# Tillage and Cover Cropping Effects on Soil Properties and Crop Production in Illinois

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## ABSTRACT

Cover crops (CCs) have been heralded for their potential to improve soil properties, retain nutrients in the field, and subsequent crop yields, yet support for these claims within Illinois remains limited. Cover crops were used in corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotations. We assessed five sets of CCs vs. fallow controls under no-till (NT) and chisel till (Till) on soil attributes and crop yields, encompassing one complete rotation cycle. The experimental layout was a split split-block where whole plot treatments (P, rotation phase; and Y, year) had a Latin square design and subplot treatments of tillage (NT vs. Till) were split into sub-subplot treatments of CC rotations. We measured soil properties, crop yields, CC stand counts in late fall, and spring biomass samples, each year. Tillage increased the level of soil organic matter (SOM) and exchangeable potassium (K) within our systems yet significantly decreased the yield of soybean by 245 kg/ha. Compared to winter fallow, soil attributes under corn–soybean rotations that included CCs did not show any statistically significant change after one cycle of production except increased N scavenging with cereal rye growing after corn harvest. Inclusion of CCs in the corn–soybean rotation did not affect cash crop yields in either till or NT systems. Our results show that cereal rye is the CC with the best potential as an N scavenger in the corn–soybean rotation, but claims of crop yield increases in the short term are not supported.

## Core Ideas

- Compared corn–soybean rotations with cover crops vs fallows under no-till or till.
- Corn–soybean rotations with cereal rye after corn decreased soil $NO_3$–N by 42%.
- Soil attributes and crop yields were generally unaffected by cover crops use.
- Tillage increased soil organic matter and exchangeable K compared to no-till.
- Tillage reduced soybean yields by 245 kg/ha compared to no-till.

Expected cash crop yield increases, increased nutrient retention within the farm limits, and overall improvement of soil properties are three main reasons put forward by invested parties to stimulate adoption of CCs during the traditional fallow period in the Midwest region. Yet despite the recent flurry of publicity (Strom, 2016), benefits from cover cropping might prove difficult to achieve within traditional corn–soybean systems in Illinois due to their already high levels of production and inherently high levels of soil fertility along with restricted growth periods to maximize the advantages of traditional CC use.

Illinois ranks among the top two states in the United States in the production of both corn and soybean, with yields of 12,554 kg/ha for corn and 3768 kg/ha for soybean in 2014 (USDA NASS, 2016a). This high productivity relies on high levels of fertilizer inputs; that is, in 2010, 1.03 Tg of N and 494,050 t of phosphate were applied to 98 and 85%, respectively, of the planted corn area (USDA NASS, 2016b). In addition, highly fertile, deep Mollisols developed under prairie vegetation on a thick mantle of loess cover more than half of the state (Soil Survey Staff, 2012); these soils are highly effective in storing, cycling, and regulating the supply of water and nutrients for the crops. Environmental consequences of these high levels of production in the Midwest region have been clearly documented, with Illinois alone responsible for about 10 and 15% of the annual total N and P loading, respectively, in the Mississippi River, with these two nutrients contributing to the hypoxic zone in the Gulf of Mexico (David and Gentry, 2000; David et al., 2010; Jacobson et al., 2011). According to the recently developed Illinois Nutrient Loss Reduction Strategy (Illinois EPA, 2015), farming accounts for 80% of the nitrate-nitrogen ($NO_3$–N) lost in the state. Cover cropping is identified as one of the most promising in-field strategies to help the state achieve the goal of decreasing the $NO_3$–N load by 15% by 2025.

Published in Agron. J. 109:1261–1270 (2017)
doi:10.2134/agronj2016.10.0613
Available freely online through the author-supported open access option

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**Abbreviations:** BD, soil bulk density; CCs, cover crops; CT, Corn _ fallow/Soybean _ fallow; CarSar, Corn_ annual ryegrass/Soybean _ annual ryegrass; CcrShv, Corn _ cereal rye/Soybean _ hairy vetch; CrdSrd, Corn _ radish/Soybean _ radish; CrpSrp, Corn _ rape/Soybean _ rape; CsoScl, Corn _ spring oat/Soybean _ red clover/; K, exchangeable potassium; $NH_4$–N, ammonium; $NO_3$–N, nitrate-nitrogen; NT, no-till; Pa, available phosphorus; PR, penetration resistance; Rcc, corn–soybean rotations including cover crops; SOM, soil organic matter; T, factor tillage; TCs, total carbon stocks; Till, chisel-tilled plots;TIN, plant available nitrogen; WAS, water aggregate stability.

