Assessment of Effects of Long Term Tillage Practices on Soil Properties in Ohio

THESIS

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Abstract

The demand for food is expected to rise due to increases in world populations over the next decades. The use of heavy machinery to meet this demand for food is expected to increase as well. Additionally, soil compaction is recognized as a major concern in agriculture dependent on the use of heavy machinery. Soil compaction has been shown to negatively impact crop production, which may occur because of overuse of heavy machinery used in tillage operations, sowing, harvesting, and manure and fertilizer applications. Soil compaction also affects physical, chemical and biological processes occurring in the soil including the mineralization of soil organic carbon and nitrogen.

Long-term experiments that include tillage and crop rotations are necessary to understand the impact of soil management practices on soil properties. Tillage practices (plow tillage-PT; minimum tillage, MT; and no tillage, NT) and crop rotations (continuous corn-CC and corn-soybean-CS) effects on soil compaction and carbon and nitrogen were studied in the long-term Triplett-Van Doren plots which are part of the Ohio Agricultural Research Development Center (OARDC). These plots are experimental sites located in northeast Ohio (Wooster) and northwest Ohio (Hoytville). These plots are the longest experimental sites maintaining no-till crop production in the
temperate zone. At the Wooster site, a well-drained Wooster silt loam soil (mixed, mesic, Typic Fragiudalf) was studied and at the Hoytville site, a poorly drained Hoytville silty clay loam (fine, illitic, mesic Mollic Epiaqualf).

The data on bulk density ($\rho_b$), water retention curves (WRC), pore size distribution (PSD), adjusted penetration resistance (APR), organic carbon (SOC) and total nitrogen (TN) across all crop rotations and tillage practices treatments were analyzed by site and depth, using the General Linear Model (GLM) in SAS to determine tillage treatment and crop rotation main effects and their interactions.

The results from this study shows there were significant tillage and crop rotations treatments effects on soil physical properties. Compaction effects on pore size distributions under different tillage systems, varied by site due to differences in soil texture and climate. A tillage main effect was observed at both sites for adjusted penetration resistance (APR), where APR increased with soil depth. At the Wooster site where higher APR, BD, and amount of water storage was observed versus transmission pores for PT than NT were observed. At the Hoytville site, NT had higher APR compared to MT and PT for the early and middle sampling and no differences were observed at the late sampling.

This study also showed that the use of long-term NT practices effects on SOC and TN varied by site. At the Hoytville site, a tillage main effect was observed with higher SOC and TN associated with NT than MT and PT. No significant differences were
observed between tillage treatments at Wooster. At both sites, crop rotation effect was not significant for SOC and TN; although trends did show CC had higher SOC and TN compared to CS.
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Chapter 1: Introduction

The demand for food in the last decades has increased as the world population increases. The use of heavy machinery to cover the demand for food has increased as well (Mehta and Gross, 2007; FAO 2015). Modern agricultural practices used in intensive cropping to increase food production play an important role on soil deterioration. More than 115 years ago Wollny (1898) described the beneficial effects of a good soil structure to both the soil itself (soil strength) and plants (root growth, gas transport, and water availability), and mentioned that further research needed to be done on the interaction between soil structure and plant growth. By then, research was focused on achieving the increase of crop yields and environmental problems were not a priority; however, it was known that soil compaction had negative effects on the crops (Horn et al., 1995). Since then much research has been done confirming the favorable effects of good soil structure and the adverse effects of soil compaction on the soil (Horn et al., 1995; Soane and van Ouwerkerk, 1995; Flowers and Lal, 1998; Hamza and Anderson, 2005), and more concern and attention is being raised to study the factors causing soil degradation on agricultural soils.

Soil tillage is one of the most influential manipulations of the soil, for instance it alters soil physical properties due to its occurrence, the depths this practice can reach and
the intensity of plowing (moldboard plow, disc plow, chisel plow) (Strudley et al., 2008, Alvarez and Steinbach, 2009). Tillage is typically done by plowing of the soil to control weeds and preparation for future seeding. This practice can lead to reduced infiltration (causing soil erosion and runoff) and increased surface sealing (Connolly et al., 1997). In contrast, the most extreme form of conservation tillage (a practice where at least 30% of plant residue is left on the soil surface) is known as no-tillage. In the no-tillage (NT) practice, minimum disturbance is applied to the soil, other than seeding and fertilizer applications, and plant residues are left on the soil surface. Kassam et al., (2009) estimated that 106 million ha are under conservation agriculture (CA) systems and that in the places CA has been adopted, positive results in agriculture and the environment have been observed. Friedrich et al. (2009) defines CA as a system to save resources in agricultural crop production, focus on environment conservation by enhancing natural occurring processes. Even though NT has been around for a while and despite the benefits, farmers seem to be resistant to the idea of changing from the practices they have used for years (e.g., overturning the soil to get a soft medium for better crop growth) (Lampurlanés and Cantero-Martínez, 2003). No-tillage provides multiple benefits to the soil including; minimizing run-off, maximizing water infiltration, reducing labor input,
recycling nutrients, increasing the rate of biomass production and minimizing the oxidation of soil organic matter and CO₂ loss (Friedrich et al., 2009; Kassam et al., 2009).

Anthropogenic soil compaction caused by heavy machinery traffic in agriculture is a well-recognized problem that can be detrimental to plant growth and production (Håkansson et al., 1988; Flowers and Lal, 1998; Chan et al., 2006; Hamza and Anderson, 2005; Li et al., 2007). Vehicular traffic is the main cause for compaction-induced soil degradation, which by 1998 covered 68 million hectares of land in the world (Flowers and Lal, 1998). Heavy vehicle traffic causing degraded soils cover an area of about 33 Mha in Europe, accounting for approximately 50% of the physically degraded soil of the world (Oldeman, 1992; Horn et al., 1995). Gupta and Allmaras (1987) defined soil compaction as the compression of the unsaturated soil mass. Soil texture, organic matter and water content, antecedent ρ₀, vehicle weight, speed, tire pressure, and number of passes all play an important role in contributing to soil compaction (Murphy et al., 2000; Miller et al., 2002; Sillon et al., 2003; Tarawally et al., 2004). Different methods can be used to detect the degree of compacted soils including measurements of soil bulk density (weight per volume, units of soil solids and water), penetrometer resistance (simulates the resistance a root would experience to elongate through a soil matrix), permeability to air or water, and image analysis of thin sections. Soil compaction is not only detrimental to
agriculture but also to the quality of the environment. Soane and van Ouwerkerk (1995) described how soil compaction has negative effects on different environmental aspects including gases (CO₂, CH₄, N₂O), surface waters (runoff from agricultural land), groundwater (nitrate moving from arable land), and biology (change in habitat for biota). It is well known that soil management practices, land use and cropping practices have an impact on soil carbon sequestration (Soane and van Ouwerkerk, 1995; Guzmán et al., 2006; Six et al., 2000; Lal, 2004) through carbon input and losses. Research has shown favorable effects on soil organic carbon (SOC) storage and total nitrogen (TN) when NT practices are used compared to conventional tillage (Dick, 1983, Lal, 2004, Kumar et al., 2012), due to the breakdown of the soil structure under conventional tillage. A well aggregated soil protects soil organic carbon (SOC) from microbial activities (Six et al., 2000 a and b).

Long-term experiments that include tillage and crop rotations are necessary to understand the impact of soil management practices on soil properties. The research presented in this thesis focus on two long-term experimental sites located at the OARDC (Ohio Agricultural Research Development Center) in Hoytville and Wooster. These two sites have similar climates but distinctive soil properties, and are the longest NT plots, 50 and 51 years in Hoytville and Wooster respectively, in the temperate region of the world.
which have been maintained and monitored (Figure 1.1 and 1.2) (Dick et al., 1991). The research presented on this thesis focuses on the evaluation of long-term agricultural management practices (tillage and crop rotation) on soil compaction, SOC and TN, and adds significant information to previous research done at these same sites (Dick, 1983; Dick et al., 1991; Dick et al., 1998, Kumar et al 2012a and 2012b).
Figure 1.1 Chronology of the experimental site in Wooster.

- 1962: Converted to agricultural land
- 1967: N, P, K started to being broadcast applied in the spring prior to tillage
- 1968: Corn row width changed to 75 cm
- 1977: Soybean row width changed to 38 cm
- 1987: Chisel plow started to be use in minimum tillage
- 2013: Soil samples were collected
- 2014: Converted to agricultural land

Replicate, Rotation, Tillage:
- Replicate: Corn-corn (1), corn-soybean (2), corn-oats-meadow (3)
- Rotation: Conventional tillage (1), minimum tillage (2), no-till (3)
Figure 1. 2 Chronology of the experimental site in Hoytville.

- Converted to agricultural land
- N, P, K started to being broadcast applied in the spring prior to tillage
- Corn row width changed to 75 cm
- Soybean row width changed to 75 cm
- Chisel plow started to be use in minimum tillage
- Rep, Rotation, Tillage: Corn-corn (1), corn-soybean (2), corn-oats-hay (3); moldboard plow (1), minimum tillage (2), no-till (3)
- Soil samples were collected

- 1963
- 1967
- 1968
- 1977
- 1987
- 2013
- 2014
Chapter 2: Effect of long-term tillage practices and crop rotations on soil physical properties

2.1 Abstract

Soil compaction is a serious form of soil degradation. Long-term experiments are essential to determine the impact of agricultural management practices, such as tillage systems and crop rotations on soil compaction. Soils samples were obtained from the Triplett - Van Doren plots located near the cities of Hoytville and Wooster, Ohio. Soil penetration resistance (SPR) was evaluated on two contrasting soils under long-term (50-51 yr) tillage practices. Soil bulk density ($\rho_b$) and penetration resistance where evaluated for both sites, and water retention curves (WRC) and pore size distribution (PSD) were evaluated at the Wooster site. Treatments consisted of tillage practice: no-till (NT), moldboard plow (PT) and minimum tillage (MT); and crop sequence: corn-corn (CC) (*Zea mays*), corn-soybean (CS) (*Glycine max*) rotation. Soil samples were collected at 0-10, 10-20 and 20-30 cm depths. Our objective was to determine the effect of long-term tillage and crop rotation on soil compaction. Soil penetration resistance was measured by using a static cone penetrometer. Soil water retention was measured at different matric potentials from 0 to -1500 kPa.
There were significant tillage treatment effects on adjusted penetration resistance (APR) for both sites but varied by sampling date. Our results show a higher APR at 20 cm in Wooster indicating a plow pan. At Hoytville, NT was significantly higher (p<0.05) in the early sampling but no differences between treatments were observed in the late sampling. Results show differences in $p_b$ due to tillage practices. In general, $p_b$ in Wooster increased for all treatments with depth and NT had higher $p_b$ compared to MT and PT and no differences were observed for crop rotation. Differences in water retentions by tillage treatments were observed at the 0-10 cm soil depth. At the soil surface in the Wooster soil, for 0 and -1 kPa, the volumetric water content was not significantly different among tillage treatments. However, significant differences were observed under -3,-5,-10,-33, and -1500 kPa, where NT was higher compared to MT and PT. Under 20 cm soil depth, no significant differences were observed among tillage treatments or crop rotation treatments. There were significant tillage treatment effects (p<0.05) on pore size distribution at the Wooster site at 0-10 and 10-20 cm soil depths. However, no differences between crop rotations were observed. The majority of the pores for all tillage systems occurred in the 0.2-30 $\mu$m size range. Additionally, this is also where the largest differences in pore distribution among tillage systems occurred.
2.2 Introduction

The use of heavy agricultural machinery to aid in food production to meet a growing world population has intensified in the past few years. Soil compaction that can negatively impact crop production may occur because of tillage operations, sowing, harvesting, and manure and fertilizer applications. The Soil Science Society of America (1996) defines soil compaction “as the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density.” Many studies have found a reduction in crop yields due to compaction, altering soil physical properties and process (Van Doren, 1959; Gill, 1971; Lowery and Schuler, 1991). Flowers and Lal (1998) estimated that there are 68 million hectares of compacted soil worldwide from vehicular traffic alone, making soil compaction a major concern (Soane and Van Ouwerkerk, 1994).

