LONG-TERM EFFECT OF CROP ROTATION AND TILLAGE ON SOIL PROPERTIES

BY

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THESIS

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ABSTRACT

Shifts in cropping systems from long-term rotations including forages to mostly annual crops has intensified tillage, and led to the development of conservation tillage practices such as no-till. There is a shortage of information about the interactive effects of rotation and tillage on soil productivity, and consequently, the long-term effect of these management practices. The objective of this study was to assess the effect of rotation and tillage on soil physical and chemical properties. Continuous corn (*Zea mays* L.), corn-soybean (*Glycine max* [L.] Merr.), corn-soybean-wheat (*Triticum aestivum* L.), and continuous soybean sequences were split into conventional tillage and no-till subplots at two western Illinois sites and were sampled 15 years after establishment. Bulk density (BD) at both sites was greater under no-till than conventional tillage over the top 20 cm but did not vary below that depth. BD varied with crop sequence only at Monmouth, with the greatest BD under continuous soybean followed by continuous corn, corn-soybean, and the lowest BD under corn-soybean-wheat. Total carbon (TC), total nitrogen (TN), and available phosphorus (P) and water aggregate stability (WAS) varied with treatment effects of rotation and tillage at Perry, but not at Monmouth, where soils had higher initial soil organic matter content. At Perry, TC, TN and P were greater at 0-10 cm depth under no-till, but were higher under conventional tillage at 10-20 cm depth. WAS over 0-20 cm at Perry was 84.7 g g^{-1} under no-till and was 81.6 g g^{-1} under conventional tillage. Soils under continuous soybean had lower TC, TN, and WAS than those soils under sequences with corn at Perry, likely due to lower residue accumulation of soybean and the use of N fertilizer on corn and wheat. Over both sites, P was greater in soils under continuous soybean than under those with corn. Within the sequences with corn, TC varied only at the 0-10 cm soil depth at Perry with 13.54, 13.27, and 12.20 g C kg $soil^{-1}$ under corn-soybean-wheat, continuous corn, and corn-soybean, respectively.

At Perry, WAS over 0-20 cm was 87.2, 83.6, and 82.6 g g^{-1} for corn-soybean-wheat, continuous corn, and corn-soybean sequences, respectively. These results indicate increased aggregate stability under no-till along with differences in nutrient stratification over the top 20 cm of the soil. The addition of wheat to the corn-soybean rotation increased TC and WAS, but levels were similar to those under continuous corn.

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INTRODUCTION

Agricultural practices throughout the Midwestern United States have undergone significant changes since the early twentieth century. In the early 1900s, a farmer likely produced corn, oats, and hay in a rotation on his fields with 20 to 30 percent dedicated to feed for draft animals (Power and Follett, 1987). The cultivation of land was accomplished by draft animals pulling a steel moldboard plow, which completely inverts the top layer of soil (Huggins and Reganold, 2008). Changes began following World War I as gasoline tractors became widely available and were extensively used by the end of World War II; with mechanization, the need for draft animals was greatly reduced (Power and Follett, 1987; Smith, 1995). Much of the acreage devoted to pasture and feedstuffs for those animals was freed to be used for the relatively newly introduced soybeans (*Glycine max* [L.] Merr.) (Smith, 1995). For the second half of the twentieth century, oat and hay acreage decreased dramatically and the most common cropping system on Midwestern farms was a short rotation of corn (*Zea mays* L.) and soybeans (Karlen et al., 2006).

In a crop rotation, different crop species are planted in a particular order over sequential growing seasons; in contrast, a continuous monoculture consists of the same crop species being grown repeatedly over many years (Bullock, 1992). With the development of chemical fertilizers and pesticides following World War II and the improvement of crop varieties, the monoculture of continuous corn became utilized as well (Power and Follett, 1987). Currently, the two-year corn-soybean is much more common than continuous corn, with only 16% of corn grown in 2010 grown as a monoculture; in 2006, 94% of soybeans were grown as part of a rotation (USDA/ERS, 2013). The shift from longer rotations, which included pastures to short rotations or monoculture also led to an intensification of tillage due to requirement of seedbed preparation every year (Bullock, 1992; Smith, 1995).

With droughts in the 1930s leading to the Dust Bowl, concerns arose about the susceptibility of the continuously tilled soil to erosion, which led to soil conservation and conservation tillage methods (Kladivko et al., 1986; Huggins and Reganold, 2008). Conservation tillage is defined as tillage practices which leave at least 30% of the residue of the previous crop remaining on the soil after planting (CTIC, 2006). Tillage practices that leave less than 30% residue are classified as conventional tillage, whether it consists of the inversion of soil with a moldboard plow or the less disruptive chisel plow (Hill, 1990). The development of the conservation tillage method of no-till began in the 1960s, but was reliant on chemical herbicides available after World War II and the development of equipment capable of planting into no-till fields (Kladivko et al., 1986; Huggins and Reganold, 2008). No-till consists of leaving the soil intact until after harvest and during planting, in which planting discs create a narrow groove half an inch to three inches across into which seeds are dropped and the rest of the plant residue left in place (Hill, 1990; Huggins and Reganold, 2008).

While the original incentive of no-till was to reduce soil losses due to erosion, no-till provides other benefits as well. Throughout the year, four or fewer passes for planting, herbicide application, and harvesting are necessary with no-till compared to seven or more passes over a field necessary with conventional tillage practices leading to a reduction in labor and machinery costs (Karlen et al., 1994c; Huggins and Reganold, 2008). Other benefits include sequestration of soil organic carbon from the recycling of crop residues (Varvel and Wilhelm, 2011).

While concern about soil degradation due to intensification of tillage led to the development of conservation tillage practices, the cropping system also drew concerns about the impact on soil productivity and quality since monocultures and a short rotation of corn-soybean produce less residue than rotations with pastures as part of the rotation (Power and Follett, 1987).

Without the additional residue produced by pasture, these shorter rotations along with intensive tillage practices have been detrimental to soil productivity and quality (Havlin et al., 1990; Tilman, 1999; West and Post, 2002). Soil productivity is of particular importance due to the doubling of global grain demand over the next several decades of as the global population grows (Cassman, 1999; Tilman et al., 2002). Therefore, any management practice that degrades the soil can reduce the productivity and reduce food production capacity (Cassman, 1999). Due to the potential impact on global food security, it is vital to evaluate the impact of management practices such as a short crop rotation or monoculture and more intensive cultivation on the soil productivity.

Soil organic carbon from soil organic matter is a key indicator of the soil productivity. Soil organic matter benefits soil by lowering bulk density, increasing nutrient availability, increasing cation exchange capacity and improving water holding capacity; in addition, soil organic matter increases soil aggregates' stability making soils less susceptible to erosion (West and Post, 2002; Varvel and Wilhelm, 2010).

A key influence on the soil organic matter content of a soil is the quantity, quality, and decomposition of the crop residues returned to the soil (Amézketa, 1999). When comparing crop rotations, it is these differences in crop residues along with any different management practices that determines the effect on the soil. Compared to corn, less soybean residue is produced, but the C:N ratio of soybean residue is narrower than corn residue resulting in less immobilization and more rapid mineralization of nitrogen in the soil (Brady and Weil, 2002). This rapid mineralization also explains why soybean residue decomposition occurs more rapidly than for corn and wheat residue, but may also be due to less water soluble substances within corn and wheat residues which slows decomposition (Broder and Wagner, 1988). Corn produces more

residue compared to wheat due to higher yields even though harvest indices are similar (Studdert and Echeverria, 2000). Other differences are a result of non-legumes such as corn and wheat dependence on the amount of nitrogen fertilizer applied, with more biomass produced with additional nitrogen fertilizer (Studdert and Echeverria, 2000; Jagadamma et al., 2007). In contrast, legumes such as soybeans are nitrogen-fixing and nitrogen fertilizer is rarely applied (Nafziger, 2009). The type of crop residue and nitrogen fertilizer requirements of the crop are important differences between different crop rotations.

Studies have shown that soil organic matter can be increased by the addition of organic matter inputs into the soil or by decreasing the decomposition of the residue remaining on the soil (West and Post, 2002). Karlen et al. (1994b) reported that maintaining or doubling crop residues returned to a no-till continuous corn system led to higher soil organic carbon. Utilizing crop rotations that incorporate winter cover crops also increases crop residue and increases soil organic matter (Follett, 2001; Villamil et al., 2006). Extended rotations that include pasture or hay usually increase soil organic matter as a result of the additional residue, while shorter rotations such as corn-soybean and continuous corn tend to deplete soil organic matter (Bullock, 1992; Karlen et al., 2006). West and Post (2002) reported that increasing the complexity of a crop rotation can sequester 20 ± 12 g C m^{-2} yr^{-1}, except when changing from continuous corn to corn-soybean, which did not cause an accumulation of soil organic carbon. The inclusion of soybean within a crop rotation causes even more depletion, likely due to lower biomass produced by soybean compared to corn (Studdert and Echeverria, 2000; Hao et al., 2002; Coulter et al., 2009; Nafziger and Dunker, 2011). For corn, adequate nitrogen fertilizer application may influence the amount of biomass produced and therefore the soil organic matter. Varvel (1994)

reported that the continuous corn sequestered carbon when nitrogen fertilizer was applied, but the soil organic carbon was depleted under continuous corn with no nitrogen applied.

Increasing soil organic matter can also be accomplished by reducing tillage intensity, which slows or decreases decomposition of organic matter (Kladivko et al., 1986; Havlin et al., 1990; Halvorson et al., 2002; West and Post, 2002). Conventional tillage increases residue decomposition by disrupting the soil, exposing the plant material and existing soil organic matter thus stimulating the activity of aerobic microorganisms (Bullock, 1992; Addiscott and Dexter, 1994; Johnson and Hoyt, 1999).

