land managers should consider the inclusion of a late summer cover crop following sweet corn and that sunn hemp in particular provides substantial benefit."

**Haghighi et al., 2010.** In a loamy soil in a Mediterranean climate, AWC after 50 years dryland wheat farming sites were 29 to 33% lower than pasture sites at the 0 to 15 cm depth. The higher AWC in the pasture sites were noted to be due to high SOM, better structural properties, and higher porosity.

**Hoorman et al., 2011.** "At best, tillage may temporarily reduce soil compaction, but rain, gravity, and equipment traffic will re-compact it. A soil's vulnerability to compaction is largely a result of biological aspects: Living plants with active root systems, along with mycorrhizal hyphae, and the glue-like secretions of each, will significantly reduce compaction susceptibility. Year after year, this process can improve soil structure considerably and provide resistance to compacting forces. Thus, a continuous living cover and long-term no tillage management act together to reduce soil compaction occurrence. Tillage increases the rate at which oxygen is supplied to microsites in the soil, thus increasing aerobic bacterial populations which consume the carbon compounds that stabilize macro-aggregates. This leads to loss of soil structure. Soil compaction is the result of traffic (or the compressing forces of tillage itself) on moist soils where tillage has previously destroyed macro-aggregates. Rainfall also causes compaction where macro-aggregation has been depleted by tillage, due to flow of infiltrated water through the destabilized pores and voids, and also from raindrop impact onto barren, exposed soil."

**Hudson, 1994.** The increase in amount of SOM in any soil is highly correlated to the increase in AWC. In all textural classes studied (sand, silt loam, silty clay loam), increasing SOM from 1 to3 percent for the sand, and 2 to 4 percent for the silt loam and silty clay loam classes, increased AWC by 73, 45, and 47 percent respectively.

**Jabro et al., 2009.** "Effects of conventional (CT) and strip (ST) tillage practices … for irrigated sugar beet on gravimetric water content (θw), and other properties on … the soil surface and at 10 to 15cm depth … were studied at two sites, … one in North Dakota (Lihen sandy loam) and one in Montana (Savage clay loam)." "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." "Soil bulk density 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."

**Jabro et al., 2011.** "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 sugar beet was grown during the 2007 and 2008 growing seasons. Under each tillage system, ⋯ Pb and w were measured ⋯ in all plots at soil surface (0 to 10 cm) and 10- to 30-cm depths. Although it was "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 w did not differ significantly between CT and ST plots at both depths."

**Jemai et al., 2013.** AWC was significantly higher in a calcareous clay loam after 7 years of no till (NT7) across the 30-cm profile while after 3 years, NT3 and CT have similar effect to each other. Soil moisture content was improved at different soil depths by the NT system during the whole agricultural season and the highest content was found with NT3. Soil moisture values increased with increasing soil depth in both NT3 and NT7 indicating a good water infiltration induced by these treatments. "Hence, water storage properties in rooting zone could be enhanced by NT7 and NT3 but water availability for plants was more important with NT7."

**Jiang et al., 2007.** On claypan soils (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 to 10 cm depth. CRP retained the most moisture and had the highest K-Sat due to roots and bio-pores while MTCS showed the lowest K-Sat. All management systems had similar AWC values. CRP had the most porosity in all but the micropore (<10 um) range. 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.