Soil compaction has been acknowledged as a serious form of soil degradation (Soane and Van Ouwerkerk, 1994; Akker and Canarache, 2001; Hamza and Anderson, 2005). Signs of soil degradation may not be evident on the surface, making recognition difficult (Hamza and Anderson, 2005). In intensive agriculture, inappropriate soil management along with the use of heavy machinery and intensive cropping/grazing are common causes of soil compaction (Hamza and Anderson, 2005; Jung et al., 2010); the
The use of heavy machines and farm animals being the major source. The degree or extent of compaction controls the soil’s capacity to store and transport water and air (Hamza and Anderson, 2005). An increase in compaction leads to higher bulk density, and decreases water infiltration and air movement (Allmaras et al., 1988). Flowers and Lal (1998) reported that the depth of compaction can range from 10-60 cm, significantly impacting root penetration and development (Jung et al., 2010). Anderson and Cassel (1984) showed a negative correlation between bulk density and depth to the B horizon, indicating that compaction due to machinery may reduce the topsoil depth. Kayombo and Lal (1994) showed that the optimum range of soil bulk density may be different among soils and crops grown.

Wagger and Denton (1989) observed an interaction between soil compaction by vehicular traffic and tillage methods. Soil bulk density was found be to higher in trafficked areas compared with the no-trafficked zone in corn under no-till. Mestelan (2008) found that in Ap soil horizons at Wooster and Hoytville, Ohio, NT plots display lower bulk density values and increased highly connective macroporosity compared to PT plots. Raper et al. (2000) found that for claypan soils, cover crops increased soil compaction, but cover crops did not affect soil compaction in non-claypan soils. Hamza
and Anderson (2005) suggest that a lack of organic matter can exaggerate the compaction of a soil.

The pore space inside and between soil aggregates is reduced by compaction as the spatial arrangement, size and shape of the aggregates are altered (Defossez and Richard, 2002). Soil texture plays a major role in creating restricting conditions for root growth (Table 2.1). Soils that have coarse texture have been shown to be less subject to compaction (Tirado-Corbalá and Slater, 2010). Light-textured soils had fewer tendencies for compaction than heavy textured soils (McCormak, 1987). Thus, persistence of the compaction effects lasts longer on clayey than on light-textured soils. Lal (1996) observed severe reduction in crop yields due to axle load treatments by heavy agricultural machinery traffic for a poorly drained silty clay loam. The adverse effect caused by soil compaction on crop yield persisted for at least 7 years. However, in a study by Lal and Ahmadi (2000) with a well-drained silt loam, 11 consecutive years of axle-load treatments had no effect on the bulk density of the soil surface.

Bulk density is the most frequently used parameter to assess soil compaction (Panayiotopoulos et al., 1994). Other measurements include soil porosity, soil strength (Canarache, 1991), and water infiltration rate (Hamza and Anderson, 2003). Soil strength is the ability of the soil to resist an applied stress without experiencing failure or
deformation, and it is commonly measured using a penetrometer (Soil Survey Division Staff, 2013). The soil’s capacity to resist penetration by a rigid object is used to assess soil compaction. Soil strength measurements, using a penetrometer, are used to assess the soil’s resistance to root penetration (Panayiotopoulos et al., 1994; Hamza and Anderson, 2005; Dexter et al., 2007). Penetrometer resistance is closely related to the effects of soil strength on crop growth. Soil penetration resistance is measured in units of pressure (also called the cone index) and is defined as the force per unit cone basal area required to push a cone penetrometer through a specified increment of soil (SSSA, 1997; ASABE, 2008). Soils can be classified into broad groups by penetration resistance (Table 2.2). Generally, the cone index increases when soil compaction and bulk density increase (Canarache, 1991). However, the cone index measurement is also strongly affected by clay and water content (Elbanna and Witney, 1897). The relationship between penetration resistance and root growth has been studied, showing that crop yields and root soil penetration are negatively affected by resistance > 2 MPa (Taylor and Gardner, 1963). Silva et al. (2000) observed in NT system values beyond 2 MPa that is the critical value that restricts root penetration.

The most important factor influencing soil compaction is soil moisture content (McCormak, 1987; Soane and Van Ouwerkerk, 1994). Interaction between moisture
The soil-water retention curve (SWRC) relates the matric potential with the volumetric soil water content and is an important soil physical description for assessing...
soil-water interactions, water transport, and mechanical strength. Water retention curves (WRC) are essential for understanding the hydrologic behavior of the vadose zone. The WRC can be divided into three regions: the air entry region, the capillary region and the adsorption region (Jury and Horton, 2004). The air entry region describes the matric potential needed to begin removing water from the large pores. The capillary region is when the small pores start to drain after air enters the soil. The adsorption region is the range of matric potentials where only tightly bounded water remains in the soil. The shape of these curves varies depending upon texture, structure, compaction and porosity. No-tilled soils generally display a higher continuity of soil pores than plowed soils (Ball, 1981), giving them distinctive retention curves.

The objective of this project is to evaluate the long-term impact of tillage practices combined with crop rotation sequences on soil compaction. Agricultural soils under different tillage practices (NT, MT and PT) and crop rotations (CC and CS) were characterized to assess changes in soil physical properties related with soil compaction and water retention.
2.3 Materials and Methods

2.3.1 Study Area: Soils and Climate

Field studies were conducted at two locations: the Ohio Agricultural Research Development Center (OARDC) Triplett-Van Doren experimental plots in Wooster (northeast Ohio, 40°45’N, 81°54’W) and Hoytville (northwest Ohio, 41°13’N, 83°45’W) to examine the effects of tillage treatments (no-till-NT, minimum tillage-MT and moldboard plow-PT) and crop rotation (corn-corn-CC and corn soybean-CS) on soil physical properties. These plots are the longest experimental sites maintaining NT crop production in the world. Numerous research papers have been published with information regarding climate, crop yields, soil, and the history of the plots for both sites (Dick et al., 1986a and b; Dick et al. 1991; Dick, 1997a and b). The experiments at both locations were established to study the impact of long-term tillage and crop rotations on soil properties and agronomic productivity (Dick et al., 1991).

a. Hoytville

The plots located in Hoytville were established in 1963 (Dick et al, 1991). Soil at the Hoytville site belong to the Hoytville series (fine, illitic, mesic Mollic Epiaqualf), a silty
clay loam soil developed in glacial lacustrine deposits (USDA-SCS, 1973). This soil series is classified as very poorly drained and having a slow to moderately slow permeability. Hoytville soils are usually formed on zero to one percent slopes. To remove the excess water, tile drainage systems were installed (Dick et al., 1986a; Dick et al., 1991). The mean annual air temperature at Hoytville is 9.5 °C (Dick et al., 1998). The majority of the precipitation occurs during the warm season (spring and summer months) (Dick et al., 1991). The approximate annual precipitation for Hoytville is 845 mm (Dick et al., 1986a, Dick et al 1998).

b. Wooster

The plots located in Wooster were established in 1962 (Dick et al, 1991). Soil at the Wooster site is a Wooster silt loam (fine-loamy, mixed, active, mesic Oxyaquic Fragiudalf), which is classified as well drained soils. This soil contains a fragipan at a depth of 50-90 cm (USDA-SCS, 1984). The parent material is low-lime glacial till. The mean annual air temperature at Wooster is 9.1 °C (Dick et al., 1998). The approximate annual precipitation for Wooster is 905 mm (Dick et al., 1986b, Dick et al 1998). In some years in Wooster, during the months of June and July, short lasting intense storms lead to severe soil erosion (Dick et al., 1991). However, the amount of precipitation received in Wooster during the summer is not always enough to fulfill the plant water needs for
maximum crop yields and plants can suffer of water stress (Dick et al., 1986 b; Dick et al., 1991).

2.3.2 Experimental setting

The Ohio Agricultural Research Development Center (OARDC) Triplett-Van Doren experimental plots in Wooster and Hoytville have the same experimental design. The soils have been subjected to tillage treatments (continuous no-till- NT, minimum tillage- MT and plow tillage- PT) combined with crop sequences (continuous corn - CC, corn soybean- CS) since 1962 in Wooster and 1963 in Hoytville (Dick et al., 1991). The combination of the tillage systems and crop rotations treatments are replicated three times according to a randomized complete block design with factorial arrangement. The three tillage systems and the two crop rotation combinations are applied each year. Under the NT system, the only soil disturbance performed is the planting of seeds directly into the previous year’s crop residue with a coulter-type planter. The MT treatment involved the use of a chisel plow to a depth of 20 - 25 cm, without any soil inversion. The chisel plow, with 5 inch wide blades spaced at 15 inches, tills a third of the soil area and lifts that soil on top of the undisturbed soil. One pass with a field cultivator to prepare a seedbed is performed if the soil conditions are ideally (dry enough) when the chisel plow is used. If
this condition is not present (soil wet) then the disk is used to break down this plowed soil before the field cultivator is used. The minimum tillage practices do not qualify as conservation tillage because even though plant residues remains on the soil surface, it is usually less than the 30% normally required for conservation tillage. The PT treatment was performed once during spring at Wooster and during fall at Hoytville. This management involves the use of a moldboard plow at 20-25 cm depth. In addition, two or more secondary tillage treatments are performed at 10 cm depth for seedbed preparation in the spring. These secondary tillage treatments include a disk harrow to break down the plowed soil which permits a finishing tool to prepare a seedbed. The finishing tool is a field cultivator and consists of S-tines followed by a leveling bar, followed by a rolling basket. Research plots at Wooster are 22.3 x 4.3 m and 27.4 x 6.1 m at Hoytville. Tile drains have been installed at the Hoytville site at 17 m spacing. Detailed agronomic practices for both locations can be found in Dick et al. (1986a and b) and Dick (1997a and b).
2.3.3 Soil Sampling

a. Penetration Resistance and Soil Moisture

The data collection was divided in two stages.