Depletion of soil organic matter also affects the soil structure by reducing aggregate stability, which is the resistance of soil aggregates to erosion by water (Haynes and Beare, 1997; Hammerbeck et al., 2012). The inclusion of soybeans in a rotation with corn has been shown to reduce aggregate stability compared to continuous corn, which is due to either reduced residue accumulation and soil organic matter depletion (Kladivko et al., 1986; Jagadamma et al., 2008) or a decrease in humic substance content as a result of the biochemistry of soybean residue (Martens, 2000). Raimbault and Vyn (1991) have shown that extended rotations or rotations incorporating other legumes such as alfalfa and red clover or legume/grass mixtures produce more biomass and increase soil aggregate stability compared to shorter rotations. Reduced tillage practices also increases soil aggregate stability as more intensive tillage depletes the soil of organic matter by accelerating decomposition of crop residues and disruption of soil structure (Kladivko et al., 1986; Addiscott and Dexter, 1994; Karlen et al., 1994c; Martens, 2000).

Soil physical parameters such as bulk density are important indicators of air and water movement in the soil and restrictions to root growth. The increase of soil organic matter can decrease bulk density by incorporating a less dense material and improving aggregate stability

(Bullock, 1992; Karlen et al., 1994a; Reeves, 1994; Blanco-Canqui and Lal, 2004). Karlen et al. (2006) reported higher bulk density values for continuous corn and corn-soybean rotation compared to extended rotations that incorporated oats, pasture, or some combination; these extended rotations produced more biomass leading to greater soil organic matter content. Coulter et al. (2009) reported that bulk density was 5% greater after 8 years under a corn-soybean rotation compared to continuous corn due to a greater aggregate stability from the addition of soil organic matter under continuous corn. However, a number of other studies report no effect on bulk density due to the cropping system (Varvel, 1994; Huggins et al., 2007; Jagadamma et al., 2007). For tillage practices, the results are also conflicting. Some studies have found that bulk density values are greater under no-till than conventional tillage (Hill, 1990; Wander and Bollero, 1999; Balesdent et al. 2000; Halvorson et al., 2002). Meanwhile, other studies have found that tillage has no effect on bulk density (Ismail et al., 1994; Karlen et al., 1994c; Kitur et al., 1994a; Hussain et al., 1998; Al-Kaisi et al., 2005; Huggins et al., 2007). While the process of tillage does loosen the soil and create macropores lowering the bulk density of the soil, the increase in organic matter and aggregate stability due to no-till may be the reason no difference was found in some studies (Hussain et al., 1998; Coulter et al., 2009).

A number of studies have examined the effects on soil properties of crop rotation and tillage independently, but there are fewer studies that have studied the interactive effect of crop rotation and tillage. Of those, many of the studies were in the Central Great Plains (Havlin et al., 1990; Benjamin et al., 2010; Varvel and Wilhelm, 2011) or Canada (Raimbault and Vyn, 1991). It is the Midwest, however, that has four states, Illinois, Iowa, Minnesota, and Indiana among the top five grain producing states in the U.S. (USDA/NASS, 2007). Despite the importance of the Midwest to United States grain production, few studies have evaluated the combined effects of

crop rotation and tillage in those states. Kladivko et al. (1986) in Indiana, Karlen et al. (1991) in Iowa, Huggins et al. (2007) in Minnesota, and Kumar et al. (2012) all examined the combined effect of crop rotation and tillage practice on soil organic matter. Karlen et al. (1991) also evaluated other soil chemical properties including nutrient availability and pH. The physical soil properties reported were bulk density (Huggins et al., 2007; Kumar et al., 2012) and aggregate stability (Kladivko et al., 1986; Kumar et al., 2012).

Karlen et al. (1991) and Kumar et al. (2012) focused on two-year corn/soybean rotation and continuous corn while Kladivko et al. (1986) and Huggins et al. (2007) also studied the less common continuous soybean rotation. The impact of extending the rotation by one year with a small grain such as winter wheat (*Triticum aestivum* L.) in combination with tillage practices remains unstudied. All of these combination studies are considered to be long-term; the fields utilized in Kladivko et al. (1986), Karlen et al. (1991), and Huggins et al. (2007) had been established seven, twelve, and fourteen years prior to sampling, respectively, while Kumar et al. (2012) were established nearly fifty years prior to sampling. The time period since establishment of the study sites is important because it takes several years for changes in the soil to develop after a change in the tillage system (Hill, 1990).

No previous studies in Illinois have simultaneously evaluated the effect of crop rotation and tillage in a long-term study despite the state's role as a top producer of grain in the U.S. The aims of this study are to address these research gaps by examining the effect of crop rotation and tillage simultaneously in a long-term stable system. The objective is to determine the effect of these management practices on both soil chemical and physical properties and to identify which of the crop rotations and tillage practices are best able to maintain the beneficial soil properties.

MATERIALS AND METHODS

Site Descriptions

This study was conducted at two locations in Western Illinois at the Northwestern Illinois Agricultural Research and Demonstration Center, approximately 5 miles northwest of Monmouth, Illinois (40°55’ N, 90°43’ W) and at the Orr Agricultural Research and Demonstration Center, approximately 5 miles northwest of Perry, Illinois in northeast Pike County (39°48’ N, 90°49’ W).

The experiments were on Sable silty clay loam (Fine-silty, mixed, mesic Typic Endoaquolls) and Muscatune silt loam (Fine-silty, mixed, mesic Aquic Argiudolls) at Monmouth and on Caseyville silt loam (Fine-silty, mixed, mesic Aeric Endoaqualfs) and Downsouth silt loam (Fine-silty, mixed, mesic Mollic Oxyaquic Hapludalfs) at Perry. Sable and Muscatune series consists of poorly drained and somewhat poorly drained soils, respectively. These soils are very deep, formed in loess and have a slope of 0-2%. Caseyville and Downsouth series consist of somewhat poorly drained and moderately well drained soils, respectively. These soils are very deep, formed in loess on till plains and have 2-5% slopes (Soil Survey Staff, 2013).

Soil Sampling and Analysis Procedure

Soils were sampled in May 2011 at the Monmouth location and at Perry in May 2012. At the Monmouth location, three soil cores with 3.1 cm diameter were taken with a hand-held split-core sampler in each plot and cut in the field at depths of 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm and stored in plastic bags in a refrigerator. For the Perry location, an Amity 4804 tractor mounted hydraulic probe (Amity Techology, Fargo, ND) was used to take three soil cores with 4.3 cm diameter in each plot. The cores were transported and stored in plastic sleeves until cut to

obtain 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm subsamples in the laboratory and stored in plastic bags in a refrigerator.

Bulk density (BD) values were determined using the core method (Blake and Hartge, 1986). The mass of the moist soil was determined and adjusted for moisture. The moisture content was determined by oven-drying a subsample. NO_3-N and NH_4-N were determined by flow injection (Lachat Quickchem Analyzer, Lachat Instruments, Loveland, CO) using colorimetry after extraction with 1 M KCl. Soil pH was determined with 1:1 soil: H_2O solution. These determinations of extractable nitrogen and pH were made following the procedures in the Soil Survey Laboratory Methods manual (USDA/NRCS, 2004)

The remaining soil samples were air-dried and sieved through 2-mm sieve, and the three replicated samples from each plot were composited to provide one sample per plot. Total carbon (TC) and total nitrogen (TN) were determined by combustion with a CHN Elemental Analyzer (Costech Analytical Technologies, Inc, Valencia, CA). Three subsamples of the 1- to 2-mm soil fraction at 0-10 and 10-20 cm depths were used to determine water aggregate stability with an Eijkelkamp wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Netherlands) using the procedure developed by Kemper and Rosenau (1986). Particle size analysis was completed on 50 grams of the air-dried, ground (<2 mm), composited soil samples using the hydrometer method (Gee and Bauder, 1986).

Available phosphorus (Bray P1) was determined by flow injection (Lachat Quickchem Analyzer, Lachat Instruments, Loveland, CO) following Bray-1 extraction. The cation exchange capacity (CEC) was determined by the summation method of exchangeable cations, which were determined with an inductively coupled plasma mass spectrometer (PerkinElmer, Waltham, MA)

following Mehlich III extraction. For determination of pH, available phosphorus, and cation exchange capacity, the Perry samples were sent to Brookside Laboratories in New Benton, OH.

Experimental Design and Statistical Analysis

The plots were established in 1997 as a split-plot arrangement of rotation and tillage treatments in randomized complete block design with four blocks at each location with each phase of the rotations present each year. The whole plot treatment was the crop rotations of continuous corn, corn-soybean, corn-soybean-wheat, and continuous soybean. Subplot treatments were two levels of tillage: chisel tillage and no-till. The whole plots were 22 m long by 12 m wide while the sub-plot treatments were 22 m long by 6 m wide. Soil samples were taken in each rotation only in those plots where corn was grown in the sampling year, and in continuous soybean. For all measurements except water aggregate stability, there were four subsamples at successive depths at 0-10, 10-20, 20-40, and 40-60 cm. Only the top two depths of 0-10 and 10-20 cm were analyzed for water aggregate stability.



Figure 1. Aerial photo of the experimental site at Monmouth, IL.



Figure 2. Aerial photo of the experimental site at Perry, IL. The fields are outlined.

Results from this experiment were analyzed both by site and across the two sites, with location treated as random. Unless otherwise noted, results discussed are combined over sites.