**Joyce et al., 2002.** Winter cover cropping may improve rainfall infiltration and enhance soil water storage in areas such as California's Sacramento Valley, where the majority of precipitation occurs in the winter over a relatively short period of time in a series of heavy rainfall events. Enhanced soil water storage within the root zone on cover-cropped fields may reduce demand for irrigation of subsequent crops. A study was conducted in the winters of 1998-1999 and 1999-2000 to determine a field's ability to conserve water for subsequent crops and to evaluate the effects of soil physical conditions on the water balance for three 4-year rotation farming systems within the Sustainable Agriculture Farming Systems (SAFS) Project at the University of California, Davis. Rainfall, runoff, and soil water content data was collected on two treatments using a winter cover crop and one treatment maintained fallow during the winter. Runoff and soil water content measurements were significantly affected by farming systems. Cumulative event runoff from one 0.67 m2 infiltration test areas was consistently higher on the fallow treatment than on the cover-cropped treatments. Winter 1999-2000 field water content measurements from 0 to 1.05 m depth were significantly higher in the cover-cropped systems than in the fallow treatment after field capacity had been reached. A hydrologic model was developed using the measured data and lysimeter data for evaporation and evapotranspiration to track daily water budget components (i.e., runoff, infiltration, evaporation, evapotranspiration, and soil water storage) and to assess changes in surface hydraulic conductivity. Model simulations showed that optimized hydraulic conductivity decreased for all treatments with successive runoff, but was less pronounced in cover-cropped plots. The study indicated that cover cropping can improve soil water storage for subsequent crops if the cover crop is destroyed before the additional soil water is lost as evapotranspiration.

**Karlen et al., 1994.** AWC in the top 75 mm, was significantly different between the removal of residue and double residue treatments in a 10-year no till study. These changes paralleled changes in total soil carbon (organic matter) supporting Hudson (1994) that SOM is important in increasing available water capacity.

**Larney and Lindwall, 1995.** An 11-year study was initiated "on a sandy clay loam soil … (Typic Haploboroll*), mean annual precipitation is 402 mm and 1.8% organic carbon at the Agriculture and Agri-Food Canada Research Centre, Lethbridge, Alberta (semi-arid), … to investigate the performance of winter wheat under conventional, minimum and zero tillage in monoculture and in 2-year rotations with fallow, canola or lentils/flax." "Continuous cropping greatly depleted soil water reserves, resulting in some crop failures. Averaged over 10 years, available water for establishment of winter wheat in fall was least after canola (45 mm), followed by continuous winter wheat (59 mm), lentils/flax (74 mm) and fallow (137 mm)." "The effect of rotation on soil water was much greater than that of tillage. Zero tillage had little impact on available water to 1.5 m depth." However, after "6 to 7 years, available water in the O-15 cm depth under winter wheat in spring was greatest under zero tillage. Precipitation storage efficiency during the fallow year was generally unaffected by tillage system." Possible reasons for the lack of a tillage effect on soil water status in the fall … (i) similar water extraction by the preceding canola, lentils/flax and wheat crops, and similar water storage on the fallow plots, irrespective of tillage system; (ii) a narrow window between harvest of the preceding crops and seeding of the winter wheat crop (especially on the W-C and W-L/Fx rotations), which allowed insufficient time for tillage system to significantly affect soil water regime; and (iii) the nature of the CT treatment, which would be considered minimum tillage in more humid climates due to the shallow working depth of the heavy-duty cultivator (10 cm) and non-inversion of the soil."

**Li et al., 2008.** The computer simulation model PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques is one of the soil-crop models that integrate the dynamics of soil, tillage and crop processes at a daily resolution. This study had two major objectives. The first was to calibrate the use of the PERFECT soil-crop simulation model to simulate soil and crop responses to changes of traffic and tillage management. The second was to explore the interactions between traffic, tillage, soil and crop, and provide insight to the long-term effects of improved soil management and crop rotation options. This contribution covers only the first objective; the second will be covered in a subsequent contribution. This paper does convey results from the experimentation therefore providing relevant data. Data were obtained from field experiments on a Vertisol in Southeast Queensland, Australia which had controlled traffic and tillage treatments for the previous 5 years. Input data for the simulation model included daily weather, runoff, plant available water capacity, and soil hydraulic properties, cropping systems, and traffic and tillage management. The results showed that the PERFECT daily soil-crop simulation model could be used to generate meaningful predictions of the interactions between crop, soil and water under different tillage and traffic systems. Ranking of management systems in order of decreasing merit for runoff, available soil water and crop yield was (1) controlled traffic zero tillage, (2) controlled traffic stubble mulch, (3) wheeled zero tillage, and (4) wheeled stubble mulch.