Stage 1

An initial survey was conducted to determine appropriate sampling locations and number. This first stage was conducted using a cone penetrometer to assess the variability in soil compaction across the fields among and between the two management systems. Soil strength was measured using a static cone penetrometer (Bradford, 2002). Soil moisture content was measured at the same time. A transect was set up in each treatment plot, along which PR was measured. Resistance was measured using the cone index in kPa, defined as the vertical force applied to the penetrometer cone divided by its horizontally projected area (SSSA, 1997). A Field Scout SC 900 soil compaction meter was used. As penetrometer measurements are influenced by soil moisture content measurements were taken at each sample location in conjunction with PR measurements.

After the resistance measurements were corrected for moisture content (Busscher et al., 1997), an analysis of variance (ANOVA) was performed to select an appropriate number and distribution of sampling points. Using the pooled sample variance from the
analysis, an appropriate sample number for the second stage was calculated using Equation 1:

\[ n = \frac{1.96^2 s_p^2}{d^2} \]  

Eq. 1

Where \( n \) is estimated sample number needed to observe results with 95% confidence, \( s_p^2 \) is the pooled sample variance and \( d \) is the desired margin of error.

Stage 2

Based on the first stage information, a more thorough sampling was conducted measuring PR and soil moisture content. Five soil strength measurements were done in each plot and three soil samples were collected for moisture content determination in Wooster and Hoytville. Soil penetration resistance was determined at 2.5 cm increments to a depth of 40 cm. The sampling was done during June and August 2013 and August and October 2014 in Wooster and during May, July and November 2013, and September, 2014 in Hoytville. Sampling performed in May and June were classified as early season. Samplings performed in July and August were classified as middle season. Sampling performed in August 2013 was classified as middle 1 and August 2014 as middle 2 for
Wooster. Samplings performed in September, October and November were classified as late in the season. Sampling performed in November 2013 was classified as late 1 and sampling performed in September 2014 was classified as late 2 for the Hoytville site. Table 2.4 shows planting dates for corn and soybean at both sites. A Field Scout SC 900 soil compaction meter was used to determine soil PR. Soil moisture content was measured at the same time. Three soil samples were collected from each plot for moisture determination into moisture tins that had been labeled and weighed. The tins with soil were weighed and put in the oven at 105º C until a constant weight had been obtained. The dry weights of the soil were recorded and the moisture content was calculated. Penetration resistance was adjusted for moisture content (APR) using equation 3 by Busscher et al., (1997) to reduce confounding effects of soil gravimetric water content at time of measurements.

\[
PR = aW^b
\]

Eq. 2

where PR is in MPa, W is water content on a dry weight basis in g g^{-3}, and a and b are empirical parameters that were calculated (Busscher et al., 1997). Corrections of PR for differences of water content were based on a first Taylor series expansion:

\[
A-SPR = SPR_o + \frac{dc}{dw} (W_c - W_o)
\]

Eq. 3
where A-SPR is in MPa, SPR<sub>o</sub> was the original PR, W<sub>c</sub> is the common water content to which the SPR is being corrected, W<sub>o</sub> is the original water content, and dC/dW was the slope of equation two. At time of PR measurements, average soil gravimetric water content throughout the whole soil profile depth at both sites was 0.27 g g<sup>-3</sup>, thus the usage of W<sub>c</sub> value.

b. Bulk Density

Undisturbed soil core samples of a 5.4 cm diameter and 6.4 cm length were collected for the 0-10, 10-20 and 20-30 cm soil depths from the long-term tillage plots in Wooster in October 2014 to determine bulk density (ρ<sub>b</sub>). Bulk density was determined using the core method (Blake and Hartge, 1986). Bulk Density was assessed by collecting two cores from each plot, one between crop rows and one in the crop row. The soil cores were oven dried at 105°C. Bulk density was calculated by dividing the oven dried soil weight by the core volume.

c. Water Retention Curves

Water retention curves (WRC) describe the relationship between soil matric potential and gravimetric water content. Undisturbed soil core samples of a 5.4 cm diameter and 6.4 cm length were collected for the 0-10, 10-20 and 20-30 cm soil depths from the long-term tillage plots in Wooster in October 2014 to determine WRC. The soil
WRC was determined for the 0 to 30 cm depth for each 10 cm soil layer. The methodology described by Klute (1986) was used to determine the WRC. The undisturbed soil core samples were saturated with water for 48 hours. The cores were placed on a tension table that was connected to a water reservoir. The water level from the reservoir was lowered to obtain three different moisture tensions (1, 3 and 5 kPa). The soil cores were weighed when a steady state was reached and no water was draining from the reservoir. The samples were then placed on pressure plates at three different moisture tensions (10, 33 and 1,500 kPa) and weighed once a steady state was reached and no water was draining from the pressure pot. Gravimetric water content for the 1,500 kPa was converted to volumetric water content using the measured bulk density. The available water holding capacity was determined by the difference between the moisture content at 33 kPa suction and 1,500 kPa pressures.

d. Pore Size Distribution

Pore size distribution was calculated from the WRC data. The capillary rise equation was used to estimate effective pore size classes (Jury et al., 1991). The data on pore size was divided into three groups (transmission, storage and residual). Transmission pores are the pores that normally drain under gravity and allow free air and water movement
and root growth (Greenland, 1977). For this research transmission pores are in the four size ranges of: >1182, 295-1182, 99-295, 59-99 µm. After the pores larger than 50 µm have drained, the remaining water corresponds to field capacity (FC, Greenland, 1977). Those pores are classified as storage pores. For this research storage pores are in the size range of: 30-59 and 0.2-30 µ m. Residual pores are the pores that hold the water and wilting of plants occurs (Greenland, 1977). For this research residual pores are in the size range of: <0.2 µ m.

2.3.4 Statistical Analysis

The data on bulk density, water retention curves, pore size distribution, and penetration resistance across all crop rotations and tillage practices treatments were analyzed by site and depth, using the least squares means statement in General Linear Model (GLM) module of SAS (version 9.3, SAS Institute, Cary, NC) to determine tillage treatment and crop rotation main effects and their interactions (SAS 2015). Mean separation was determined using the PDIF procedure and statistical differences were declared significant at $P \leq 0.05$ level.
2.4 Result and Discussion

2.4.1 Penetration Resistance and Soil Moisture

a. Wooster

Since soil water content strongly influences PR (Hamsa and Anderson, 2005), PR measurements were adjusted (APR) to a common value of soil gravimetric water content to reduce confounding effects of soil gravimetric water content at time of measurements by using Eq. 2. There were significant tillage treatment effects on penetration resistance (APR) in the silt loam soil but varied by sampling date. During early sampling (Figure 2.5), APR in NT was significantly higher compared to PT at 0-10 cm soil depth (p=0.02). At 12.5, 15.0 and 17.5 cm there were no differences (p=0.06, 0.09, 0.6, respectively) observed among the two tillage treatments. Below 17.5 cm to 40 cm soil depth, the reverse was true and PT was always significantly higher compared to NT (p<0.05). The APR in general increased with soil depth, with the lowest PR from NT being 0.60 MPa at the soil surface (0-10 cm) and highest at 1.72 MPa at 35.0 cm. Focusing at the plow zone of the soil surface (0-2.5cm), APR in NT was 43% (1.09 MPa) higher when compared with PT (0.63 MPa). However, PT had 22% higher APR (2.32 MPa) compared to NT (1.81 MPa) at the 20 cm. The presence of a plow pan could explain the increase in APR
observed. In an APR sampling carried out two years prior at much drier soil conditions (adjusted PR to 0.10 g g\(^{-1}\) moisture content), Kumar et al., (2012a) found at the same site that plow tillage (3.58 MPa) had 27% higher PR compared to NT (2.82 MPa) for the 0-5 cm depth. At the 5-10 cm soil depth plow tillage increased by 12 % (4.46 MPa) compared with NT (3.98 MPa). Crop rotation also influenced APR (Figure 2.7). In general, APR was higher in CS rotation when compared to CC to 20 cm soil depth.

During the middle 1 sampling of the growing season (Figure 2.5), APR still varied by tillage treatment. At the soil surface (2.5 cm) NT (1.31 MPa) was 27% and 28% significantly higher (p=0.02) compared to MT (0.95 MPa) and PT (0.93 MPa), respectively. At 5 cm soil depth the same trend was observed where NT was significantly higher (p=0.01) compared to MT and PT. No differences were observed below 7.5 cm across tillage systems (p=0.66). No differences (p>0.05) were observed at any soil depth across crop rotations for APR (Figure 2.7).

During the middle 2 sampling of the growing season (Figure 2.6), APR varied by tillage treatment at the soil surface. At 2.5, 5, 7.5 and 10 cm, NT was significantly higher compared to PT but no differences were observed between NT and MT (p=0.06, 0.06, 0.01, 0.05, respectively). No differences were observed below the 12.5 cm soil depth for any of the tillage treatments. Below 17.5 cm depth even though no significant differences
(p>0.05) were observed, APR was higher for MT>PT>NT. Crop rotation also significantly affected APR (Figure 2.8). In general, CC rotation always trended higher than CS for the entire soil profile. From the 0-17.5 cm soil depth, CC was significantly higher compared to CS. However, below 20 cm soil depth, there were no significant differences observed. Higher APR values at the soil surface in NT treatments compared to PT could be contributed to lack of sufficient disturbance of the soil from natural resettlements of the soil particles (i.e. freezing and thawing and wetting and drying cycles) which are more strongly observed in clayey soils (Mahboubi et al., 1993). Mahboubi et al. (1993) also observed in this same site more resistance in NT compared to MT and PT treatments.