The linear model used for statistical analysis of the dependent variable for each site was

$$y_{ijkl} = \mu + B_i + \alpha_j + \varepsilon_{1(ij)} + \gamma_k + \alpha\gamma_{jk} + \varepsilon_{2(ijk)} + \theta_l + \alpha\theta_{jl} + \gamma\theta_{kl} + \alpha\gamma\theta_{jkl} + \varepsilon_{3(ijkl)}$$

where,

y_{ijkl} =observation for within ith BLOCK of the jth ROTATION and kth TILLAGE at the lth DEPTH

μ =overall mean

B_i =random effect of the ith BLOCK (i=1, 2, 3, 4), (0, σ_b^2)

α_j =fixed effect of the jth ROTATION (j=1, 2, 3, 4)

$\varepsilon_{1(ij)}$ =random whole-plot error of the jth ROTATION in the ith BLOCK—$NID\ (0, \sigma_{e1}^2)$

γ_k =fixed effect of the kth TILLAGE (k=1, 2)

$\alpha\gamma_{jk}$ =fixed interaction effect of the jth ROTATION and the kth TILLAGE

$\varepsilon_{2(ijk)}$ =random sub-plot 1 error of the jth ROTATION and k[th] TILLAGE in the ith BLOCK—$NID\ (0, \sigma_{e2}^2)$

θ_l =fixed effect of the lth DEPTH (l=1, 2, 3, 4 OR l=1, 2)

$\alpha\theta_{jl}$ =fixed interaction effect of the jth ROTATION and the lth DEPTH

$\gamma\theta_{kl}$ =fixed interaction effect of the kth TILLAGE and the lth DEPTH

$\alpha\gamma\theta_{jkl}$ =fixed interaction effect of the jth ROTATION, the kth TILLAGE and the lth DEPTH

$\varepsilon_{3(ijkl)}$ =random experimental error of the ith BLOCK, j[th] ROTATION, k[th] TILLAGE at the lth DEPTH or the residual—$NID\ (0, \sigma_{e3}^2)$

For analysis over sites, the blocks are nested within the sites and site is a random factor. The linear model used for statistical analysis of the dependent variable over both sites was

$$y_{ijklm} = \mu + S_i + B_{(i)j} + \alpha_k + \varepsilon_{1(ijk)} + \gamma_l + \alpha\gamma_{kl} + \varepsilon_{2(ijkl)} + \theta_m + \alpha\theta_{km} + \gamma\theta_{lm} + \alpha\gamma\theta_{klm} + \varepsilon_{3(ijklm)}$$

where,

y_{ijklm} =observation for the kth ROTATION and l[th] TILLAGE at the mth DEPTH within j[th] BLOCK of the ith SITE

μ =overall mean

S_i =fixed effect of the ith SITE (i=1, 2)

$B_{(i)j}$ =random effect of the jth BLOCK at the ith SITE (j=1, 2, 3, 4), (0, σ_b^2)

α_k =fixed effect of the kth ROTATION (k=1, 2, 3, 4)

$\varepsilon_{1(ijk)}$ =random whole-plot error of the kth ROTATION in the jth BLOCK at the ith SITE — $NID\ (0, \sigma_{e1}^2)$

γ_l =fixed effect of the lth TILLAGE (l=1, 2)

$\alpha\gamma_{kl}$ =fixed interaction effect of the kth ROTATION and the lth TILLAGE

$\varepsilon_{2(ijkl)}$ =random sub-plot 1 error of the kth ROTATION and l[th] TILLAGE in the jth BLOCK of the ith SITE—$NID\ (0, \sigma_{e2}^2)$

θ_m =fixed effect of the mth DEPTH (m=1, 2, 3, 4 OR m=1, 2)

$\alpha\theta_{km}$ =fixed interaction effect of the kth ROTATION and the mth DEPTH

$\gamma\theta_{lm}$ =fixed interaction effect of the lth TILLAGE and the mth DEPTH

$\alpha\gamma\theta_{klm}$ =fixed interaction effect of the kth ROTATION, the lth TILLAGE and the mth DEPTH

$\varepsilon_{3(ijklm)}$ =random experimental error of the ith SITE, j[th] BLOCK, k[th] ROTATION, l[th] TILLAGE at the mth DEPTH or the residual—$NID\ (0, \sigma_{e3}^2)$

These models were analyzed using the MIXED procedure of SAS software (SAS Institute Inc., 2012). Dependent variables measured at four successive depths were analyzed using a repeated measures approach (Littell et al., 2006). The models used for the variance-covariance matrix of the residuals were selected based on the Akaike's Information Criterion and the corrected Akaike's Information Criterion. The chosen models were AR(1), first order autoregressive, ARH(1), heterogeneous first order autoregressive, or TOEP, Toeplitz depending on the variable.

The SAS coding for the first model with SITEs run separate is as follows:

```
proc mixed data=thesis; by E;
class B R T D;
model variable=R|T|D/ddfm=kr;
random B B*R B*R*T;
repeated D/type=ar(1) subject= B*R*T; run;
```

The SAS coding for the second model with sites combined as a random effect is as follows:

```
proc mixed data=thesis;
class S B R T D;
model variable= R|T|D/ddfm=kr;
random S B(S) R*B(S) R*T*B(S);
repeated D/type=ar(1) subject= R*T*B(S); run;
```

The variables water aggregate stability, available phosphorus, soil nitrate, and soil ammonium required transformations to normalize the data. The transformations were determined using the BOXCOX and SYMBOX macros in SAS (Friendly, 1991). When more than one transformation was possible, the more common one in the literature was used. The transformations used were x^2 for water aggregate stability, $\log_{10} x$ for available P and NO_3-N and $x^{-1/2}$ for NH_4-N. For mean separations and determination of significance, the probability of Type I error or alpha level (α) was set at 0.10.

RESULTS

Soil Texture and Particle Size Distribution

The soils on which the study was conducted include two different soil orders (Mollisol and Alfisol) and several different soil series. However, the results from the particle size analysis show that the overall particle size distribution between all the series is homogeneous (Table 1). The textural class of the soils at the two locations differs by depth (Fig. 3). At Monmouth, the textural classes of the soils are silt loam and silty clay loam, but the particle size distributions, regardless of depth, are not significantly different as they are clustered tightly near the threshold between the two textural classes. At Perry, the textural classes vary by depth since two different horizons were sampled. The textural class of the A horizon is silt loam. The Bt horizon begins at approximately 30 cm with a textural class of silty clay loam. This increase in clay content at greater depth is typical of an Alfisol, which is characterized by translocated clays into an argillic horizon.

Table 1. Mean values of particle size separates for each crop rotation over 0-60 cm soil depths at two sites-Monmouth and Perry, IL.

		Particle size separate (%)		
Site	Rotation[†]	Sand	Silt	Clay
Monmouth	CCC	2.9	69.3	27.8
	CS	2.4	71.1	26.5
	CSW	2.7	71.2	26.2
	SSS	2.1	70.9	26.9
SE[‡]		0.22	0.89	0.89
Perry	CCC	2.7	69.8	27.5
	CS	3.2	70.5	26.3
	CSW	2.4	69.9	27.7
	SSS	3.4	71.3	25.3
SE		0.52	1.97	1.69

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]SE , standard error of the mean

The lack of statistical differences within each location is of importance due to the influence of soil texture on the nature and behavior of soils (Hillel, 1998). Variability in the particle size distribution may lead to incorrect conclusions as many physical soil properties, such as bulk density and water aggregate stability are very sensitive to differences in particle size distribution (Daddow and Warrington, 1983; Amézketa, 1999). With consistent particle size at a site, differences can be attributed to effect of the treatments.

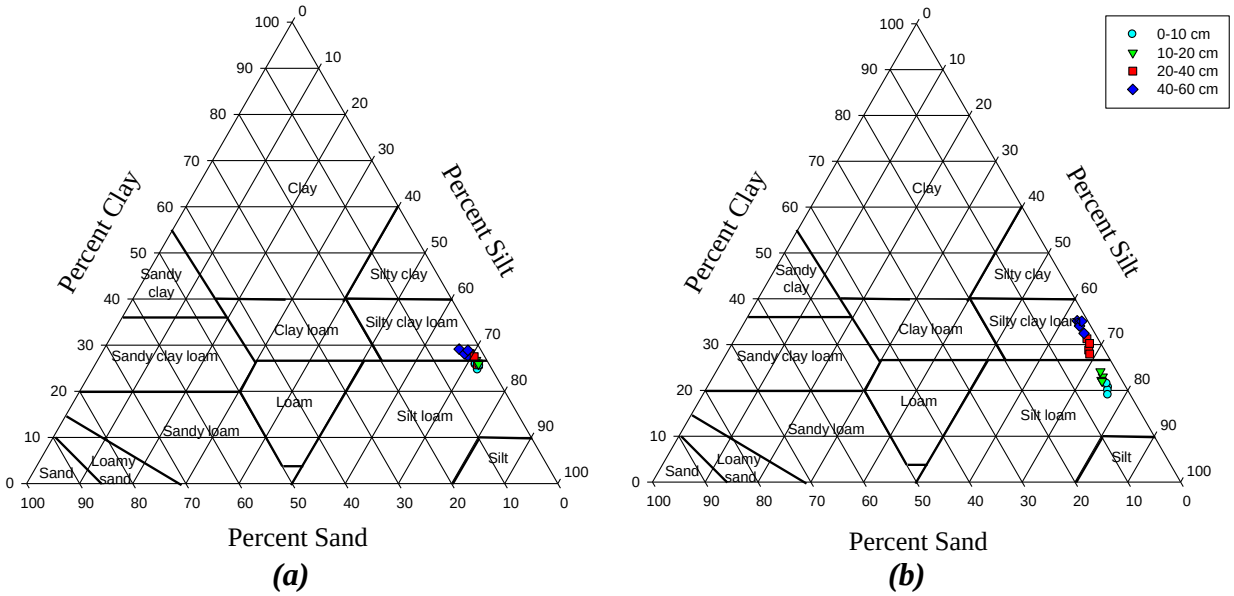

Figure 3. Textural triangle showing the percentages by weight of clay (<0.002 mm), silt (0.002-0.05 mm), and sand (0.05-2 mm) separates of the soils at (a) Monmouth and (b) Perry, IL at varying depths in the USDA soil textural classes.

Soil Physical Properties

Bulk Density

At Monmouth, the interaction effect of tillage and depth ($p<0.008$) and the main effects of rotation ($p<0.012$), tillage (0.004), and depth (<0.0001) were determined to be statistically significant for soil bulk density (BD). The ANOVA tables for each soil property can be found in the appendix. The bulk density under no-till was significantly greater than that under tillage in the surface (0-10 cm) but not at greater depths (Table 2). Under both conventional tillage and no-

till, BD was higher at deeper positions than at the surface. In no-till, BD values at the surface did not differ from the soil profile below 20 cm, while the conventional tillage had significantly lower BD at the surface than the soil below. The highest BD for both tillage practices is found at the 10-20 cm depth. The effect of crop rotation on bulk density values also differed at Monmouth (Table 3). The highest BD were observed in the monocultures (SSS; CCC), followed by the two-year rotation (CS) and the smallest BD in the three-year rotation (CSW). The overall trend was a decrease in BD as more crop species were added to the rotation.

Table 2. Mean values of bulk density as affected by tillage practice and depth at Monmouth, IL.