**Liu et al., 2013.** This study found that in a loess silt loam under apple production, subsoiling and straw mulch (SS) treatment had the most significant effect on the soil structure and soil water content among the SS, NT-Straw and PTS treatments. The NTS treatment also increased the soil water content, although the effect of NTS was weaker than SS. However, NT decreased the soil water-holding capacity. Straw mulching is an effective practice for increasing the soil water-holding capacity and subsoil tillage and straw mulching may be optimal approaches for improving the soil water-holding capacity.

**Mobius-Clune et al., 2008.** In a 32-year study on a coarse-silty soil, corn stover removal decreased AWC in both CT and NT. There was a significant 23% increase in AWC under NT over CT where stover was retained for both systems but no significant difference where stover was harvested (samples represented the 5 to 66 mm depth).

**Mugdal et al., 2010.** This study compared various properties between a native prairie and a field that had been under cultivation for 132 years, the last 18 years in mulch till corn-soybean-grain sorghum. “On a volume basis (data adjusted for bulk density differences), the upper 20 cm … (similar clay contents) … showed the prairie site had 42% more SOM and 27% higher AWC than the cultivated site.”

**Mulumba and Lal, 2008.** “Long term field plots studied the effects of mulching on soil physical properties of a Crosby silt loam (Aeric Ochraqualf* or stagnic luvisol) soil in central Ohio. Treatments included mulch application at 0, 2, 4, 8 and 16 Mg ha-1 year-1 without crop cultivation. Soil samples from 0 to 10 cm depth were obtained 11 years after establishing the plots. Mulch rates significantly increased available water capacity by 18 to 35%, total porosity by 35 to 46% and soil moisture retention at low suctions from 29 to 70%. At high suctions, no differences in soil moisture content were observed between mulch levels. Optimum mulch rates of 4 Mg/ha for increased porosity and 8 Mg/ha for enhanced available water capacity, moisture retention and aggregate stability.”

**O’Dea et al., 2013.** This study found that replacing summer fallow practices with annual legumes as green manures (LGMs) may increase the sustainability of northern Great Plains wheat systems. Viability hinges on soil water use management and realizing biologically fixed nitrogen (N) benefits. Managing LGMs with first-flower stage termination and no till practices conserves soil water and that rotational N benefits can increase wheat grain quality. An on-farm assessment of no till LGM versus summer fallow-wheat rotations in north-central Montana was conducted. Soil water and nitrate (NO3) levels to 0.9 m (3 ft), potentially mineralizable N (PMN) to 0.3 m (1 ft), wheat yields, conservation potential, and producer adoption challenges were assessed at five farmer-managed, field-scale sites. “Compared to fallow, LGM treatment diminished mean wheat yield by 6%, … diminished grain protein by 9 g kg-1 when wheat was fertilized with N, and increased grain protein by 5 g kg-1 when wheat was unfertilized. Small soil water depletions in LGM treatments below fallow at wheat seeding (17%; 30 mm [1.2 in]) and near-record high rainfall during the wheat growing season (280 to 380 mm [11 to 14 in]) suggest that LGMs likely did not limit soil water available to wheat in this study.” “Results illustrated that farmers viably managed LGM soil water use with early termination and no till practices but that LGM adoption may be hindered by a lack of immediate wheat yield or protein benefits from legume-N and seed costs for LGMs. Appropriate incentives, management strategies, and yield benefit expectations (short versus long term) should be fostered to increase the adoption potential of this N-economizing soil and water conservation strategy.”

**Olness and Archer, 2005.** The affect soil organic carbon has on soil available water capacity depends on soil texture and the initial organic carbon content. Water content is mainly affected by soil organic matter and soil structure. “Because of the changing nature of the soil matrix (mineral-dominated to organic carbon dominated surfaces), the change in AWC ranges from about 2.5 to 5% per 1.0% change in organic carbon … in soils containing less than 2.5% organic carbon and less than 40% clay.”

**Raczkowski et al., 2012.** During an 8-year field study on two SE coastal plain sandy loams, the no till treatment developed higher bulk density, lower total porosity and macroporosity, but higher capillary porosity (microporosity) and water retention capacity (field capacity) than the conventionally tilled treatment.