During the late growing season (Figure 2.6) sampling, differences in APR by tillage treatments were very different than compared to the early and middle sampling periods. No differences were observed at the soil surface (0 cm) across tillage treatments. However, from 2.5 cm to 12.5 cm soil depth, APR was in the order: NT > PT ≈ MT. Below 15 cm soil depth, there were no differences observed among treatments. In general, APR was not different for crop rotation (Figure 2.8). Root elongation at resistances greater than 4 MPa is completely restricted (Kirkegaard, 1990). However, Taylor (1971) found that root elongation ceases at 2.5 MPa.
b. **Hoytville**

At the Hoytville site, APR was significantly higher \((p=0.04)\) in soils under NT compared to soils under PT at the early sampling at all soil depths (Figure 2.9). In general, APR increased with soil depth. NT APR ranged from 0.16 MPa to 1.81 MPa. Plow tillage ranged from 0.09 to 1.64 MPa. Crop rotation did not significantly affect APR at this site at any soil depth \((p=0.21)\). Similarly, Kumar et al. (2012a) observed in this same site no differences \((p=0.08\) for 0-5 cm and \(p=0.94\) for 5-10 cm) among crop rotation treatments. At the Hoytville site, the soil texture is a silty clay loam, and heavy textured soils are more prone to compaction (McCormak, 1987). The overturning of the soil cause by tillage if performed at the right time could alleviate soil compaction (Hamza and Anderson, 2005; Leão et al., 2014). Whereas, soils under NT are undisturbed and natural processes of drying and wetting and freezing and thawing play an important role to alleviate soil compaction, but these processes occur more slowly when compared to tillage (Leão et al., 2014).

During the middle of the growing season sampling (Figure 2.9), tillage and crop rotation significantly affected APR. At the soil surface \((0-2.5 \text{ cm})\), tillage treatment was highest in \(MT\approx NT>PT\) \((p=0.03)\). No differences were observed at 2.5 to 7.5 cm soil
depth. At 7.5 to 17.5 cm soil depths, NT was significantly higher (p<0.05) than MT and PT. Below 20 cm soil depth, PT was always significantly lower (p<0.05) compared to MT and NT tillage treatments, although there were no differences observed between NT and MT. In general, APR in the CC rotation was significantly higher (p<0.05) compared to CS at all soil depths (Figure 2.11).

During late 1 sampling in the growing season (Figure 2.9), APR varied by tillage treatment. At the soil surface no differences were observed between any of the tillage treatments (p=0.57). At 5 cm soil depth NT (0.46 MPa) was significantly higher than PT (0.33 MPa) but no differences were observed among NT and MT (0.36 MPa) and MT and PT. Plow tillage was significantly lower (p<0.03) from 7.5-32.5 cm soil depth compared to NT. No differences (p=0.41) were observed under 35 cm soil depth among tillage treatments. No-till APR ranged from 0.16 MPa at the soil surface to 0.63 MPa at 40 cm. MT ranged from 0.14 MPa at the soil surface to 0.64 MPa at 40 cm. Plow tillage ranged from 0.12 MPa at the soil surface to 0.64 MPa at 40 cm. Crop rotation treatments (Figure 2.11) did not have a significant effect on the first 5 cm of the soil (p=0.57). At 7.5 and 10 cm, CC had a significantly higher APR compared to CS (p=0.03). Below 12.5 cm soil depth no differences were observed among tillage treatment, however CC had higher APR compared to CS.
During late 2 sampling in the growing season (Figure 2.10), in general, tillage effect was significant. At all depths NT was higher compared to MT and PT. At 2.5, 5, 7.5, 10 cm soil depth NT was significantly higher (p<0.05) compared to MT and no differences were observed between NT and PT. From 12.5-22.5 cm soil depth No differences were observed among tillage treatments. At 25 and 27.5 cm NT (1.08, 1.04 MPa) was significantly higher (p=0.01) compared to PT (0.94, 0.93 MPa) and MT (0.87, 0.86 MPa). In general, crop rotation effect on APR was not significant at the Silty clay loam soil.

2.4.2 Soil Bulk Density

Soil $\rho_b$ in Wooster increased by soil depth across tillage and crop rotation treatments (Table 3). Although there was not a significant tillage or row main effect observed on $\rho_b$ by soil depths (p=1.23), it is interesting to note that, in general, NT at 0-10 cm had 6.3% lower $\rho_b$ in the row compared to the middle of the row. This was not observed under MT or PT systems. Higher $\rho_b$ values in the middle of the row in NT can be attributed to compaction caused by vehicle traffic. At the 10-20 cm soil depth, significant differences were observed among tillage treatments in the row. NT was 8% significantly higher (p=0.02) compared to PT and MT. There were no significant
differences observed at the 20-30 cm depth for the tillage or row main effects. Lal (1999) found differences in $\rho_b$ for the row zone (RZ) and traffic zone (TZ) in this same site after 25 years of continuous corn. Bulk density at the 0-10 cm soil depth was not significantly different among tillage treatments for the RZ. However, he observed at the 10-20 cm soil depth, $\rho_b$ was significantly lower in NT compared with MT and PT treatments for RZ. In the TZ, $\rho_b$ was 0.7%, 6.6% and 8.0% higher in NT, MT, PT, respectively compared to the RZ. Researchers have also reported that soil type and crop system play an important role on $\rho_b$ and that it could take multiple years to observe a decrease in $\rho_b$ under NT systems (Balesdent et al., 2000). In a silt loam in Wooster, OH, Lal and Ahmadi (2000) reported no significant differences in soil $\rho_b$ after harvest traffic was complete when comparing (RZ and TZ). However, tillage treatments (no till, chisel plow and plow tillage) did have a significant effect ($p=0.05$) on $\rho_b$, with plow tillage having the highest values. They also reported that tillage treatments did not significantly vary in a silt loam located in South Charleston, OH. However in the same site Lal and Jarecki (2005) found that soil $\rho_b$ decreased in the 0-15 cm layer under NT. Ismail et al. (1994) observed no $\rho_b$ significant differences on no-till and plow tillage. Wager and Denton (1989) observed in a sandy loam soil in North Carolina, higher $\rho_b$ in the trafficked zone (1.74 Mg m$^{-3}$) compared with the untrafficked zone (1.52 Mg m$^{-3}$) of the no till plot. Similarly, on a loam soil, da
Silva et al. (1997) observed significantly higher $\rho_b$ in the inter-row compared to the row position. In the same study they observed significantly higher $\rho_b$ on NT compared to PT (moldboard plowing in fall).

Previous studies have shown that crop rotation can have an impact on soil $\rho_b$ (Unger and Jones, 1998; Lal and Jarecki, 2005; Kumar et al., 2012a). Although row main effects on soil $\rho_b$ was not significantly different ($p=0.12$), in general, CS was higher compared to CC in the Wooster site. The higher $\rho_b$ in CS compared to CC can be attributed to less plant residues returning to the soil by adding the soybean to the rotation. Another explanation could be the root effect on the soil. Soybean has a tap root whereas corn has a fibrous root that expands at the soil surface. No significant differences were observed at deeper depths. Mestelan (2008) did not find a crop rotation effect on the same site for $\rho_b$.

However, in the poorly drained soil at Hoytville, $\rho_b$ was significantly higher under CS compared to CC. Under CC, $\rho_b$ was significantly lower ($p=0.02$) at the 0-10 cm depth in the row compared to the middle of the row. No significant differences for $\rho_b$ were observed in a clay loam soil in Hoytville in a corn-soybean rotation under NT and subsoiling soil management in this study or previous done by Lal and Jarecki, 2005. In the same study, $\rho_b$ decreased in the 0-15 cm soil depth under NT in a Crosby silt loam.
soil. Lal et al. (1994) reported at the Wooster site after 28 yr, lower $\rho_b$ on the NT-CC compared with (list treatments) they reported a mean $\rho_b$ of 1.18 and 1.24 Mg m$^{-3}$ for CC and CS crop rotation, respectively. Dam et al. (2005) observed in CC on a loamy sand soil in Québec, 10% higher $\rho_b$ on NT compared with PT (moldboard plowing after harvest to a depth of 0.20 m and tandem disking in the spring to a depth of 0.10 m), especially at the 0-10 cm. Similarly, Kushwaha et al. (2001) reported in a sandy loam soil 10% higher $\rho_b$ in NT compared to PT (disked twice to 20 cm depth). In a silty clay loam in central Ohio, Shukla et al. (2003) found lower $\rho_b$ in the 0-10 cm layer in long term NT experiments compared to chisel plow and moldboard plow. Other researchers have also found that NT and conservation tillage systems generally result in higher bulk densities and smaller soil porosities (Hill et al. 1985; Hill 1990).

2.4.3 Water Retention Curves

Differences in water retained at different tensions by tillage treatments were observed at the 0-10 cm soil depth (Figure 2.3-A). At saturation (0 kPa) and at -1 kPa, the volumetric water content was not significantly different ($p=0.54$ and $p=0.34$, respectively) among tillage treatments at the 0-10 cm depth. Significant differences were observed under -3,-5,-10,-33, and -1500 kPa, where NT had a higher content compared to
MT and PT at 0-10 cm soil depth. At field capacity (FC) (-33 kPa), NT was 14% and 16% significantly higher (p<0.05) compared to MT and PT, respectively. At the permanent wilting point (PWP, -1,500 kPa), NT was 12% and 10% higher than MT and PT, respectively. These findings are in accordance with Kumar et al. (2012b), who took similar measurements in the same plots, two years prior. However, they found significant differences up to 30 cm soil depth, while in this study differences were only observed in the top 10 cm soil depth. In general, no significant differences were observed at the 10-20 cm soil depth (Figure 2.3-B), with the exception of NT at saturation where it was 5% lower compared to the MT and PT tillage treatments. At 20-40 cm soil depth, no significant differences were observed among tillage treatments (Figure 2.3-C). Additionally, there were no significant differences between CC and CS treatments on WRC observed at any soil depth (Figure 2.4).

The higher amount of water retained under NT system compared to MT and PT at the 0-10 cm (Figure 2.3) is attributed to the higher volume of pores that fall in the storage size distribution (Figure 3-A), which favor water retention. The majority of the changes observed in the WRC occurred between -5 kPa and -33 kPa. Soils under NT system had higher volume of pores that retain plant available water (storage pores) compared to the MT and PT tillage treatments. Hence, water retained at FC was higher in NT. Several
researchers have concluded that tillage systems and crop rotation effects on soil properties were more prevalent at the soil surface layer at 7.5 cm (Liebig et al. 2004; Mielke and Wilhelm 1998; Wuest et al. 2006). Hill et al. (1985) determined the effects of conservation and plow tillage on soil water retention and pore size distribution of two Mollisols under continuous-corn in Iowa. He reported that across the entire tension gradient, MT was higher than NT and NT was higher than conventional till in the amount of water retained in CC crop rotation after two years of establishment. No differences were observed at the second location after eight years of CC.