	Tillage[†]			
	CT		NT	
Depth (cm)	g cm^{-3}			
0-10	1.28	a[‡]A[§]	1.35	a B
10-20	1.43	c A	1.45	b A
20-40	1.38	b A	1.37	a A
40-60	1.36	b A	1.40	ab A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 3. Mean values of bulk density over 0-60 cm soil depth as affected by tillage practice or crop rotation at Monmouth, IL.

Factor	Levels[†]	g cm^{-3}
Tillage	CT	1.36 A[§]
	NT	1.39 B
Rotation	CCC	1.39 bc[¶]
	CS	1.37 ab
	CSW	1.35 a
	SSS	1.40 c

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[§]Between tillage practice, means followed by the same uppercase letter are not significantly different at p=0.1 over 0-60 cm depths
[¶]Among crop rotations, means followed by the same lowercase letter are not significantly different at p=0.1 over 0-60 cm depths.

Significant effects on BD at Perry included the interaction effect of tillage and depth ($p<0.008$) and the main effects of tillage ($p<0.018$) and depth ($p<0.0001$). Unlike Monmouth, rotation was not significant for BD, but the three-way interaction (rotation x tillage x depth) was significant ($p<0.0535$) at Perry.

The 3-way interaction effect shows that BD for two of the rotations (CCC and CS) over the studied soil depths was similar to the overall pattern at Monmouth with BD greater for no-till at the surface (Fig. 2). However, at Perry, BD for no-till was also greater than conventional tillage at 10-20 cm. For the corn-soybean rotation, BD was greater for no-till at 10-20 cm and 20-40 cm depths, but there was no difference between tillage practices at 0-10 cm. No differences between tillage practices were observed within the soil profile for the continuous soybean rotation. Over all the rotations, no-till BD was greater than the conventional tillage BD only at 10-20 cm (Table 4).

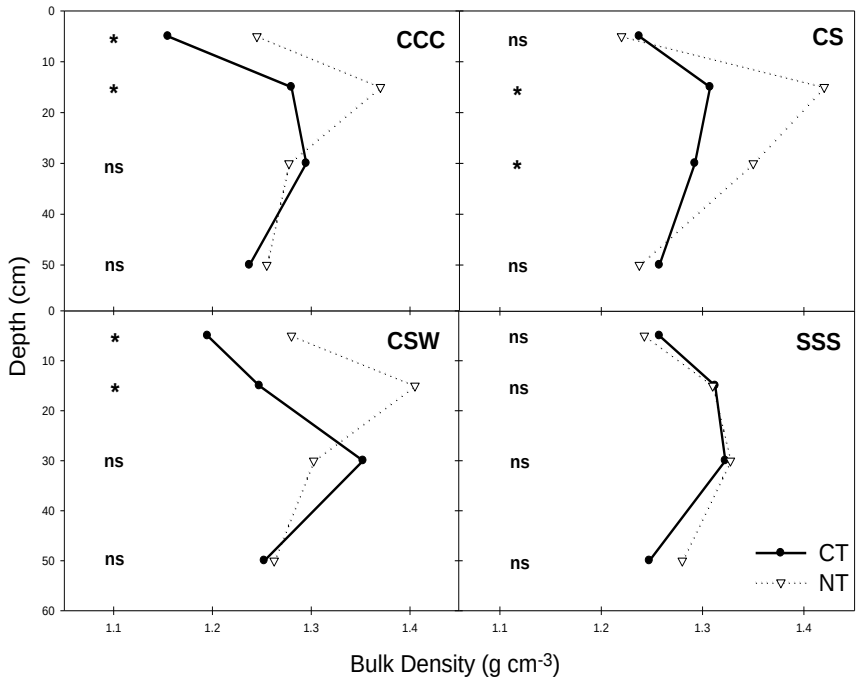

Figure 4. Effect of tillage practice and depth on bulk density for each crop rotation at Perry, IL. Significant and not significantly different at p=0.1 are indicated by * and ns, respectively. CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.

Table 4. Mean values of bulk density as affected by tillage practice and soil depth at Perry, IL.

	Tillage[†]			
	CT		NT	
Depth (cm)	——————g cm^{-3}——————			
0-10	1.21	a[‡]A[§]	1.25	a A
10-20	1.29	c A	1.38	c B
20-40	1.32	d A	1.31	b A
40-60	1.25	b A	1.26	a A

[†]CT, conventional tillage; NT, no-till.
[‡] Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§] Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Over sites, the interaction effect of tillage and depth ($p<0.029$) as well as the main effects of tillage ($p<0.002$) and depth ($p<0.0001$) were statistically significant for BD. Over sites, the BD for no-till is greater than conventional tillage for the top 20 cm of the soil (Table 5). The BD is greater below the surface regardless of tillage practice, especially in the traffic/plow pan layer at 10-20 cm depth.

Table 5. Mean values of bulk density as affected by tillage practice and depth over sites.

	Tillage[†]			
	CT		NT	
Depth (cm)	——————g cm^{-3}——————			
0-10	1.25	a[‡]A[§]	1.30	a B
10-20	1.36	c A	1.41	c B
20-40	1.35	c A	1.34	b A
40-60	1.31	b A	1.33	b A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Water Aggregate Stability

There were no significant interaction or main effects at Monmouth for water aggregate stability (WAS), but the trend was observed of a higher WAS in the three-year rotation (CSW) compared to the other rotations and in no-till compared to conventional tillage (Table 6).

Table 6. Mean values of water aggregate stability over 0-20 cm depth as affected by tillage practice or crop rotation at Monmouth, IL, Perry, IL, and over sites.

		Monmouth		Perry		Over Sites	
Factor	Levels[†]	g g^{-1}					
Tillage	CT	87.0	ns[‡]	75.6	A[§]	81.6	A
	NT	88.4		80.9	B	84.7	B
Rotation	CCC	86.7	ns	80.1	b[¶]	83.6	bc
	CS	85.2		80.0	b	82.6	ab
	CSW	93.2		80.8	b	87.2	c
	SSS	85.3		72.1	a	79.0	a

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Means are not significantly different at p=0.1 over all depths.
[§]Between tillage practices at a given site or over sites, means followed by the same uppercase letter are not significantly different at p=0.1 over all depths.
[¶]Among crop rotations at a given site or over sites, means followed by the same lowercase letter are not significantly different at p=0.1 over all depths.

At Perry, the main effects of rotation ($p<0.070$) and tillage ($p<0.010$) were statistically significant for WAS. The WAS was greater for no-till compared to conventional tillage and for all rotations that included corn (CCC, CS, CSW) compared to continuous soybean.

With combined results over sites, the significant effects are the same as at Perry, rotation ($p<0.033$) and tillage ($p<0.030$). Again, as at Perry, WAS was greater for no-till compared to conventional tillage. Continuous soybean was found to have the lowest WAS, but was not statistically different from corn-soybean. The three year corn-soybean-wheat rotation produced the highest WAS, but this was not statistically different from the continuous corn.

Soil Chemical Properties

Cation Exchange Capacity

No interaction effects were statistically significant for cation exchange capacity (CEC) at Monmouth, but the main effect depth ($p<0.0001$) was significant. In Monmouth, CEC decreased with depth (Table 7). At Perry, the interaction effect between rotation and depth ($p<0.0001$) and the main effects of rotation ($p<0.001$) and depth ($p<0.0001$) were significant for CEC. At the surface level, CEC in the three rotations with corn were higher than in the continuous soybean. For the corn-soybean and corn-soybean-wheat rotations, CEC was lower in the 20-40 cm depth than any other depths at Perry (Table 8). In the combined model over sites, only the main effect of depth was significant for CEC, which decreased with depth (Table 9).

Table 7. Mean values of cation exchange capacity by depth at Monmouth, IL.

Depth (cm)	cmol kg^{-1}	
0-10	27.4	c[†]
10-20	22.7	b
20-40	13.2	a
40-60	13.0	a

[†]Between depths, means followed by the same lowercase letter are not significantly different at p=0.1.

Table 8. Mean values of cation exchange capacity by depth as affected by rotation at Perry, IL.

	Rotation[†]			
	CCC	CS	CSW	SSS
Depth (cm)	cmol kg^{-1}			
0-10	19.2 a[†]B[§]	22.2 b B	20.3 b B	14.9 a A
10-20	20.3 a B	20.7 b B	19.1 ab B	15.1 a A
20-40	19.4 a C	18.2 a BC	17.1 a AB	15.9 a A
40-60	21.9 a AB	20.3 ab A	22.5 b AB	24.0 a B

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a rotation and for each column, means followed by the same lowercase letter are not significantly different at p=0.1.
[§]Among crop rotations, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 9. Mean values of cation exchange capacity by depth over sites.

Depth (cm)	cmol kg^{-1}
0-10	23.3 d[‡]
10-20	20.8 c
20-40	15.4 a
40-60	17.6 b

[†]Between depths, means followed by the same lowercase letter are not significantly different at *p*=0.1.

pH

At Monmouth, statistically significant interaction effects between tillage and depth ($p<0.044$) and between rotation and depth ($p<0.0001$) as well as main effects rotation ($p<0.012$), tillage ($p<0.060$), and depth ($p<0.0001$) on soil pH were determined. At Monmouth, the soil pH of no-till was lower than conventional tillage, but only at the surface (Table 10). Soil pH was greater in continuous soybean, intermediate in corn-soybean and corn-soybean-wheat, and lowest in continuous corn, but only near the surface. There are no differences in pH below 20 cm at Monmouth.

Table 10. Mean values of pH as affected by tillage practice or crop rotation at Monmouth, IL.

	Tillage[†]		Rotation			
Depth (cm)	CT	NT	CCC	CS	CSW	SSS
0-10	6.3 a[‡]B[§]	5.9 a A	5.5 b A	6.1 b B	6.0 b B	6.8 a C
10-20	6.6 b A	6.6 b A	6.3 a A	6.6 a AB	6.5 a AB	6.8 a B
20-40	6.5 b A	6.5 b A	6.5 a A	6.5 a A	6.5 a A	6.6 a A
40-60	6.5 b A	6.5 b A	6.5 a A	6.5 a A	6.5 a A	6.7 a A
Mean[¶]	6.5 B	6.4 A	6.2 A	6.4 B	6.4 AB	6.7 C

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a treatment and for each column, means followed by the same lowercase letter are not significantly different at *p*=0.1.
[§]Between tillage and among rotation treatments, means followed by the same uppercase letter at a given depth are not significantly different at *p*=0.1.
[¶]Mean values of tillage and rotation treatments over all depths. Within tillage and within rotation, means followed by the same uppercase letter are not significantly different at *p*=0.1.