**Raper et al., 1994.** “The soil condition resulting from a 5-year cotton-wheat double cropping experiment in a sandy loam Coastal Plain soil was investigated … using cone index and dry bulk density. Four tillage treatments including a strip-till (no surface tillage with in-row subsoiling) were analyzed. Besides benefits of maintaining surface residue, the strip-till treatment (with subsoiling) decreased cone index directly beneath the row, decreased surface bulk density, increased surface moisture content, decreased energy usage and increased yields. Controlled traffic was beneficial only when in-row subsoiling was not used as an annual tillage treatment.”

**Rawls et al., 2003.** The U.S. National Soil Characterization database and the database from pilot studies on soil quality as affected by long-term management was used to study the effects of SOC on AWC. “At low organic carbon contents, the sensitivity of the water retention to changes in organic matter content was highest in sandy soils. Increase in organic matter content led to increase of water retention in sandy soils, and to a decrease in fine-textured soils. At high organic carbon values, all soils showed an increase in water retention. The largest increase was in sandy and silty soils.” Results are expressed as equations that can be used to evaluate effect of the carbon sequestration and management practices on soil hydraulic properties.

**Reeves, 1994.** A review chapter on the benefits and negative aspects of cover crops and crop rotations. Biological, physical and chemical aspects are discussed covering wide geographical/environmental settings.

**Reynolds et al., 2007.** This study found that after a 13-year trial in a clay loam soil (Argiaquoll), NT did not have significantly different AWC than Moldboard plow (MP) treatment although SOC was 13% higher with NT. Neither treatment produced SOC in amounts to generate a favorable structural index of the soil texture studied. NT exhibited AWC of ~0.12 cm/cm; MP~ 1.3 cm/cm.

**Sharratt et al., 2006.** “The objective of this study was therefore to characterize infiltration, water retention, and saturated hydraulic conductivity of a soil 20 years after establishing tillage and straw management treatments in interior Alaska.” “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.” “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.” There was however, no difference in stored water between chisel till and disk tilled treatments and significantly less water in chisel till vs. no till plots.

**Singh et al., 1996.** “The hydraulic properties of an Orthic Black Chemozem (Typic Cryoboroll*) were studied under three tillage-residue systems in central Alberta - tillage after 9 y with straw incorporated (till+straw) or removed (till-straw) - and no tillage with straw on the surface (no till+straw) - were studied for 2 years. Measurements began in the 9th year of continuous barley. Plant-available water capacity differed among treatments only in the 0 to 2.5 cm layer, 7.8% less under NT-S than T-S due to differences in water retention at -1,500 kPa.” “The common similarity of the no till+straw and the till+straw treatments and their usual difference from the till-straw treatment, especially in the water transmission characteristics, indicate the importance of the return of residue to the soil. The influence of straw on soil hydraulic properties does not appear to depend on whether it was incorporated or not."

**So et al., 2009.** After 14 y of CT or NT of soybean-oats, in a silt loam over clay loam Ultisol, AWC increased 19% under NT while yields increased 28% (CT yields were greater than NT yields for the initial 4 years). SOM increased 102% under NT in the surface 20 cm.

**Sojka et al., 1997.** Much of New Zealand's agriculture integrates animal and crop production on poorly drained, easily compacted soils. Soil properties affecting forage oat (Avena satiua, cu Awapuni) establishment on land compacted by 15 years of CT might be influenced by various subsoiling and surface tillage combinations. Plots on a Moutoa silty clay (Typic Haplaquoll*) were paraplowed (P), deep subsoiled (V), shallow subsoiled (S), or were left as non-subsoiled controls (C). The surface 15 cm was surface-tilled (T) using a power rotary-tiller and firmed with a Cambridge roller or were not tilled (N). Oats were sown with a cross-slot drill. Subsoiling greatly reduced soil strength. Subsoiling without T continued to show improved profile cone index cumulative frequency 233 days after subsoiling. T reduced emergence from 142 to 113 plants per square meter and reduced yield from 5,318 to ,3679 kg ha-1. Forage yield increased from 3,974 to 4,674 kg ha-1 with subsoiling. Soil porosity, saturated and slightly unsaturated hydraulic conductivities (KSat and Km) and air permeability were highly variable but generally increased with subsoiling. Generally, subsoiling without T produced better soil conditions and oat crop performance than the prevailing practice of T without subsoiling.