2.4.4 Pore Size Distribution

There were significant tillage treatment effects (p<0.05) on PSD at the Wooster site at the first 20 cm of soil (Figure 2.1). However, no differences between crop rotations were observed (Figure 2.2). The majority of the pores for all tillage systems occurred in the 0.2-30 µm size range. Additionally, this is also where the largest differences in PSD among tillage systems occurred. This is especially important when considering that available water capacity is primarily determined by the amount of storage pores, when there are no differences in soil texture. No-till had a 14.5% and 16.6% significantly (p<0.05) higher proportion of storage pores (57.3%) compared with MT (49.0%) and PT
(47.8%) at the 0-10 cm soil depth. The transmission pore sized fraction decreased with soil depth across all tillage treatments. No differences were observed at the residual pore fraction at any depth. At the transmission pore sized fraction, NT had in general significantly lower proportion (p<0.01) compared with the MT and PT tillage treatments. However, Kumar et al. (2012b) did find differences in tillage and crop rotation treatment effects on PSD in a sampling performed two years prior to measurements taken in this study at the same plots. They reported that NT had more macro- (>1000 µm) and micro- (<10 µm) pores compared with MT and PT treatments. For the PT and MT tillage treatments, the majority of the pores were distributed in the coarse (60-1000 µm) and fine (10-60 µm) mesopores size fractions. Additionally, they observed that CS had a higher volume of macro- and micropores at the 0-10 cm depth compared to CC. Shukla et al., (2003) also reported on a Kokomo silty clay loam in Columbus Ohio, a higher volume of the transmission and storage pores in NT compared to chisel plow and plow tillage at the 0-10 cm soil depth.

The smaller distribution of transmission pores on the NT treatments compared to MT and PT treatments could be contributed to the higher $\rho_b$ (Table 2.3) and PR (Figure 2.5) observed at the soil surface (0-20 cm). The higher $\rho_b$ and PR were likely caused by compaction from wheel traffic, but to a lower extent in MT and PT treatments which
broke up some of the physical compression of soil particles (Hamza and Anderson, 2005; McHugh et al., 2009; Voorhees, 1983; Voorhees and Lindstrom, 1984). When soil compaction occurs, a change in PSD takes place, thus a decrease in the proportion of transmission and storages pores could be produced (Greenland, 1977). Compaction effects on PSD under different tillage systems vary by soil texture, climate, susceptibly of compaction during time of tillage, and duration of tillage (Greenland, 1977, Hamza and Anderson, 2005). For instance, Tarawally et al., (2004) also reported a reduction of soil pores >50 µm and an increase in <0.5 µm pores with an increase in soil compaction for a Rhodic Ferralsol in western Cuba. Additionally, Hill et al. (1985) determined the effects of conservation and conventional tillage on soil water retention and PSD of two Mollisols under continuous-corn in Iowa. However, they reported no significant differences for pore size distribution between the two tillage systems.

2.5 Conclusion

The results from this study shows that tillage and crop rotations treatments effects on soil physical properties varied by site. Soil inherent properties play an important role in how management practices impact the soil compaction. Compaction effects on PSD
under different tillage systems vary by soil texture, climate, susceptibility of compaction during time of tillage, and duration of tillage. A tillage main effect was observed at both locations for APR. At the Wooster site where higher APR was observed, higher $\rho_b$ was also observed and higher amount of storage vs transmission pores in NT compared to PT. In the Hoytville soil higher APR was observed at the early and middle sampling for NT compared to MT and PT but no differences were observed during the late sampling among treatments, indicating an important role of soil texture on the compactability of the soil. This shows how soil compaction relates to soil physical properties.

2.6 Acknowledgments

We thank all the people involved on maintaining the long-term Triplett-Van Doren plots. We would like to thanks Jared Shaffer, Emma Snyder, Dave Thomashefski, Sandy Jones and José Guzmán for their invaluable help during field sampling and soil preparation for analysis. Helpful comments during preparation of the chapter were received from José Guzmán and Jared Shaffer.
<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Bulk density Mg m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse, medium, and fine sand and loamy sands</td>
<td>1.80</td>
</tr>
<tr>
<td>Very fine sand, loamy very fine sand</td>
<td>1.77</td>
</tr>
<tr>
<td>Sandy loams</td>
<td>1.75</td>
</tr>
<tr>
<td>Loam, sandy clay loam</td>
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<tr>
<td>Clay loam</td>
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</tr>
<tr>
<td>Sandy clay</td>
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<tr>
<td>Silt, silt loam</td>
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<tr>
<td>Silty clay loam</td>
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<tr>
<td>Silty clay</td>
<td>1.45</td>
</tr>
<tr>
<td>Clay</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 2.1: Typical values for the minimum bulk density at which a root-restricting condition will occur (adapted from *USDA-NRCS*, 1996).
### Penetration Resistance Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Penetration Resistance (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td></td>
</tr>
<tr>
<td>Extremely Low</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Very Low</td>
<td>0.01 – 0.1</td>
</tr>
<tr>
<td>Intermediate</td>
<td></td>
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<tr>
<td>Low</td>
<td>0.1 – 1</td>
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<td>Moderate</td>
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<td>High</td>
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</tr>
<tr>
<td>Very High</td>
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<tr>
<td>Extremely High</td>
<td>&gt;8</td>
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</table>

Table 2.2: Soil classification by penetration resistance classes (adapted from Soil Survey Manual, 2012).
<table>
<thead>
<tr>
<th>Treatment</th>
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<th>0-10 cm</th>
<th>10-20 cm</th>
<th>20-30 cm</th>
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* Row 1; in the row, Row 2; between two rows

† Means with the different letter in the same column are significantly different, p<0.05

Table 2.3 Bulk density from the silt loam soil in Wooster. Tillage (NT: no tillage; MT: minimum tillage; CT: conventional tillage), and crop rotation (corn-corn; CC and corn-soybean CS) effects on soil bulk density at Wooster.
Table 2.4 Planting dates for corn and soybean at Wooster and Hoytville.

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<td>Soybean</td>
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Figure 2.1 Pore size distributions under no-till (NT), minimum tillage (MT), and conventional tillage (CT) systems at different soil depths for Wooster. Different letters within each pore diameter and depth indicate significant difference between tillage treatments at p=0.05.
Figure 2.2 Pore size distributions for corn-corn (CC) and corn-soybean (CS) crop rotation systems at different soil depths for Wooster. Different letters within each pore diameter and depth, indicate significant difference between crop rotation treatments at p=0.05.
Figure 2.3 Soil Water Retention Curves (WRC) for no-till (NT), minimum tillage (MT) and conventional tillage (CT) at different soil depths at Wooster. An * indicates significant difference between tillage systems at p=0.05.
Figure 2.4 Soil Water Retention Curves (WRC) for corn-corn (CC) and corn-soybean (CS) at different soil depths at Wooster.
Figure 2.5 Adjusted penetration resistance (APR) for no-till (NT), minimum tillage (MT) and conventional tillage (CT) at different soil depths at Wooster in 2013. Different letters indicates significant difference between tillage treatments at p=0.05. No letters indicates no significant differences between tillage treatments.
Figure 2.6  Adjusted penetration resistance (APR) for no-till (NT), minimum tillage (MT) and conventional tillage (CT) at different soil depths at Wooster in 2014. Different letters indicates significant difference between tillage treatments at p=0.05. No letters indicates no significant differences between tillage treatments.
Figure 2.7 Adjusted penetration resistance (APR) for corn-corn (CC) and corn-soybean (CS) crop rotation systems at different soil depths for Wooster in 2013. Different letters indicates significant difference between crop treatments at p=0.05. No letters indicates no significant differences between crop treatments.
Figure 2.8  Adjusted penetration resistance (APR) for corn-corn (CC) and corn-soybean (CS) crop rotation systems at different soil depths for Wooster in 2014. Different letters indicates significant difference between crop treatments at p=0.05. No letters indicates no significant differences between crop treatments.
Figure 2.9 Adjusted penetration resistance (APR) for no-till (NT), minimum tillage (MT) and conventional tillage (CT) at different soil depths at Hoytville in 2013. Different letters indicate significant differences between tillage treatments at p=0.05. No letters indicate no significant differences between tillage treatments.
Figure 2.10  Adjusted penetration resistance (APR) for no-till (NT), minimum tillage (MT) and conventional tillage (CT) at different soil depths at Hoytville in 2014. Different letters indicates significant difference between tillage treatments at $p=0.05$. No letters indicates no significant differences between tillage treatments.
Figure 2.11 Adjusted penetration resistance (APR) for corn-corn (CC) and corn-soybean (CS) crop rotation systems at different soil depths for Hoytville in 2013. Different letters indicates significant difference between crop treatments at p=0.05. No letters indicates no significant differences between crop treatments.
Figure 2.12 Adjusted penetration resistance (APR) for corn-corn (CC) and corn-soybean (CS) crop rotation systems at different soil depths for Hoytville in 2014. Different letters indicates significant difference between crop treatments at p=0.05. No letters indicates no significant differences between crop treatments.
2.7 References


Ball, B.C. 1981. Pore characteristics of soils from two cultivation experiments as shown by gas diffusivities and permeabilities and air-filled porosities. J. Soil Sci. 32:483-498.


Chapter 3: Effect of long-term tillage practices and crop rotations on soil organic carbon and total nitrogen

3.1 Abstract

Long-term experiments are essential to determine the impact of agricultural management practices, such as tillage systems and crop rotations, in soil organic carbon (SOC) and nitrogen accumulation. Soil organic carbon and total nitrogen (TN) were evaluated on two contrasting soils under long-term (50-51 yr) tillage practices. Treatments consisted of tillage practice: no-till (NT), plow tillage (PT) and minimum tillage (MT); and crop sequence: corn-corn (CC) (Zea mays), corn-soybean (CS) (Glycine max) rotation. Soils samples were obtained from the Triplett - Van Doren plots located near the cities of Hoytville and Wooster, Ohio in September 2013. The soil located in northeast Ohio is a well-drained Wooster silt loam (mixed, mesic, Typic Fragiudalf) and the soil located in northwest Ohio is a poorly drained Hoytville (fine, illitic, mesic Mollic Epiaqualf) silty clay loam. Soil samples were collected at 0-10, 10-20 and 20-30 cm depths. Our objective was to determine the effect of long-term tillage and crop rotation on organic C and TN. Results show that SOC and TN varied by long-term tillage management (P < 0.0001). No-till practices increased SOC stock and TN in the top 20 cm for the silty clay loam soil, but no differences were observed in the silt loam soil. Total N
followed a similar pattern as SOC in both soils. At Hoytville, NT plots had 29% greater C stock compared to PT plots, at the soil surface. No significant differences were observed at any of the locations for crop rotation, however, CC rotation did show higher trends in SOC and TN which is attributed to greater plant biomass added by corn.
3.2 Introduction

Among the general public and scientific communities, concern of the potential impacts of climate change on food security, soil and water quality is increasing (Lal, 2004a and b, Lal, 2007). Atmospheric carbon dioxide (CO$_2$) has been shown to be the primary greenhouse gas contributing to climate change. As soils play an important role on the global C cycle, soil degradation contributes highly to C emissions. Powlson et al. (2011) estimated that the total amount of soil organic carbon (SOC) in the 0–30 cm soil layer is about twice the amount of carbon in atmospheric CO$_2$. Losses of SOC have been observed under temperate regions of up to 60% and up to 75% in tropical soils, due to the conversion of natural to agricultural ecosystems (Lal, 2004a). Thus, research evaluating how agricultural management practices, such as tillage systems and crop rotation, can reverse the depletion of C from the soil or increase C sequestration is critical.