Cover crops are legumes, grasses, mustards, or mixtures of species grown specifically to protect the soil against erosion, ameliorate soil structure, enhance soil fertility, decrease the leaching of nitrate N ($NO_3$–N)and other nutrients from the root zone, and suppress pests (Sainju et al., 2002; Snapp et al., 2005; Villamil et al., 2006, 2008; Kaspar et al., 2012). Soil productivity with CC is increased through increased SOM, enhanced nutrient cycling, and improved soil structure, resulting in greater cash crop yields and/or enhanced yield stability (Sainju et al., 2002; Snapp et al., 2005). Mustards including radishes (*Raphanus sativus* L.) and rape (*Brassica napus* L.), and some grass CCs such as cereal rye (*Secale cereale* L.) and oat (*Avena sativa* L.) produce root systems that can extend deep in the soil, thus increasing nutrient use efficiency by capturing N from deeper soil layers (Dean and Weil, 2009; Kaspar et al., 2012), by penetrating compacted soil layers (Williams and Weil, 2004; Chen and Weil, 2010), and by suppressing weeds (Cherr et al., 2006). According to the meta-analysis conducted by Tonitto et al. (2006) to compare N dynamics under CCs with bare fallow in conventional systems, $NO_3$–N leaching is reduced on average by 70 and 40% under non-legume and legume CC, respectively. There are few studies that show what these reductions might be under Illinois conditions.

Results of a mailed survey including 3500 farmers in Illinois, Indiana, Iowa, and Minnesota showed that only 18% of farmers had used CC once, and only 11% had planted CC between 2001 and 2005 (Singer et al., 2007; Singer, 2008). Singer et al. (2007) surveyed preferences and management practices used by CC growers. Farmers prefer those CCs that do not winterkill and that fix N. In Illinois, farmers most frequently reported planting cereal rye, annual ryegrass, or winter wheat (*Triticum aestivum* L.) as cover crops. A major concern regarding the adoption of CC is the possibility of lower yields of the main crops following the CC. Yet, in a meta-analysis of the effects of CCs on subsequent corn yield, Miguez and Bollero (2005) found that grass CC did not affect corn yield, while legume and mixed grass–legume CCs increased the yield of unfertilized corn by 24 and 21%, respectively. These yield increases due to CC use however, disappeared as the N added from fertilizers increased.

Cover crop effects on yields, nutrient retention, and soil properties are likely dependent on the length of the CC growing season, weather conditions, and the tillage option used. In Illinois, the inclusion of CC into the traditional corn–soybean rotation typically means that the CCs need to be aerially seeded into the standing crop in September to get timely establishment, or be drilled into crop stubble after crop harvest (in late September–October) to ensure proper seed/soil contact. Aerial seeding into standing crop is costly and often fails to produce good CC stands, while waiting until crop harvest means a late start and limited fall growth of the CC. In either event, CC biomass accumulation in the fall is limited by the time of first frost, which on average occurs in mid- to late October. Overwintering CCs usually need to be suppressed long enough before cash crop planting to limit spring CC biomass for easier planting and to allow enough time for the residue to deteriorate and for the soil to dry before planting the cash crop. These characteristics of the CC growing season and their management constrain the potential benefits from CC use in the short and long terms in Illinois (Acuña and Villamil, 2014; Welch et al., 2016).

Tillage breaks down crop residues and incorporates them into the soil, improving aeration and facilitating the breakdown of organic material and release of nutrients. These short-term effects may mirror some of the benefits that CCs can provide, but tillage might also negate the long-term benefits of CCs use. In a recent study on soybean, Acuña and Villamil (2014) found that CC treatments drilled into wheat stubble each year significantly lowered the $NO_3$–N levels in the soil the following spring without affecting soybean crop yields. Yet no additional effects related to cover cropping were evident in soils or crops after one CC growing season. Also for Illinois and under no-till, Villamil et al. (2006, 2008) found that after three cycles of corn–soybean production with and without CCs, CC mixtures of cereal rye and hairy vetch drilled onto crop stubble each year increased SOM, nutrient retention, and water aggregate stability compared with winter fallow (no CC). Again, no effect on cash crop yields was detected in these systems for either corn (Miguez and Bollero, 2006) or soybean (Ruffo et al., 2004). According to the cover crop surveys performed every year since 2012 by the Conservation Technology Information Center (CTIC-SARE, 2016) however, farmers that have adopted CCs consistently report positive effects on crop yields and soil fertility in the Midwest region. Due to the importance of cover cropping as a conservation practice and nutrient retention tool, more information is needed to elucidate CC feasibility and benefits to encourage adoption within the traditional corn–soybean rotation in the state.

The objectives of this study were to assess soil properties and crop yields in the corn–soybean rotation following several species of CCs hand seeded simulating aerial seeding, under Till and NT practices. We hypothesized that including CCs would show evidence of nutrient scavenging and improvements in SOM, bulk density, water aggregate stability, and penetration resistance through increased input of residues and root activities when compared to winter fallow systems. Larger effect sizes were anticipated for overwintering CCs due to their longer growing season and greater biomass, as well as under NT. Results from this study will contribute valuable information for farmers and stakeholders regarding the feasibility of cover cropping and the potential benefits attainable within our particular agroecosystem.