Interaction effects between rotation and depth ($p<0.0001$) and the main effects of rotation ($p<0.001$), tillage ($p<0.089$), and depth ($p<0.0001$) were determined to be significant for soil pH at Perry. As at Monmouth, soil pH was greatest in continuous soybean and lowest in continuous corn with corn-soybean and corn-soybean-wheat rotations intermediate between the two monocultures (Table 11). The pH values decreased with depth down to 40 cm, but below 40 cm either decreased (CS, CSW, SSS) or was not significantly different (CCC). Soil pH was greater for conventional tillage than no-till.

Table 11. Mean values of pH as affected by tillage practice or crop rotation at Perry, IL.

	Tillage[†]		Rotation			
Depth (cm)	CT	NT	CCC	CS	CSW	SSS
0-10	5.2	5.0	4.6 a[‡]A[§]	4.9 a B	4.9 a B	5.9 b C
10-20	5.4	5.2	4.7 a A	5.1 b B	5.4 b B	6.1 c C
20-40	6.1	5.9	5.8 b A	6.1 d B	6.1 d B	6.1 bc B
40-60	5.7	5.8	5.8 b AB	5.8 c AB	5.9 c B	5.6 a A
[¶]Mean	5.6 B	5.5 A	5.2 A	5.5 B	5.6 B	5.9 C

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a rotation treatment and for each column, means followed by the same lowercase letter are not significantly different at p=0.1.
[§]Among rotation treatments, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.
[¶]Mean values of tillage and rotation treatments over all depths. Within tillage and within rotation, means followed by the same uppercase letter are not significantly different at p=0.1.

For the combined results of Monmouth and Perry, the interaction effect between rotation and depth ($p<0.0001$) and main effects of rotation ($p<0.0001$), tillage (0.014), and depth ($p<0.0001$) were determine statistically significant for soil pH. The significant differences were the same as Perry with highest pH with continuous soybean, followed by corn-soybean, corn-soybean-wheat, and the lowest pH in continuous corn (Table 12). The soil pH in conventional tillage was higher than in no-till.

Table 12. Mean values of pH as affected by tillage practice or crop rotation over sites.

	Tillage[†]		Rotation			
Depth (cm)	CT	NT	CCC	CS	CSW	SSS
0-10	5.7	5.4	5.0 a[‡]A[§]	5.5 a B	5.4 a B	6.4 b C
10-20	6.0	5.9	5.5 b A	5.9 b B	5.9 b B	6.4 b C
20-40	6.3	6.2	6.1 c A	6.3 c AB	6.3 c AB	6.4 b B
40-60	6.1	6.2	6.1 c A	6.2 c A	6.2 c A	6.1 a A
[¶]Mean	6.0 B	5.9 A	5.7 A	6.0 B	6.0 B	6.3 C

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a rotation treatment and for each column, means followed by the same lowercase letter are not significantly different at p=0.1.
[§]Among rotation treatments, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.
[¶]Mean values of tillage and rotation treatments over all depths. Within tillage and within rotation, means followed by the same uppercase letter are not significantly different at p=0.1.

Total Carbon

The main effect of depth ($p<0.0001$) was the only statistically significant effect on total carbon (TC) at Monmouth. As expected, TC is greater at the soil surface where plant residues provide the main source of organic matter and decreases deeper into the soil profile as the amount of plant material decreases (Table 13).

Table 13. Mean values of total carbon at a given depth as affected by tillage practice or crop rotation at Monmouth, IL.

	Tillage[†]		Rotation			
	CT	NT	CCC	CS	CSW	SSS
Depth (cm)	g kg soil^{-1}		g kg soil^{-1}			
0-10	26.64	26.58	27.15	23.99	29.68	25.64
10-20	21.94	22.25	22.84	20.08	24.45	21.01
20-40	19.38	19.89	19.04	18.68	22.96	17.88
40-60	10.26	12.18	11.01	8.80	13.19	11.88

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.

At Perry, statistically significant interaction effects of tillage and depth ($p<0.0001$) and rotation and depth ($p<0.0001$) were detected along with the main effect of depth ($p<0.0001$). TC was significantly higher in no-till at the 0-10 cm depth and in conventional tillage over the 10-20 cm depths (Table 14). This result reflects the mixing of the plant residues into the soil in conventional tillage, while residues are introduced into no-till only through the surface. Below the surface, none of the rotations have significantly different TC (Table 15). However, at the surface, TC was lower for rotations incorporating soybeans more frequently. TC was 17% lower under continuous soybean and 9% lower under corn-soybean than under continuous corn and corn-soybean-wheat. As mentioned previously, soybeans produce less biomass and therefore the addition of carbon and organic matter each growing season is less under soybean than under corn or wheat.

Over sites, the depth ($p<0.0001$) main effect was significant with the same pattern of decreasing TC deeper into the soil (Table 16). No other interaction or main effects were significant in the combined model.

Table 14. Mean values of total carbon at a given depth as affected by tillage practice at Perry, IL.

	Tillage[†]	
	CT	NT
Depth (cm)	——————g kg soil^{-1}——————	
0-10	11.76 d[‡]A[§]	13.32 d B
10-20	9.49 c B	8.97 c A
20-40	6.43 b A	6.41 b A
40-60	4.73 a A	4.74 a A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 15. Mean values of total carbon at a given depth as affected by crop rotation at Perry, IL.

	Rotation[†]			
	CCC	CS	CSW	SSS
Depth (cm)	g kg soil^{-1}			
0-10	13.27 d[‡]C[§]	12.20 d B	13.54 d C	11.16 d A
10-20	9.49 c A	9.24 c A	9.10 c A	9.10 c A
20-40	6.32 b A	6.64 b A	6.28 b A	6.43 b A
40-60	4.59 a A	4.90 a A	4.66 a A	4.78 a A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a crop rotation and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Among crop rotations and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 16. Mean values of TC at a given depth as affected by tillage practice or crop rotation over sites.

	Tillage[†]		Rotation			
	CT	NT	CCC	CS	CSW	SSS
Depth (cm)	g kg soil^{-1}					
0-10	19.20	19.95	20.21	18.09	21.61	18.40
10-20	15.72	15.61	16.17	14.66	16.78	15.06
20-40	12.91	13.15	12.68	12.66	14.62	12.15
40-60	7.49	8.46	7.80	6.85	8.93	8.33

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.

Total Nitrogen

At Monmouth, no interaction effects are statistically significant for total nitrogen (TN), but the main effect of depth ($p<0.0001$) is statistically significant. As with TC, TN decreased with depth (Table 17).

Table 17. Mean values of total nitrogen at a given depth as affected by tillage or crop rotation at Monmouth, IL.

	Tillage[†]		Rotation			
	CT	NT	CCC	CS	CSW	SSS
Depth (cm)	g kg soil^{-1}		g kg soil^{-1}			
0-10	2.06	2.13	2.13	2.00	2.25	2.00
10-20	1.68	1.71	1.74	1.63	1.85	1.55
20-40	1.47	1.51	1.49	1.49	1.66	1.31
40-60	0.83	0.97	0.91	0.76	1.03	0.89

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.

At Perry, the interaction effects of tillage and depth ($p<0.0003$) and rotation and depth ($p<0.010$) are statistically significant. The main effects of rotation ($p<0.042$) and depth ($p<0.0001$) are also significant, but tillage is not. Differences between the tillage practices over the soil profile follow the same pattern with TN as with TC, where no-till is greater in the surface soil to 10 cm and conventional tillage is greater in the 10-20 cm depth soil (Table 18). As at Monmouth, TN decreases with depth. TN was greater for the three rotations that include corn at the 0-10 cm and 10-20 cm depths compared to continuous soybean, but there were no significant differences below those depths for TN (Table 19).

Table 18. Mean values of total nitrogen at a given depth as affected by tillage at Perry, IL.

	Tillage[†]	
	CT	NT
Depth (cm)	g kg soil^{-1}	
0-10	1.22 d[‡]A[§]	1.37 d B
10-20	1.02 c B	0.96 c A
20-40	0.70 b A	0.70 b A
40-60	0.54 a A	0.54 a A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at $p=0.1$.
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at $p=0.1$.

Table 19. Mean values of total nitrogen at a given depth as affected by rotation at Perry, IL.

	Rotation[†]			
	CCC	CS	CSW	SSS
Depth (cm)	g kg soil^{-1}			
0-10	1.37 d[‡]B[§]	1.35 d B	1.39 d B	1.08 d A
10-20	1.00 c B	1.02 c B	1.00 c B	0.93 c A
20-40	0.69 b A	0.73 b A	0.69 b A	0.67 b A
40-60	0.53 a A	0.56 a A	0.55 a A	0.54 a A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a crop rotation and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Among crop rotations and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

For the combined model of Monmouth and Perry, no interaction effects were significant for TN, but the main effects of rotation ($p<0.079$) and depth (<0.0001) were determined to be statistically significant. TN was greater for the three-year corn-soybean-wheat rotation than continuous soybean, but continuous corn and corn-soybean did not differ from any of the others (Table 20).

Table 20. Mean values of total nitrogen over all depths and tillage practices as affected by crop rotation over sites.

Factor	Levels[†]	g kg soil^{-1}	
Rotation	CCC	1.23	ab[‡]
	CS	1.19	ab
	CSW	1.30	b
	SSS	1.12	a

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Among crop rotations, means followed by the same lowercase letter are not significantly different at p=0.1 over all depths.

Carbon: Nitrogen Ratio

Statistically significant main effects of rotation ($p<0.077$) and depth ($p<0.0001$) were determined for the carbon: nitrogen (C:N) ratio at Monmouth. The lowest C:N ratio was observed in the corn-soybean rotation, but this was not statistically different from the C:N ratio

of continuous corn (Table 21). The C:N ratio at Monmouth was the lowest at the surface and at 40-60 cm depths. At Perry, only the main effect of depth ($p<0.0001$) was statistically significant for C:N ratio. The widest ratio was found at the surface and decreased with depth. Within the model containing sites as a random factor, both main effects of rotation ($p<0.018$) and depth ($p<0.0001$) were determined to be statistically significant. The C:N ratio of the corn-soybean rotation was the narrowest over sites. The C:N ratio did not differ between 0-10, 10-20, and 20-40 cm depths, but was statistically lower in the deepest portion of the soil profile measured (40-60 cm).