Long-term studies are necessary to quantify the magnitude of the effects of agricultural management practices, such as tillage systems and crop rotations, on sequestration of SOC and soil total (TN). Long-term experiments serve as a tool to evaluate soil quality and crop productivity and to understand how agricultural systems can be better managed to sustain that productivity (Karlen et al., 2013). Long-term conservation tillage practices, such as no-till (NT) and minimum tillage (MT), can greatly affect the capacity of soil to sequester C and retain essential nutrients for plant growth (Dick, 1983, Salinas-Garcia et al. 1997, Gál et al. 2007,). Tillage intensity and crop
rotation affect fluctuations in SOC and TN (Monaco et al., 2008, Mazzoncini et al., 2011) therefore playing an important role on soil quality (Karlen et al., 2013). Bolinder et al. (1999) reported SOC as a sensitive indicator of soil responses to agricultural management practices, such as tillage and crop rotation. As agricultural management practices can affect soil C storage, its impact on SOC has been extensively reviewed. Several researchers have observed how changes in the management of agricultural systems can result in an increase in SOC (Dick, 1983, Mazzoncini et al., 2011, Álvaro-Fuentes et al., 2012, Kumar et al., 2012,) and TN (Salinas-García et al., 1997, Watts et al., 2010, Van Eerd et al., 2014). West and Post (2002) reported that conversion from PT to NT could sequester 570 kg C ha\(^{-1}\) y\(^{-1}\) after the analysis of field experiments globally. Increasing organic C in the soil also enhances crop production through the improvement of the soil fertility (Álvaro-Fuentes et al., 2008). It is well known that soil management (tillage practices), land use (natural vs agricultural ecosystems) and cropping practices (crop rotation, cover crops, and fertilizer application) have an impact on soil organic carbon sequestration (Six et al., 2000, Lal 2004a, Guzman et al., 2006). The implementation of recommended management practices (RMPs) can lead to SOC sequestration (Lal 2004a). Climate and soil properties play an important role on the effectiveness of NT practices in SOC sequestration (Burke et al., 1989; Miller et al., 2004). The adoption of conservation tillage systems has rapidly increased during the last few decades (Triplett and Dick, 2008) due to the many benefits it provides the soil. No-tillage practices leave the soil
undisturbed, except when seeding. Many scientific reports have shown a more pronounced stratification of SOC (Gál et al. 2007, Kumar et al. 2012) in soils under NT compared to plow tillage (PT), attributed to the lack of soil mixing under NT practices. No-till maintains the SOC and TN by reducing the rates of crop residue decomposition (Sainju et al., 2002), and the breakdown of soil aggregates (Kou et al., 2012). Previous long-term studies have reported that increases in SOC and TN usually occur under NT soils rather than in tilled soils, especially at the soil surface (Carter. 2005, Angers and Eriksen-Hamel. 2008, Sainju et al., 2010).

The long-term Triplett - Van Doren plots located in northwest (Hoytville) and northeast (Wooster) Ohio have different soil properties, including drainage class. These plots provide an opportunity to study soils under long-term tillage systems (NT, MT, and PT) and crop rotations (corn-corn: CC, corn-soybean: CS) to determine the impact on SOC and TN. We hypothesized that, after 50 years, these two soils will show differences in SOC accumulation and TN under the different management practices. The objectives of this study were to: (i) determine the effects of long-term NT, MT and PT on SOC and TN in well drained and poorly drained soils after 51 and 50 years, respectively, and (ii) examine the effects of corn-corn, corn-soybean rotations on SOC and TN in well drained and poorly drained soils after 51 and 50 years, respectively.
3.3 Materials and Methods

3.3.1 Study Site: Soil and Climate

This study was conducted at two long-term experimental sites at the northwest Agricultural Research Station of The Ohio Agricultural Research and Development Center (OARDC), located in Hoytville, OH (latitude 41º 13’ N, longitude 83º 45’ W ) and at the OARDC Triplett-Van Doren plots located in Wooster, OH (latitude 40º45’ N, longitude 81º54’ W). The plots located in Hoytville were established in 1963, and the Wooster plots in 1962 (Dick et al, 1991). These plots are the longest experimental sites maintaining no-till crop production in the world. Numerous research papers have been published with information regarding climate, crop yields, soil, and the history of the plots for both sites (Dick et al., 1986a and b; Dick et al. 1991; Dick, 1997a and b).

The taxonomic classification of the soil at the northwest location is a Hoytville Fine, illitic, mesic, Mollic Epiaqualf (USDA-SCS, 1973). The silty clay loam at the Hoytville site is classified as a very poorly drained soil with a slow to moderately slow permeability. Hoytville soils are usually formed on zero to one percent slopes; due to an overall low relief landscape, the risk to soil erosion is minimal (Dick et al., 1991). The soil at the northeast site is a Wooster silt loam, which is classified as well drained and having a moderate to moderately slow permeability. The taxonomic classification is Fine-loamy, mixed, mesic Typic Fragiaudalf. Wooster soils are usually formed on two to four
percent slopes (Soil Survey Staff, 2013). The soil taxonomy and site characteristics of both locations are described in Table 3.1.

The climate at both experimental locations is typically continental. The mean annual air temperature at Hoytville is 9.5 ºC and 9.1ºC in Wooster (Dick et al., 1998). The majority of the precipitation occurs during the warm season (spring and summer months) (Dick et al., 1991). The approximate annual precipitation for Hoytville is 845 mm (Dick et al., 1986a, Dick et al 1998) and 905 mm in Wooster (Dick et al., 1986b, Dick et al 1998). In some years in Wooster, during the months of June and July, short lasting intense storms lead to severe soil erosion (Dick et al., 1991). However, the amount of precipitation received in Wooster during the summer is not always enough to fulfill the plant water needs for maximum crop yields and plants can suffer water stress (Dick et al., 1986 b; Dick et al., 1991). No erosions problems have been observed at Hoytville. The experiments at both locations were established to study the impact of long-term tillage and crop rotations on soil properties and agronomic productivity (Dick et al., 1991).

3.3.2. Experimental Setting

The treatments for this study included three tillage systems: continuous no-till (NT), minimum tillage (MT), and plowtillage (PT), and two crop rotations: corn-corn (CC) and corn-soybean (CS) in a two year rotation. At both locations (Hoytville and
Wooster) the combination of the tillage systems and crop rotations treatments are replicated three times according to a randomized complete block design with factorial arrangement. The three tillage systems and the two crop rotation combinations are applied each year. Under the no-tillage (NT) system, the only soil disturbance performed is the planting of seeds directly into the previous year’s crop residue with a coulter-type planter. The minimum tillage (MT) treatment involved the use of a chisel plow to a depth of 20 - 25 cm, without any soil inversion, and a single pass of a field cultivator to the 10 cm depth prior to planting. The minimum tillage practices do not qualify as conservation tillage because even though plant residues remains on the soil surface, it is usually less than the 30% normally required for conservation tillage. Plow tillage (PT) was performed once during spring at Wooster and during fall at Hoytville. This management involves the use of a moldboard plow at 20-25 cm depth. In addition, two or more secondary tillage treatments are performed at 10 cm depth for seedbed preparation in the spring. Research plots at Wooster are 22.3 x 4.3 m and 27.4 x 6.1 m at Hoytville. Tile drains have been installed at the Hoytville site at 17 m spacing. Detailed agronomic practices for both locations can be found in Dick et al. (1986a and b) and Dick (1997a and b).

3.3.3 Soil Sampling

In September 2013, soil samples at Hoytville and Wooster were collected for TC and TN analyses. At both locations, three spatially random soil samples were taken per
plot at three depths (0-10 cm, 10-20 cm and 20-30 cm) for the entire factorial of treatments, CC and CS crop rotations and NT, MT and PT practices. The samples for each treatment and depth were composited in a bucket, mixed and a sub-sample was collected for further analyses. The samples were transported to the laboratory, air dried, sieved to pass a 2-mm screen and stored.

3.3.5 Soil Organic Carbon, Soil Total Nitrogen and Soil Bulk Density

Soil samples that were previously 2-mm sieved and air-dried, were ground with a mortar and pestle in preparation for C and N analysis. The ground samples were then weighed in tin capsules and combusted at 1000°C in an elemental analyzer under a stream of oxygen. The total C values of the soil samples were determined by using an elemental analyzer (Carlo Erba CHN EA 1108, now Thermo Fisher Scientific, Waltham, MA). The SOC concentration and TN concentration (g kg⁻¹) was determined by converting the % results from instrument analysis to g g⁻¹ and then multiplying it by 1000 to convert g of C or N per kg of soil basis. Soil pH was determined by a glass electrode (1:1 volume soil:water). The pH of these soils was <7.2, therefore, the inorganic carbonate content was negligible. Under these conditions, total C was considered to be the same as soil organic C (SOC). In Wooster, soil bulk density samples (ρb) for the 0-10, 10-20 and 20-30 cm depths were collected in October 2014 and determined by the core method (Blake and Hartge, 1986). Two cores were collected from
each plot, one in the row and one between rows. The soil cores were oven dried at 105°C. Bulk density was calculated by dividing the oven dried soil weight by the core volume. The results of both cores per plot were averaged to give a single \( \rho_b \). Soil \( (\rho_b) \) from the Hoytville location were obtained from Kumar et al. (2012). The SOC and TN stocks \( (\text{Mg C ha}^{-1}) \) were calculated by multiplying the C and N concentration by the thickness of the soil layer \( (\text{m}) \) and the soil bulk density \( (\text{Mg m}^{-3}) \).