**Stipešević and Kladivko, 2002.** Winter wheat cover crops were studied "under two Indiana soils in corn-soybean rotation under NT or CT (spring disking) systems." For 3 years, "winter wheat cover crop plots were split into 'early' (E) desiccated (3-4 weeks before planting), and standard (S), desiccated (within the week before planting)." "Cover crop treatments had higher soil moisture content in spring than control, with S wetter than E, except during 2001, where E treatment conserved soil water during early spring drought better than the other treatments. Both S and E cover crop treatments promoted better early maize growth than the control in five of six site-years." Early cover crop desiccation should be performed, thus gaining soil physical properties improvement "over no cover crop control, and at the same time, avoiding soil water overconsumption by additional cover crop growth on the standard cover crop treatment."

**Sundermeier and Reeder, 2011.** In this university extension publication, results of a study of Ohio corn and soybean plots were shown. "The long-term no pre-compaction, no till treatments did not have significant difference in yield compared to 10-ton compaction no till. However, the 20-ton compaction no till had significantly lower yield compared to 10 ton or no compaction no till. Subsoil tillage compared to No till had significantly lower yields in the corn and soybean plots for both 10-ton and 20-ton compaction. The disadvantage for subsoiling continues a trend of" 7 years. "Long-term No till may be able to withstand the compaction pressure due to improved soil structure compared to annual subsoiling. Subsoil tillage did not improve crop yields after compaction has occurred at 20-ton (full grain cart)." "Cover crop established in fall 2009 before corn planting in 2010 showed the benefits of compaction correction by significantly increasing corn yield compared to subsoiling with 20-ton compaction. Due to lack of fall 2009 cover crop plant growth, soybean yields did not respond to cover crop treatments." "The loosened soil structure created by subsoiling means that heavy axle loads that follow, even months or years later, may compact the soil and reduce yields. Repeating the subsoiling treatment after intentional compaction did not correct the problem." "Late fall subsoil tillage may not be the best time to perform compaction correction, due to wet soil. Planning to subsoil after wheat harvest instead means that soil is more likely to be drier and conducive to good shatter. Research was not conducted to make this comparison."

**Teasdale and Mohler, 1993.** A study of cover crop residue thickness on weed suppression, soil temperature and moisture showed that residue prevented the decline of soil water content during droughty periods. “Reductions in light transmittance and daily soil temperature amplitude by cover crop residue were sufficient to reduce emergence of weeds but that maintenance of soil moisture could increase weed emergence.”

**Tomer et al., 2006.** “Soil properties and water contents (µ) vary spatially, but management effects on spatial patterns are poorly understood. This study’s objective was to compare surface-soil properties and µ in two small watersheds (30 to 43 ha) in Iowa’s loess hills. Both watersheds were in continuous corn from 1972 through 1995, one (CW1) under conventional tillage and the other (RW3) (pasture until 1971) under ridge tillage. In 1996, CW1 was converted to no till (no cover crop). Surface-soil (0 to 0.2 m) samples were collected along hillslope transects during 2002 and 2003, including four dates with water-content measurements by gravimetry in both watersheds. Soil bulk density (rb), organic carbon (OC), and texture were determined, along with terrain attributes (elevation, slope, surface curvature, contributing area, and wetness index). After accounting for landscape-position effects, RW3 had more OC (2.1 versus 1.7%) and smaller rb (1.16 versus 1.25 Mg m-3) than CW1. Larger µ values occurred in RW3 when µ was >33%. Landscape position and terrain attributes better explained variation in µ in RW3 than CW1. Also, OC was correlated with µ in RW3, but not in CW1. Soil textures were similar (within 2%) but finer in CW1. Pedotransfer functions confirmed that differences in soil properties between watersheds resulted in greater µ in RW3 than CW1, particularly at low soil-water potential, and that more distinct patterns of µ should occur in RW3. Results indicate prior long-term conventional tillage in CW1 affected soil properties and water-holding characteristics in ways that decreased water retention and muted spatial patterns of µ.”