Table 21. Main effects of rotation and depth on C:N ratio separately at Monmouth, IL and Perry, IL and combined over sites.

Factor	Levels[†]	Monmouth	Perry	Over Sites
Rotation	CCC	12.71 AB[‡]	9.28	10.99 B
	CS	12.15 A	8.98 ns[§]	10.56 A
	CSW	13.27 B	9.04	11.15 B
	SSS	13.21 B	9.60	11.41 B
Depth (cm)	0-10	12.69 a[¶]	9.75 c	11.22 b
	10-20	13.06 b	9.34 b	11.20 b
	20-40	13.20 b	9.14 b	11.17 b
	40-60	12.40 a	8.67 a	10.53 a

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Among crop rotations at a site or over sites, means followed by the same uppercase letter are not significantly different at p=0.1 over all depths.
[§]Means are not significantly different at p=0.1 over all depths.
[¶]Between depths at a site or over sites, means followed by the same lowercase letter are not significantly different at p=0.1.

Soil NO_3-N

The interaction effect of tillage and depth ($p<0.020$) and main effect of rotation ($p<0.004$) were determined to be statistically significant for soil nitrate (NO_3-N) at Monmouth. Nitrate levels were higher in the surface of no-till compared to conventional tillage (Table 22). More NO_3-N was observed in the rotations including corn than in the continuous soybean

rotation (Table 23). The soil samples were taken after nitrogen fertilizer was applied to corn plots, but none was applied to the soybean plot.

Table 22. Mean values of soil nitrate at a given depth as affected by tillage at Monmouth, IL.

	Tillage[†]	
	CT	NT
Depth (cm)	——————mg NO_3-N kg $soil^{-1}$——————	
0-10	11.1 a[‡]A[§]	20.5 b B
10-20	11.9 a A	11.8 a A
20-40	17.0 a A	9.4 a A
40-60	14.4 a A	14.0 ab A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 23. Main effect of rotation on soil nitrate over 0-60 cm soil depths at Monmouth, IL.

Rotation[†]	mg NO_3-N kg $soil^{-1}$
CCC	27.0 B[‡]
CS	17.0 B
CSW	14.8 B
SSS	4.7 A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Among crop rotations, means followed by the same uppercase letter are not significantly different at p=0.1 over 0-60 cm soil depths.

At Perry, the interaction effect of rotation and depth ($p<0.013$) and the main effects of rotation (<0.003) and depth ($p<0.0001$) were statistically significant. However, neither the main effect of tillage or any interaction effect with tillage were significant at Perry. The levels of NO_3-N in continuous soybean were lower than the three rotations with corn at every depth (Table 24). The NO_3-N levels decreased with depth.

Table 24. Mean values of soil nitrate at a given depth as affected by rotation at Perry, IL.

	Rotation[†]			
	CCC	CS	CSW	SSS
Depth (cm)	mg NO_3-N kg $soil^{-1}$			
0-10	37.2 c[‡]B[§]	72.6 d B	39.0 c B	12.4 b A
10-20	29.3 c B	43.1 c B	33.1 c B	5.7 a A
20-40	19.0 b B	17.5 b B	16.0 b B	6.8 a A
40-60	11.7 a B	10.4 a B	10.3 a B	7.1 ab A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Within a crop rotation and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Among crop rotations and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

The interaction effect of tillage and depth ($p<0.014$) and the main effects of rotation ($p<0.0001$) and depth ($p<0.0001$) were statistically significant on NO_3-N levels over sites. The levels of NO_3-N were lower in the continuous soybean rotation (Table 25). Differences between tillage practices were found by depth with NO_3-N levels greater in no-till in the surface soil to 10 cm, but no differences at greater depths (Table 26). The NO_3-N levels were greater at the 0-10 cm depth compared to the deeper part of the soil profile in no-till; however, in conventional tillage, reduced NO_3-N levels were only found in the 40-60 cm depth over Monmouth and Perry.

Table 25. Main effect of rotation on soil nitrate over 0-60 cm soil depths over sites.

Rotation[†]	mg NO_3-N kg $soil^{-1}$	
CCC	24.6	B[‡]
CS	21.6	B
CSW	17.8	B
SSS	6.0	A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Among crop rotations, means followed by the same uppercase letter are not significantly different at p=0.1 over 0-60 cm soil depths.

Table 26. Mean values of soil nitrate at a given depth as affected by tillage practice over sites.

	Tillage[†]	
	CT	NT
Depth (cm)	mg NO_3-N kg $soil^{-1}$	
0-10	18.6 b[‡]A[§]	27.5 b B
10-20	17.3 b A	15.4 a A
20-40	15.0 b A	11.7 a A
40-60	11.6 a A	11.9 a A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Soil NH_4-N

At Monmouth, no interaction effects were significant for soil ammonium (NH_4-N), but the main effects of rotation ($p<0.043$), tillage ($p<0.041$), and depth ($p<0.0001$) were all significant. The levels of NH_4-N were found to be greater in no-till than conventional tillage and decreased with depth (Table 27). NH_4-N concentrations were greater in continuous corn, followed by corn-soybean-wheat and corn-soybean, with the lowest concentrations in continuous soybean.

As with Monmouth, no interactions were significant at Perry for NH_4-N. The main effects of rotation ($p<0.008$) and depth (<0.0001) were found statistically significant, but tillage was not at Perry. The NH_4-N concentrations were lower in the continuous soybean rotation than in the three rotations which include corn.

Over sites, rotation ($p<0.002$) and depth ($p<0.0001$) main effects were determined to be statistically significant for soil NH_4-N concentration. The overall results were the same as with Perry, with lower NH_4-N levels in continuous soybean than the other rotations and a decrease with depth.

Table 27. Mean values of soil ammonium over 0-60 cm soil depth as affected by tillage practice or crop rotation at Monmouth, IL, Perry, IL, and combined over sites.

		Monmouth		Perry		Over Sites	
Factor	Levels[†]	mg NH_4-N kg $soil^{-1}$					
Tillage	CT	0.0077	A[‡]	0.0079	ns[§]	0.0078	ns
	NT	0.0079	B	0.0080		0.0080	
Rotation	CCC	0.0082	c[¶]	0.0082	b	0.0081	b
	CS	0.0077	ab	0.0084	b	0.0080	b
	CSW	0.0079	bc	0.0081	b	0.0080	b
	SSS	0.0075	a	0.0071	a	0.0073	a

[†]CT, conventional tillage; NT, no-till; CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡] Between tillage practices at a given site, means followed by the same uppercase letter are not significantly different at p=0.1 over 0-60 cm soil depths.
[§]Means are not significantly different at p=0.1 over 0-60 cm soil depths.
[¶]Among crop rotations at a given site or over sites, means followed by the same lowercase letter are not significantly different at p=0.1 over 0-60 cm soil depths.

Soil Available Phosphorus

At Monmouth, only the main effect of depth ($p<0.0001$) was statistically significant for soil available phosphorus (P). The average Bray-1 P levels decreased with depth (Table 28). The interaction effect between tillage and depth ($p<0.001$) was statistically significant at Perry along with the main effect of depth ($p<0.0001$). The levels of available P were greater in no-till at 0-10 cm depth and in conventional tillage at 10-20 cm depth (Table 29). Available P decreased with depth, but below 20 cm, levels of available P did not differ at Perry.

No interaction effects were significant in the combined results over sites, but the main effects of rotation ($p<0.027$) and depth ($p<0.0001$) were significant for soil available P. Soil P concentrations decreased with depth. Lower soil P concentrations were found in the continuous corn and corn-soybean-wheat rotations than in continuous soybean while corn-soybean was intermediate between the other corn rotation and continuous soybean (Table 30).

Table 28. Mean values of available phosphorus at a given depth as affected by tillage practice at Monmouth, IL.

	Tillage[†]	
	CT	NT
Depth (cm)	mg P kg soil^{-1}	
0-10	24.4 d[‡]	23.6 c
10-20	14.6 c	14.7 b
20-40	8.2 b	8.8 a
40-60	7.7 a	6.6 a

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1

Table 29. Mean values of available phosphorus at a given depth as affected by tillage practice at Perry, IL.

	Tillage[†]	
	CT	NT
Depth (cm)	mg P kg soil^{-1}	
0-10	52.6 c[‡]A[§]	61.4 c B
10-20	18.8 b B	15.6 b A
20-40	9.6 a A	10.1 a A
40-60	9.8 a A	10.4 a A

[†]CT, conventional tillage; NT, no-till.
[‡]Within tillage practice and for each column, means followed by the same lowercase letter are not significantly different at p=0.1
[§]Between tillage practices and for each row, means followed by the same uppercase letter at a given depth are not significantly different at p=0.1.

Table 30. Main effects of rotation over 0-60 cm soil depths and depth on available phosphorus over sites.

Factor	Level[†]	mg P kg soil^{-1}
Rotation	CCC	13.90 a[‡]
	CS	14.77 ab
	CSW	13.66 a
	SSS	16.24 b
Depth (cm)	0-10	37.20 C[§]
	10-20	15.83 B
	20-40	9.14 A
	40-60	8.46 A

[†]CCC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat; SSS, continuous soybean.
[‡]Among crop rotations, means followed by the same lowercase letter are not significantly different at p=0.1 over 0-60 cm soil depths.
[§]Among soil depths, means followed by the same uppercase letter are not significantly different at p=0.1.

DISCUSSION

Fixed vs. Random Site in Statistical Analysis

The results of this study were analyzed two different ways with separate results from each site and also combined with site as a random factor. The reasoning for this was to answer different questions depending on the statistical model used.