3.3.5 Statistical Analysis

The data for SOC and TN across all crop rotations and tillage practices treatments were analyzed by site and depth, using the least squares means statement in General Linear Model (GLM) module of SAS (version 9.3, SAS Institute, Cary, NC) to determine tillage treatment and crop rotation main effects and their interactions (SAS 2015). Mean separation was determined using the PDIF procedure and statistical differences were declared significant at \( P \leq 0.05 \) level.

3.4 Results and Discussion

3.4.1 Soil organic carbon

\textit{a. Tillage treatments}

Results for SOC concentrations \( (\text{g kg}^{-1}) \) and C stock \( (\text{Mg ha}^{-1}) \) in the three tillage treatments \( (\text{NT, PT, MT}) \) and the two crop rotations \( (\text{CC, CS}) \) for both Hoytville and
Wooster are presented in Table 3.2. In the poorly drained soil at the Hoytville site, SOC concentrations varied by tillage treatment. Mean SOC concentrations ranged from 10.1 to 22.0 g kg\(^{-1}\) and C stock ranged from 9.45 to 18.9 Mg ha\(^{-1}\). More stratification was observed under NT than PT tillage. Significantly higher SOC concentrations were observed under NT (22.0 g kg\(^{-1}\), 20.2 g kg\(^{-1}\)) compared to PT (16.2 g kg\(^{-1}\), 16.1 g kg\(^{-1}\)) and MT (17.6 g kg\(^{-1}\), 15.9 g kg\(^{-1}\)) at the 0-10 (P<0.0001) and 10-20 (P < 0.008) cm depths. Beyond the 20 cm depth, PT had higher SOC concentrations (P < 0.002) (14.7 g kg\(^{-1}\)) compared to NT (14.6 g kg\(^{-1}\)) and MT (10.1 g kg\(^{-1}\)). This difference is due to crop residues being buried by frequent moldboard plowing. The accumulation of SOC at the soil surface under NT is commonly attributed to increase in C inputs from the reduced tillage intensity, which resulted in reduced breakdown or oxidation of SOM (Dick, 1983, Dick et al., 1991, Bono et al., 2008, Halpern et al., 2010, Watts et al., 2010). On the contrary, PT tillage practices incorporate plant residues, increase oxidation and microbial activity, and disrupt soil aggregates, thus enhancing SOC and N mineralization (Balesdent et al., 1990, Stevenson, 1986). Huggins et al. (2007) reported 26% more SOC in the MT system using chisel plow compared to the PT system using a moldboard plow.

Carbon stock was also influenced by tillage treatment at Hoytville. Across all the tillage treatments, C stocks were significantly different in the 0-10 cm layer (P < 0.05), with higher values under NT followed by MT and PT (18.9, 15.5, 14.6 g kg\(^{-1}\), respectively). At the 20-30 cm depth, PT (13.6 Mg ha\(^{-1}\)) and NT (13.5 Mg ha\(^{-1}\)) had
higher C stock than MT (9.45 Mg ha\(^{-1}\)) (P=0.06). These differences are attributed to the increment of crop residues at deeper depths by the mixing of the soil due to moldboard plowing. Similar studies at this same site did not find significant differences below the 30 cm soil depth (Kumar et al., 2012). Soil organic carbon stocks for the entire 0-30 cm depth under NT (73.6 Mg ha\(^{-1}\)) was 14% higher than PT (64.6 Mg ha\(^{-1}\)) and 28% higher than MT (57.2 Mg ha\(^{-1}\)). In general, after the continuous use of NT practice for five decades in a poorly drained silty clay loam soil, SOC concentration and carbon stock were higher compared to soils under MT and PT.

At the well-drained soil in the Wooster site, the SOC concentration and stock data differ from previous studies where significant differences were found at the soil surface under NT compared with tillage in Dick, (1983) and Kumar et al., (2012). The duration of those studies were 19 yr and 49 yr respectively. No significance differences (P =0.96) were observed among the different tillage treatments at the 0-10 cm for SOC concentration and stock during the time of this study. Mean SOC concentration ranged from 7.41 to 16.2g kg\(^{-1}\). Dick (1983) did find significant differences at the same site for tillage treatments where NT had higher accumulation of organic carbon at the soil surface (0-7.5 cm) compared to MT and PT. However below the 7.5 cm depth no significant differences were observed among the three tillage treatments. Similarly, Jarecki and Lal (2005) reported from a experiment established in 1987 in Hoytville, OH, higher C stock at the soil surface under NT compared to PT. For all the tillage treatments SOC
concentration and stock decreased with soil depth. A study by Watts et al. (2010) on a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludult) in Alabama reported higher C sequestration at 0-5 cm depth for soil under NT compared to PT, but no significant differences were found below five cm. Similarly, Gál et al. (2007) reported that NT did not have a significant impact in the 0-50 cm soil depth compared with conventional tillage (fall moldboard plowing to a depth of 20–25 cm, followed by disking plus field cultivation to 10 cm prior to planting each spring).

The lack of difference among tillage treatments might be due to the addition of top soil to the PT and MT plots in autumn 2006. Heavy rains at Wooster were causing erosion problems and water ponding at the PT and MT plots. The loss of topsoil was exacerbated by water runoff from uneven soil elevations between NT plots and PT and MT plots (Dick, 1986b), which caused constraints to plant growth. Topsoil was added in order to minimize difference in soil elevations between the plots. Miller et al. (2004) showed that differences in soil properties and climate play an important role on SOC content. Therefore, differences between the well-drained soil in Wooster and poorly-drained Hoytville soil can be explained by soil properties such as the fine texture and drainage (Dick, 1983).
For both locations our data showed trends of higher SOC concentration and stocks at all depths under CC rotation compared to CS; however the differences were not significant (P > 0.05). The higher SOC concentrations and stocks in the CC rotation is associated with higher crop residues added from the continuous corn to the soil compared to the biomass returned when soybean is included in rotation (Dick et al., 1998, Huggins et al., 2007) and higher SOC decomposition rates in CS rotations (Soon et al., 2001). Total C stocks for the 0-30 cm depth was 8% higher under CC (67.6 Mg ha\(^{-1}\)) than CS (62.6 Mg ha\(^{-1}\)) at the Hoytville location and 6% higher in Wooster (55.0 Mg ha\(^{-1}\), 51.8 Mg ha\(^{-1}\), respectively). No significant differences were found on the interaction effects of tillage practices and crop rotation (Table 3.2.). A study done by Huggins et al. (2007) in a Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquoll) in Minnesota involving 14 years of moldboard plow, chisel plow, and NT on continuous corn observed the greatest SOC under chisel plow (26%) and NT (20%) than moldboard plow. They also observed on the CS rotation no significant difference among NT and moldboard. They reported 1.8 times higher C inputs from corn compared to soybean.

3.4.2 Soil Total Nitrogen

Results for soil TN concentrations (g kg\(^{-1}\)) and nitrogen stock (Mg ha\(^{-1}\)) for both locations (Hoytville and Wooster) are presented in Table 3.3. Significant differences (P <
0.05) were observed in the Hoytville soil for all depths. The soil TN concentrations and stocks tend to follow a similar pattern as SOC, as reported by others (Dick. 1983, Gál et al. 2007, Fuentes et al. 2009, Van Eerd et al. 2014). The soil TN concentrations at the soil surface were 20% higher under NT (2.44 g kg\(^{-1}\)) than MT (2.02 g kg\(^{-1}\)) and 35% higher compared to PT (1.80 g kg\(^{-1}\)). At the 10-20 cm depth NT still had significantly (P < 0.005) higher N concentration, however, no difference was seen between MT and PT. Total N stock decreased with soil depth for the NT and MT treatments, but the reverse was observed under PT. At the soil surface (0-10 cm), NT had the highest N stock compared to the other tillage treatments. No significant differences were observed for the 10-20 cm depth. No significant differences were observed between PT and NT (2.02 Mg ha\(^{-1}\), 1.97 Mg ha\(^{-1}\)) for N stock at the 20-30 cm depth, but MT was significantly lower (1.66 Mg ha\(^{-1}\)).

Overall, soil TN stocks varied by tillage practices for the 0-30 cm soil profile at the Hoytville location. No-till (8.26 Mg ha\(^{-1}\)) had 13% and 23% higher N stock than PT (7.26 Mg ha\(^{-1}\)) and MT (6.72 Mg ha\(^{-1}\)), respectively. Total amount of N stocks in the 0-30 cm soil profile for the crop rotation was significantly higher in Hoytville soil under CC (7.76 Mg ha\(^{-1}\)) than CS (7.07 Mg ha\(^{-1}\)). The higher amount on N stock observed in NT is due to the higher amount of crop residue left on the soil surface compared to the other tillage systems where the plant residues are incorporated into the soil. Thereby, NT
supplies more residual organic matter to the soil and the N that is in organic form slowly decomposes, causing a buildup of soil N.

At the well-drained Wooster site, no significant differences were observed for N concentration at 0-10 and 10-20 cm depth among the three tillage treatments. However, at the 20-30 cm depth MT (1.12 g kg\(^{-1}\)) and PT (0.97 g kg\(^{-1}\)) had significantly higher N concentration compared to NT (0.85 g kg\(^{-1}\)). No significant differences (P > 0.05) were observed between tillage practices for N stocks in the 0-30 cm soil profile. However, MT had the higher amounts (5.77 Mg ha\(^{-1}\)) compared to PT (5.50 Mg ha\(^{-1}\)) and NT (4.98 Mg ha\(^{-1}\)). At this site even though crop rotation was not significant, CC (5.50 Mg ha\(^{-1}\)) had 3% higher N stock compared to CS (5.33 Mg ha\(^{-1}\)) for the 0-30 cm soil depth.

In a 25-yr experiment involving conventional tillage and no-till on a Hartsells fine sandy loam (Fine-loamy, siliceous, subactive, thermic Typic Hapludult) in northeast Alabama, Watts et al. (2010) observed 81% higher TN values in soil with a continuous corn cropping system under NT compared to PT (moldboard plow and disking followed by rototiller in the spring). Similarly, a study by Van Eerd et al. (2014) on a clay loam soil in southwestern Ontario observed higher TN in the first 120 cm of soil in NT compared to CT. Gál et al. (2007) conducted a study in a 28-yr experiment on a Chalmers silty clay loam (a fine-silty, mixed, superactive, mesic Typic Endoaquoll) and observed 32% higher TN concentration from NT than PT (fall moldboard plowing to a depth of 20–25 cm, followed by disking plus field cultivation to 10 cm prior to planting each
spring) at the 0-5 cm depth and at the 5-15 cm depth a 9% difference. No significant differences were observed at the 15-30 cm depth and below 30 cm PT had higher total N than NT.