**Unger and Vigil, 1998.** Cover crops can have positive, neutral, or negative effects on the soil water for the next crop. The effect is negative when not enough time is available after termination to recharge soil water before the next crop or when the greater infiltration and reduced evaporation aggravate an overly-wet soil condition. In general, “cover crops are more suited for use in sub humid to humid regions than in semi-arid regions.” “In sub humid to humid regions, cover crops can be terminated or removed (by haying or grazing) to provide time to recharge the soil water supply for the next crop. In semiarid regions, cover crops often reduce yields of subsequent crops because of reduced soil water supplies.” “Use of conservation tillage with residue maintenance has improved water conservation and crop yields, and has provided benefits similar to those obtained with cover crops, except for N fixation with legumes, uptake of soil nutrients (nitrates) to prevent their leaching, and provision of additional organic matter to improve soil conditions.”

**USDA NRCS, 2017.** Conservation Practices Standards specific to your area can be found by visiting your local USDA Natural Resources Conservation field office.

**Vepraskas, 1995.** This 3-year “study compared longevity of slit-till and subsoiling compared to no till vs. corn grain yield and root development … in a Norfolk loamy sand (Typic Kandiudult*) with a tillage pan.” Pan penetration resistance was not measured but bulk density was. Two years had sufficient rainfall and one year did not. Even though there was root penetration for 2 years along shank and slit openings, there was no significant difference in yield between treatments in any of the 3 years.

**Villamil et al., 2006.** 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) were evaluated for … total porosity (TP), pore-size distribution, water retention and other properties. Compared with winter fallow, crop sequences that included winter cover crops provided substantial benefits from the soil productivity standpoint. “C-R/S-V or C-R/SVR increased SOM down to 30 cm.” WCC sequences increased total and storage porosity along with plant available water.

**Ward et al., 2012.** In Mediterranean environments with hot dry summer periods, maintaining ground cover can be difficult, as these periods are generally too arid for plant growth. The use of cover crops, grown solely to increase ground cover and not harvested for grain or biomass were studied on 2 soils, one sandy and the other finer textured. Examined was the impact of cover crops and residue retention on evapotranspiration, both over the summer fallow period and during the winter and spring crop growth period. In contrast to previously published research, cover crops and residue retention were found to have limited impact on total evaporation during the summer and autumn period, although there were occasional short-term impacts on the rate of evaporation shortly after rainfall. There was also limited evidence of changes in evaporation during early crop growth. The inclusion of cover crops in farming systems in regions with a Mediterranean climate is unlikely to have major impacts on the water balance, but may still increase overall sustainability of the farming system.

**Zentner et al., 2003.** This article assessed the use of annual legume green manure crop (LGM) as a partial-fallow replacement in western Canada to protect the soil against erosion and increase N fertility, particularly when combined with tall wheat stubble left to trap snow to replenish soil water used by the LGM. Yields, N use efficiency, water use efficiency, and economic returns for hard red spring wheat (W) grown in rotation with Indianhead black lentil a green manure (LGM-W-W) vs. a traditional F-W-W system were compared. “The study was conducted over 12 years (1988 to 1999) on a medium-textured soil near Swift Current, Saskatchewan.” Wheat stubble was left tall to trap snow, tillage kept to a minimum, and the wheat was fertilized based on NO3 soil tests. After 6 years, it was concluded that waiting until full bloom to turn down the legume (usually late July or early August) to maximize N2 fixation was too late and utilized too much soil water hurting wheat yields. After 1993, LGM turndown was changed to an earlier date resulting in equal wheat yields following a LGM to those after fallow (due to improved water use efficiency). Results suggest that the use of LGM cover crops to replace fallow can be a viable option in this region.

## Citations

Full literature citations are available at:
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