In combining both sites and treating sites as a random factor, the results can be used to make inferences about sites with similar soil and climate. As a random factor, it accounts for variability due to the site within covariance parameters rather than within the residual error. This allows any conclusions made to be applied beyond just Monmouth and Perry, IL. Another important aspect of this analysis is that the larger sample size with more degrees of freedom and power to the analysis. It is possible that an effect can be determined to be significant over sites despite not being significant in either Monmouth or Perry separately. This was the case for available phosphorus where despite being not significant at Monmouth and Perry the main effect of rotation was statistically significant in the combined analysis. The standard error of the separate analysis by site was larger than the standard error of the analysis over sites, which had the data points from both locations, doubling the sample size and thereby reducing standard error.

In the case of the separate sites, the site is considered fixed and the results cannot be used to make inferences beyond a specific site. It also does not allow for comparison of results between Monmouth and Perry directly; however, it does allow comparison of significant effects within each site. For example, while only the main effect of depth was significant at Monmouth for total carbon, several interaction effects as well as main effects were significant at Perry. It is possible to compare these general trends between the two sites, even though specific results

cannot. This analysis can answer how the effects of treatments differ between the two sites and allow examination of inherent differences in environmental conditions such as soil type or climate that may explain the differing reaction to the treatments.

Site Sensitivity to Organic Matter Additions

The primary difference between the two locations is the response of water aggregate stability, cation exchange capacity, total carbon, total nitrogen and available phosphorus to treatments. Each of these soil properties is related to levels of soil organic matter (SOM). Due to the role of organic matter in formation and stabilization of soil macroaggregates, WAS has been positively correlated to SOM (Haynes et al., 1991; Amézketa, 1999). The ability of the soil to hold cations in an exchangeable form is determined by both the clay content and organic matter of the soil. Therefore, the addition of SOM can lead to an increase in CEC (Brady and Weil, 2002). By definition, TC in noncalcareous soils is equivalent to soil organic carbon (SOC) and directly related to SOM. While TN and available P levels may change due to fertilization, the return of nitrogen and phosphorus to the soil from plant residues is another important source and is related to SOM.

At Monmouth, only the main effect of depth was statistically significant for CEC, TC, TN and available P, while there were no significant effects for WAS. In contrast, multiple interaction and main effects were significant at Perry for all of these soil properties. The soil at Perry was more sensitive to the treatments differing contributions to SOM compared to those soils at Monmouth. Coulter et al. (2009) also reported the lack of treatment effect for SOC and TN at locations in Central and Southern Illinois, but found significant effects at a location in Northern Illinois. This difference was explained by differences in soil texture and cooler conditions at the northern location. In contrast in this study, while both locations are in West

Central Illinois significant effects were found at more southern location, Perry, which has an average annual temperature 2.2°C warmer than Monmouth. The textures of the soils also do not differ, especially over the top 20 cm where most of the differences between treatments were found.

Rather than texture or climate, this differing response to treatment may be related to the initial SOC levels in the soil. The soil at Perry is an Alfisol, which typically has an average SOC of 14 g kg^{-1} compared to a Mollisol as found at Monmouth with a typical SOC of 24 g kg^{-1} (Brady and Weil, 2002). With the higher inherent SOC at Monmouth, contributions from the crop rotations and tillage practices might have little impact on the soil properties; however, at Perry, differing additions of organic matter from crop residues may have been enough to cause changes to the soil properties due to the lower initial SOC.

Bulk Density

Another soil property that can be affected by SOM is bulk density. With higher levels of organic matter, BD should decrease since the organic matter is less dense than mineral particles and also through the related increase in aggregate stability, which increases medium size pores (mesopores) in the soil (Bullock, 1992; Brady and Weil, 2002). Based on the higher levels of SOM in the Mollisols at Monmouth and similar soil texture, it would be expected that BD values should be greater at Perry than at Monmouth. However, the mean BD over the top 20 cm of the soil profile was moderately greater at Monmouth (1.38 g cm^{-3}) than at Perry (1.28 g cm^{-3}), which may be related to differing water content at sampling.

BD at the surface under no-till was greater than those under conventional tillage. This is consistent with BD under no-till residue management in many studies (Cassel et al., 1995; Logsdon et al., 1999; Wander and Bollero, 1999; McVay et al., 2006). In contrast, there are also

a number of studies that showed no effect on BD by no-till (Ismail et al., 1994; Karlen et al., 1994c; Al-Kaisi et al., 2005). However, the common characteristic of these studies is the timing of the soil sampling. For these studies in which no-till BD did not differ from conventional tillage, soil samples were taken either in the fall following the growing season or in the spring prior to tillage operations. Kitur et al. (1993) reported higher BD under no-till at planting, but no differences between no-till and chisel-plow BD values later in the growing season, which indicates that the reduction of BD in conventional tillage is likely temporary. The length of the study may also be a factor in the differing reports on no-till effect on BD since there have been long-term studies that reported lower BD under no-till than conventional tillage (Dao, 1996; Kumar et al., 2012). This is attributed to greater residue accumulation under no-till which leads to increased soil aggregation and subsequently reduction in BD (Blanco-Canqui and Lal, 2004).

Despite the statistical differences between tillage treatments, there is little negative effect on plant growth on these soils. For these soils (silt loam and silty clay loam), root restrictions can occur when BD values are greater than 1.50-1.55 g cm^{-3} (Arshad et al., 1996). The highest values reported were at Monmouth in no-till (1.45 g cm^{-3}) and conventional tillage (1.43 g cm^{-3}) at 15 cm depth. The higher BD values found at 10-20 cm depth at both Monmouth and Perry are evidence of traffic or plow pan, which can be caused by the weight of machinery driven over the soil and in the conventional tillage, downward pressure from the tillage implements.

Nutrient and pH Stratification Under No-till

Nutrient concentrations over all the soil depths were not significantly different between conventional tillage and no-tillage. This runs counter to what may be expected from the greater residue production under conventional tillage due to yield differences. Conventionally tilled corn yielded 4% more than no-till at Monmouth over all rotations (Nafziger and Villamil, 2013).

While overall corn yields did not differ between tillage practices at Perry, continuous corn and the corn-soybean-wheat rotation had 4% higher yields under conventional tillage than no-till. The lack of differences in nutrient levels despite greater residue production in conventional tillage may be explained by the rapid decomposition of residue as they are mixed into the soil under conventional tillage (Al-Kaisi et al., 2005). The results of this study are in contrast to a number of studies reporting an increase in SOC with no-till (Kladivko et al., 1986; Havlin et al., 1990; West and Post, 2002). However, Yang and Wander (1999) reported that in spite of increased SOC concentrations in the top few centimeters of the soil under no-till, overall SOC was not increased as a result of no-till.

While there was a lack of differences in nutrient concentration between conventional tillage and no-till over the studied soil depths, WAS under no-till was greater than in conventional tillage. These results are in accordance with other studies also reporting greater aggregate stability under no-till compared to conventional tillage (Kladivko et al., 1986; Kumar et al., 2012). Greater aggregate stability is typically attributed to more rapid decomposition of residues and degradation of soil aggregates by the tillage processes.

Although the overall nutrient concentrations did not differ between tillage practices, a trend was found illustrating decreasing nutrient levels and increasing pH with depth under no-till over the soil profile. This stratification in no-till was found at Perry with greater TC, TN, and available P concentrations at 0-10 cm depth and decreased below the surface to the point where nutrient concentrations were greater under conventional tillage at 10-20 cm depth. While the results for Monmouth did not show evidence of stratification of nutrients under no-till, stratification of pH was found at Monmouth but not at Perry. This agrees with the results reported in a number of studies for carbon and nitrogen (Al-Kaisi et al., 2005; Varvel and

Wilhelm, 2011), available P (Karlen et al., 1994c; Kitur et al., 1994b), and pH (Ismail et al., 1994).

The cause of stratification is typically attributed to the accumulation of residues on the surface and the slower decomposition as the residues remain in larger pieces on the surface with less contact with soil microorganisms (Ismail et al., 1994; Al-Kaisi, 2005). Another factor is the application of lime and fertilizers adding nutrients and affecting the pH to the surface of the soil (Crozier et al., 1999). While Crozier et al. (1999) reported stratification of nutrients and pH in both conventional and no-tillage, it was more evident in no-till. Stratification in conventional tillage is less pronounced since residues are mixed into the soil profile to the depth of the tillage implement, which is typically around 20 cm for a chisel plow (Allmaras et al., 1988).

Differing Residue Contribution

The values of CEC, WAS, and TC were statistically greater for crop rotations including corn than for continuous soybean. The detection of these differences was dependent on the site with only WAS significant over sites while CEC and TC were only significant at Perry. These soil properties are related to organic matter additions and again, the soil at Perry has lower inherent SOM and may be more sensitive to additions of organic matter in the form of crop residues. The greater values for crop rotations including corn are likely due to the differing amounts of crop residue. With both higher yield and larger harvest index, corn produces approximately 2.5 times the amount of residue as either soybean or wheat (Allmaras et al., 1998).

While differences between continuous soybean and the corn rotations were found, continuous corn did not differ from corn-soybean for these soil properties, which contradicts the results of a number of studies which found greater soil organic carbon and related properties in

continuous corn than corn-soybean (West and Post, 2002; Karlen et al., 2006; Jagadamma et al., 2008). Riedell et al. (1998) and Liebig et al. (2002), like this study, did not find differences between continuous corn and corn-soybean rotation. The lack of significant difference between corn-soybean and continuous corn may be due to the yield penalty of continuous corn. The corn yields of the corn-soybean rotation were 26% and 17% greater over the 15 year period compared to the continuous corn at Monmouth and Perry, respectively (Nafziger and Villamil, 2013). Despite lower residue contribution from the soybean, the greater residue from the corn may have negated differences between the corn monoculture and the corn-soybean rotation. The lack of difference between corn-soybean-wheat and continuous corn is less explicable. Corn produces on average 60% and 50% more above ground residue and 65% and 60% more carbon from roots than soybean and wheat, respectively (Johnson et al., 2006). Despite corn yielding 32% more in corn-soybean-wheat than continuous corn (Nafziger and Villamil, 2013), the corn-soybean-wheat has lower residue production in two of every three years from soybean and wheat.