3.5 Conclusion

The results from this study show that the use of long-term NT practices effects on SOC and soil TN varied by site. A tillage main effect was observed at Hoytville with higher SOC and TN associated with NT than MT and PT. This effect is attributed to lower decomposition rate of organic matter due to the lack of soil mixing in NT. No significant differences were observed between tillage treatments at Wooster. The lack of difference is attributed to the recent addition of top soil in the PT and MT plots. The crop rotation effect was not significant (P < 0.05) for both sites; however, although trends did show CC had higher SOC and TN compared to CS. This is linked to the higher amounts of crop residue returning to the soil by corn compared to soybean. It can be concluded that the use of NT can be beneficial for the environment by sequestering higher amounts of SOC compared to PT and MT.

3.6 Acknowledgements

The authors of this paper would like to gratefully acknowledge the support from Dr. Richard Dick’s laboratory personnel for access to the equipment for C analysis,
especially to Nathan Lee for his time running the instruments. We would also like to express our gratitude to Jared Shaffer for his help collecting the soil samples and to, Lumarie Pérez Guzman and Jose A. Mercado for their help processing the soil samples. We would also like to express our gratitude to José G. Guzmán for his invaluable help.
### Description of experimental plots

<table>
<thead>
<tr>
<th>Common soil name</th>
<th>Wooster silt loam</th>
<th>Hoytville silty clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxonomic soil name</td>
<td>Fine-loamy, mixed, mesic Typic Fragiudalf</td>
<td>Fine, illitic, mesic Mollic Epiaqualfs</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>2.5-4.5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Minimum saturated hydraulic condition (cm h)</td>
<td>0.6 (120-150)</td>
<td>0.1 (55-85)</td>
</tr>
<tr>
<td>Prior cropping</td>
<td>6 yr grass meadow</td>
<td>6 yr corn-oats-meadow</td>
</tr>
<tr>
<td>Prior tillage</td>
<td>none for 6 yr</td>
<td>plow + disk for 4 of 6 yr</td>
</tr>
<tr>
<td>Experimental design</td>
<td>Factorial, randomized block</td>
<td>Factorial, randomized block</td>
</tr>
<tr>
<td>Crop</td>
<td>CC, CS</td>
<td>CC, CS</td>
</tr>
<tr>
<td>Tillage</td>
<td>NT, MT, PT</td>
<td>NT, MT, PT</td>
</tr>
<tr>
<td>Plot size</td>
<td>4.3 by 22 m</td>
<td>6.4 by 31 m</td>
</tr>
</tbody>
</table>

CC- corn, corn; CS- corn-soybean

NT- no-tillage; MT- minimum tillage; CT- conventional tillage

Table 3. 1 Soil and site characteristics at the long-term tillage and rotation experiment (Adapted from Dick et al., 1991).
Table 3. 2 Tillage and crop rotation effects on soil organic carbon and carbon stocks in Hoytville and Wooster.

<table>
<thead>
<tr>
<th>Treatment*</th>
<th>SOC (g kg(^{-1}))</th>
<th>C Stock (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10 cm</td>
<td>10-20 cm</td>
</tr>
<tr>
<td><strong>Hoytville</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tillage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>22.0 a†</td>
<td>20.2 a</td>
</tr>
<tr>
<td>PT</td>
<td>16.2 c</td>
<td>16.2 b</td>
</tr>
<tr>
<td>MT</td>
<td>17.6 b</td>
<td>15.9 b</td>
</tr>
<tr>
<td><strong>Rotation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>19.1 a</td>
<td>18.3 a</td>
</tr>
<tr>
<td>CS</td>
<td>18.1 a</td>
<td>16.5 a</td>
</tr>
<tr>
<td><strong>Wooster</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tillage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>15.9 a</td>
<td>10.8 b</td>
</tr>
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<td>PT</td>
<td>15.7 a</td>
<td>13.3 a</td>
</tr>
<tr>
<td>MT</td>
<td>16.2 a</td>
<td>12.5 ab</td>
</tr>
<tr>
<td><strong>Rotation</strong></td>
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<td></td>
</tr>
<tr>
<td>CC</td>
<td>17.5 a</td>
<td>12.4 a</td>
</tr>
<tr>
<td>CS</td>
<td>14.4 a</td>
<td>12.0 a</td>
</tr>
</tbody>
</table>

Analysis of variance P>F

<table>
<thead>
<tr>
<th></th>
<th>Tillage</th>
<th>Rotation</th>
<th>Tillage</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;0.0001</td>
<td>0.09</td>
<td>0.82</td>
<td>0.57</td>
</tr>
<tr>
<td>Houytville</td>
<td>0.008</td>
<td>0.08</td>
<td>0.85</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.22</td>
<td>0.29</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>0.75</td>
<td>0.94</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>0.59</td>
<td>0.90</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.30</td>
<td>0.57</td>
<td></td>
</tr>
</tbody>
</table>

*NT = no-till; PT = plow tillage; MT = minimum tillage; CC = continuous corn; CS = corn-soybean
†Means with the different letter in the same column are significantly different, p<0.05

Table 3. 2 Tillage and crop rotation effects on soil organic carbon and carbon stocks in Hoytville and Wooster.
<table>
<thead>
<tr>
<th>Treatment*</th>
<th>N (g kg(^{-1}))</th>
<th></th>
<th></th>
<th>N Stock (Mg ha(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0-10 cm</td>
<td>10-20 cm</td>
<td>20-30 cm</td>
<td>0-10 cm</td>
<td>10-20 cm</td>
<td>20-30 cm</td>
</tr>
<tr>
<td><strong>Hoytville</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Tillage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NT</td>
<td>2.44 a†</td>
<td>2.25 a</td>
<td>1.67 a</td>
<td>2.66 a</td>
<td>2.48 a</td>
<td>1.97 a</td>
</tr>
<tr>
<td>PT</td>
<td>1.80 c</td>
<td>1.81 b</td>
<td>1.67 a</td>
<td>2.19 b</td>
<td>2.22 a</td>
<td>2.02 a</td>
</tr>
<tr>
<td>MT</td>
<td>2.02 b</td>
<td>1.81 b</td>
<td>1.30 b</td>
<td>2.35 b</td>
<td>2.18 a</td>
<td>1.66 b</td>
</tr>
<tr>
<td><strong>Rotation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>2.16 a</td>
<td>2.08 a</td>
<td>1.62 a</td>
<td>2.46 a</td>
<td>2.38 a</td>
<td>1.94 a</td>
</tr>
<tr>
<td>CS</td>
<td>2.02 b</td>
<td>1.83 b</td>
<td>1.47 a</td>
<td>2.34 a</td>
<td>2.20 a</td>
<td>1.83 a</td>
</tr>
<tr>
<td><strong>Analysis of variance P&gt;F</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tillage</td>
<td>&lt;0.0001</td>
<td>0.0045</td>
<td>0.0018</td>
<td>0.03</td>
<td>0.28</td>
<td>0.08</td>
</tr>
<tr>
<td>Rotation</td>
<td>0.01</td>
<td>0.02</td>
<td>0.07</td>
<td>0.34</td>
<td>0.25</td>
<td>0.42</td>
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<tr>
<td>Tillage x Rotation</td>
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<td>0.95</td>
<td>0.25</td>
<td>0.84</td>
<td>0.82</td>
<td>0.56</td>
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<tr>
<td><strong>Wooster</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Tillage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>1.57 a</td>
<td>1.17 a</td>
<td>0.848 b</td>
<td>2.16 a</td>
<td>1.77 a</td>
<td>1.36 a</td>
</tr>
<tr>
<td>PT</td>
<td>1.52 a</td>
<td>1.34 a</td>
<td>0.974 ab</td>
<td>2.06 a</td>
<td>1.90 a</td>
<td>1.54 a</td>
</tr>
<tr>
<td>MT</td>
<td>1.64 a</td>
<td>1.30 a</td>
<td>1.12 a</td>
<td>2.18 a</td>
<td>1.85 a</td>
<td>1.74 a</td>
</tr>
<tr>
<td><strong>Rotation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>1.66 a</td>
<td>1.28 a</td>
<td>0.931 a</td>
<td>2.23 a</td>
<td>1.84 a</td>
<td>1.66 a</td>
</tr>
<tr>
<td>CS</td>
<td>1.50 a</td>
<td>1.26 a</td>
<td>0.103 a</td>
<td>2.04 a</td>
<td>1.84 a</td>
<td>1.43 a</td>
</tr>
<tr>
<td><strong>Analysis of variance P&gt;F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tillage</td>
<td>0.77</td>
<td>0.37</td>
<td>0.10</td>
<td>0.85</td>
<td>0.76</td>
<td>0.14</td>
</tr>
<tr>
<td>Rotation</td>
<td>0.29</td>
<td>0.85</td>
<td>0.29</td>
<td>0.29</td>
<td>0.96</td>
<td>0.14</td>
</tr>
<tr>
<td>Tillage x Rotation</td>
<td>0.22</td>
<td>0.06</td>
<td>0.92</td>
<td>0.20</td>
<td>0.09</td>
<td>0.97</td>
</tr>
</tbody>
</table>

*NT = no-till; PT = plow tillage; MT = minimum tillage; CC = continuous corn; CS = corn-soybean
†Means with the different letter in the same column are significantly different, p<0.05

Table 3. 3 Tillage and crop rotations effects on total soil nitrogen and nitrogen stocks in Hoytville and Wooster.
<table>
<thead>
<tr>
<th>Treatment*</th>
<th>C stock (Mg ha⁻¹)</th>
<th>N stock (Mg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hoytville</td>
<td>Wooster</td>
</tr>
<tr>
<td>Tillage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>73.6 a†</td>
<td>49.3 a</td>
</tr>
<tr>
<td>PT</td>
<td>64.6 b</td>
<td>55.1 a</td>
</tr>
<tr>
<td>MT</td>
<td>57.2 c</td>
<td>55.8 a</td>
</tr>
<tr>
<td>Rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>67.6 a</td>
<td>55.0 a</td>
</tr>
<tr>
<td>CS</td>
<td>62.6 b</td>
<td>51.8 a</td>
</tr>
</tbody>
</table>

*NT = no-till; PT = plow tillage; MT = minimum tillage; CC = continuous corn; CS = corn-soybean
†Means with the different letter in the same column are significantly different, p<0.05

Table3.4 Soil carbon and nitrogen stock for 0-30 cm soil depth at Hoytville and Wooster.
3.7 References


Bibliography


Ball, B.C. 1981. Pore characteristics of soils from two cultivation experiments as shown by gas diffusivities and permeabilities and air-filled porosities. J. Soil Sci. 32:483-498.