Available phosphorus was found at greater levels in continuous soybean than in either continuous corn or corn-soybean-wheat, but was not statistically different from corn-soybean. The differential removal of soil P by different crop species is likely the main cause for these differences. Soybean utilizes approximately 60% as much phosphorus as corn and while most of the P is removed at harvest with the grain, some remains in the residue (Karlen and Sharpley, 1994). Sharpley and Smith (1989) reported that the amount of phosphorus in soybean residue was 62% that of corn residue despite almost triple the amount of corn residue. The combination of lower P usage and similar P return in the residues for soybean compared to corn can explain the greater available P levels under rotations that incorporate soybean more frequently.

Effect of Nitrogen Fertilization on Soil Properties

An important difference between the rotations including corn and continuous soybean beyond the crop species is differential application of nitrogen fertilizer. While nitrogen fertilizer applications are made to both corn and wheat, soybean does not receive any nitrogen fertilizer. Since the establishment of the experimental plots, the continuous soybean plots have received no nitrogen fertilizer and corn-soybean less frequently than continuous corn. Despite being able to fix nitrogen, Salvagiotti et al. (2008) reported soybean only gains 50-60% of its nitrogen from the atmosphere through biological nitrogen fixation with the remainder taken from the soil. Because of this and the high nitrogen content of the grain soybean is a net user of soil nitrogen (Karlen et al., 1994a). As expected due to lack of nitrogen fertilization and net nitrogen removal by soybean, TN, NO_3-N, and NH_4-N levels for continuous soybean were found to be significantly less than the levels of the corn rotations.

The differential application of nitrogen fertilizer is also the likely explanation for the differences in the pH between rotations. In the continuous corn, corn-soybean, and corn-soybean-wheat rotations, the pH of the soil near the surface was significantly lower than the pH under continuous soybean. This agrees with the results of Karlen et al. (1991) which found lower soil pH in corn-soybean than in continuous corn, which had more frequent nitrogen fertilizer applications. Bouman et al. (1995) reported acidification of the soil with the application of either anhydrous ammonia and urea in the top 15 cm of the soil. The acidification occurs as nitrification of each ammonium ion releases two hydrogen ions (Brady and Weil, 2002). Greater acidification has been reported with higher nitrogen rates (Liebig et al., 2002; Jagadamma et al., 2008).

CONCLUSIONS

The management practices of crop rotation and tillage have been studied throughout the Midwest separately; however, this work is one of a few studies that have looked at the interactive effects of rotation and tillage after 15 years of the establishment of the experimental plots. Although studies have previously evaluated the effect of rotation and tillage on soil properties, the majority were completed outside the Midwest. While there have been studies in the Midwest focused on the separate effects of rotation and tillage, much of that work has focused on short-term systems. Long-term studies, such as this one, are important in that they provide information about a stable system, while short-term results vary and continue to change over time. This work represents the first long-term study of the interactive effect of rotation and tillage on soil properties in Illinois and is one of only a few completed in the Midwest.

As in a number of previous studies, no-till aggregate stability and bulk density were greater at the surface than conventional tillage. However in this study, tillage practice had little effect on the other soil properties. Despite greater yields and residue production under conventional tillage, nutrient concentrations were unaffected except for causing nutrient and pH stratification under no-till. In many studies, no-till has often been reported to increase soil organic carbon. While no initial SOC values were available for the soils in this study to provide actual SOC changes, the lack of differences between no-till and conventional tillage in the results of this work did not exhibit a greater accumulation of carbon under no-till as compared to conventional tillage.

Comparison among rotations highlighted the differences between continuous soybean and the three rotations that include corn. While this was likely caused by less residue return or lack of nitrogen fertilization in the continuous soybean rotation, it does indicate that soil

properties are affected by the long-term use of continuous soybean. The use of a continuous soybean rotation is rare in the Midwest region and based on these results may not be a viable long-term practice, especially on soils with lower organic matter, like the Alfisols at Perry.

Previous research has indicated a greater accumulation of SOC and increases in associated soil properties under continuous corn due to greater residue production of corn each year compared to corn interspersed with lower residue producing soybean in the corn-soybean rotation. In contrast, the result of this study did not show differences in soil properties after 15 years under continuous corn and corn-soybean. While no previous study of rotations in the Midwest has included wheat as part of a rotation with corn and soybean, prior research has indicated increasing the diversity of a crop rotation by adding another crop species cause an increase in SOC. In this study, despite the incorporation of another crop species, the corn-soybean-wheat rotation did not differ from the corn-soybean or continuous corn monoculture; this indicates no benefit to the soil from adding wheat to the most common rotations in the Midwest.

Future Research Needs

The results of this study differ from previous research relating to crop rotations, which may be explained by the residue contribution of different crop species. To fully understand why the lack of differences occurred between various rotations, future work should quantify the residue production of each crop within a rotation over the years. For instance, the lower yields of continuous corn in high stress years may lead to much less residue production and lead to the similar results between continuous corn and corn-soybean seen in this study. Other improvements to the study could focus on the effect of a specific crop on the soil properties

within a growing season. Each of the corn rotations had a different crop residue from the previous growing season, which may have led to different results.

While this study was unable to quantify the sequestration of SOC, it does establish a baseline for future work to determine how SOC changes for the rotation and tillage treatments at these sites within a long-term stable system.

The differences between this study and previous work may be due to differences in other parts of the soil system. While this work focused on the soil physical and chemical properties, a full understanding of the dynamics of the system requires investigation of the biological properties of the soil. Future investigations should examine the effect of rotation and tillage on microbial biomass and enzymes as these are important factors in nutrient cycling.

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APPENDIX

Table A.1. Analysis of variance and probability values for bulk density values for Monmouth, IL and Perry, IL sites separately and over sites.

	Bulk Density		
	By Site		Over Sites
Source	Monmouth	Perry	Random
Rotation	0.0121	0.7788	0.4406
Tillage	0.0040	0.0177	0.0016
Rotation*Tillage	0.2954	0.5804	0.3716
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.3855	0.4413	0.1515
Tillage*Depth	0.0082	0.0076	0.0288
Rotation*Tillage*Depth	0.6115	0.0535	0.1757

Table A.2. Analysis of variance and probability values for water aggregate stability values for Monmouth, IL and Perry, IL sites separately and over sites.

	Water Aggregate Stability		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.1537	0.0704	0.0326
Tillage	0.5234	0.0100	0.0299
Rotation*Tillage	0.7357	0.7630	0.6806
Depth	0.1026	0.7547	0.1347
Rotation*Depth	0.8676	0.5626	0.9785
Tillage*Depth	0.8390	0.4391	0.7778
Rotation*Tillage*Depth	0.2638	0.6359	0.1778

Table A.3. Analysis of variance and probability values for cation exchange capacity for Monmouth, IL and Perry, IL sites separately and over sites.

	Cation Exchange Capacity		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.2561	0.0568	0.8400
Tillage	0.7660	0.9661	0.8688
Rotation*Tillage	0.5164	0.9819	0.8360
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.3230	0.0220	0.6126
Tillage*Depth	0.9445	0.4353	0.8232
Rotation*Tillage*Depth	0.5947	0.9047	0.9136

Table A.4. Analysis of variance and probability values for pH for Monmouth, IL and Perry, IL sites separately and over sites.

	pH		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.0120	0.0008	<0.0001
Tillage	0.0599	0.0886	0.0137
Rotation*Tillage	0.1574	0.5334	0.1666
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	<0.0001	<0.0001	<0.0001
Tillage*Depth	0.0439	0.1344	0.1363
Rotation*Tillage*Depth	0.9517	0.8806	0.9805

Table A.5. Analysis of variance and probability values for total carbon values for Monmouth, IL and Perry, IL sites separately and over sites.

	Total Carbon		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.1548	0.3492	0.1748
Tillage	0.3208	0.0627	0.2596
Rotation*Tillage	0.3999	0.5502	0.5299
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.5603	<0.0001	0.3676
Tillage*Depth	0.7564	<0.0001	0.5249
Rotation*Tillage*Depth	0.7550	0.1117	0.9142

Table A.6. Analysis of variance and probability values for total nitrogen values for Monmouth, IL and Perry, IL sites separately and over sites.

	Total Nitrogen		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.1670	0.0419	0.0790
Tillage	0.1275	0.1740	0.1013
Rotation*Tillage	0.5554	0.2500	0.4289
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.9035	0.0098	0.8379
Tillage*Depth	0.7450	0.0003	0.2491
Rotation*Tillage*Depth	0.8368	0.3867	0.9389

Table A.7. Analysis of variance and probability values for carbon: nitrogen ratio for Monmouth, IL and Perry, IL sites separately and over sites.

	Carbon: Nitrogen Ratio		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.0765	0.2014	0.0181
Tillage	0.9069	0.7205	0.7626
Rotation*Tillage	0.2410	0.9421	0.6323
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.3427	0.5423	0.3946
Tillage*Depth	0.2264	0.9866	0.6919
Rotation*Tillage*Depth	0.4035	0.9780	0.7668

Table A.8. Analysis of variance and probability values of soil nitrate and ammonium for Monmouth, IL and Perry, IL sites separately and over sites.

	Soil NO_3-N			Soil NH_4-N		
	By Site		Over Sites	By Site		Over Sites
Effects	Monmouth	Perry	Random	Monmouth	Perry	Random
Rotation	0.0036	0.0032	<0.0001	0.0426	0.0084	0.0017
Tillage	0.9951	0.9434	0.9422	0.0410	0.6642	0.1747
Rotation*Tillage	0.7959	0.8477	0.5260	0.7359	0.9412	0.9151
Depth	0.1658	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.5892	0.0133	0.1054	0.3463	0.1387	0.1264
Tillage*Depth	0.0199	0.2264	0.0142	0.1842	0.6742	0.3665
Rotation*Tillage*Depth	0.2026	0.9225	0.3800	0.9859	0.8057	0.7102

Table A.9. Analysis of variance and probability values for available phosphorus for Monmouth, IL and Perry, IL sites separately and over sites.

	Available Phosphorus		
	By Site		Over Sites
Effects	Monmouth	Perry	Random
Rotation	0.1615	0.2978	0.0271
Tillage	0.5805	0.7220	0.8566
Rotation*Tillage	0.5995	0.2785	0.2440
Depth	<0.0001	<0.0001	<0.0001
Rotation*Depth	0.1770	0.4599	0.2615
Tillage*Depth	0.5630	0.0008	0.1633
Rotation*Tillage*Depth	0.6347	0.7981	0.8894