## MATERIALS AND METHODS

### Site Characterization and Management

This study was established beginning in the fall of 2013 at the University of Illinois, Crop Sciences Research and Education Center at Urbana, IL (40°05′73″ N, −88°22′73″ W). The experimental plots were set up across the Drummer–Catlin–Flanagan soil association (Soil Survey Staff, 2012) with 70% of the plot area Drummer silty clay loam (fine-silty, mixed, superactive, mesic, Typic Endoaquoll), 20% Flanagan silt loam (fine, smectitic, mesic, Aquic Argiudoll), and 10% Catlin silt loam (fine-silty, mixed, superactive, mesic, Oxyaquic Argiudoll). These are dark-colored soils developed under prairie in 1 to 1.2 m of loess over till on mostly level to very gently sloping topography in upland positions. Slope ranges from 0 to 2%. Flanagan is somewhat poorly drained and Catlin is moderately to well drained, occupying the higher landscape positions while Drummer is poorly drained soil that occupies the lower positions in the landscape. Two side-by-side fields in a corn–soybean rotation, rotated annually, were used to set up the experimental plots. Corn crop was planted on

17 May 2013, 21 May 2014, and 15 May in 2015 and harvested on 17 October, 3 November, and 24 October, in 2013, 2014, and 2015, respectively. Soybean was planted on 7 June 2013, 21 May 2014, and 16 May 2015 and harvested on 14, 30, and 24 October in 2013, 2014, and 2015, respectively. Pre-plant N fertilizer at a rate of 190 kg N/ha was added to the corn crop. Weed biomass was negligible in all plots; volunteer corn plants were removed by hand from soybean plots in early summer. Tillage was conducted with chisel plow 20- to 25-cm deep in the spring following CC suppression and before planting of the cash crop each year. No tillage was performed on the NT plots.

Cover crops were broadcasted by hand into standing cash crop to simulate aerial seeding on 16 and 17 September in 2013 and 2014, respectively. Seeding rates and growth suppression times were selected using the online decision tool developed by the Midwest Cover Crop Council (online at: mcccdev.anr.msu.edu/Vertindex.php). Accordingly, we used seeding rates of 5.6 kg/ha for rape; 9 kg/ha for radish; 16.8 kg/ha for annual ryegrass; 22.4 kg/ha for each red clover (*Trifolium pratense* L.) and hairy vetch (*Vicia villosa* Roth.); 67.2 kg/ha for spring oat (*Avena sativa* L.); and 100 kg/ha for cereal rye (*Secale cereale* L.). Cover crops were chemically suppressed with glyphosate [*N*-(phosphonomethyl)glycine] at 1.12 kg a.i./ha at the time of biomass sampling toward the end of April each year. Fall stand counts of CCs (plants/$m^2$) were taken during the first week of November each year using a 0.25 $m^2$ quadrat to estimate growing CC populations entering winter or before winterkill. Spring biomass samples were collected by triplicate on 25 Apr. 2014, and again on 27 Apr. 2015 using a 0.5 m side square randomly placed within each plot. Overwintering biomass samples (g/$m^2$) were cut at ground level and oven-dried at 60°C and weighed. Cash crop yields were taken using an Almaco (Nevada, IA) plot combine and adjusted to 15 and 13% moisture basis for corn and soybean, respectively.

## Soil Sampling and Analyses

Soil samples were collected during the first week of May in 2014 and 2015 after CCs were sprayed with herbicide and before cash crop planting. Penetration resistance (PR, kPa) was recorded at the time of spring soil sampling using a Field Scout SC 900 Soil Compaction Meter (Spectrum Technologies, Plainfield, IL) with a cone basal area of 1.28 $cm^2$ and a cone angle of 30°. Five PR measurements were taken per subplot and averaged to depths of 0 to 15, 15 to 30, and 30 to 45 cm. Three soil core samples were taken with a tractor-mounted soil sampler (Amity Tech, Fargo, ND) to 45 cm within each subplot. After being pulled from the field, samples were taken to the Sustainable Systems Lab for further analysis. Each core had a diameter of 4.3 cm, and was cut into three 15-cm increments for lab determinations at successive depths. Soil was oven-dried at 105°C to measure gravimetric water content at each depth, to obtain soil bulk density (BD, Mg/$m^3$) using the core method (Blake and Hartge, 1986). Field moist soil was analyzed for available N ($NO_3$–N and $NH_4$–N, in mg/kg) using KCl extraction (1:5 ratio soil/solution) followed by flow injection analysis with a Lachat automated analyzer (Lachat Intruments, Loveland, CO). Soil samples were then air dried and passed through a 2 mm sieve. Soil pH (1:1 soil/water) was determined via potentiometry with a Mettler Toledo AG SevenEasy pH Meter (Schwerzenbach, Switzerland). Soil aggregates of the soil fraction ranging between 1 and 2 mm from each depth were tested for water aggregate stability (WAS, %) with an Eijkelkamp wet sieving apparatus (Eijkelkamp, Giesbeek, the Netherlands) following Kemper and Rosenau (1986). Remaining samples were sent to a commercial laboratory (Brookside Laboratories Inc, New Bremen, OH) for the determination of available P (Pa, mg/kg) with Bray 1; exchangeable K (K, mg/kg) with Mellich III extraction; and SOM (%) by loss on ignition (Soil and Plant Analysis Council, 1992). Loss on ignition values were adjusted following Konen et al. (2002) for Illinois soils. Bulk density values were used to convert SOM in percent to a basis of weight per unit area, or total carbon stocks (TCs, Mg/ha) for each 15-cm depth increment.

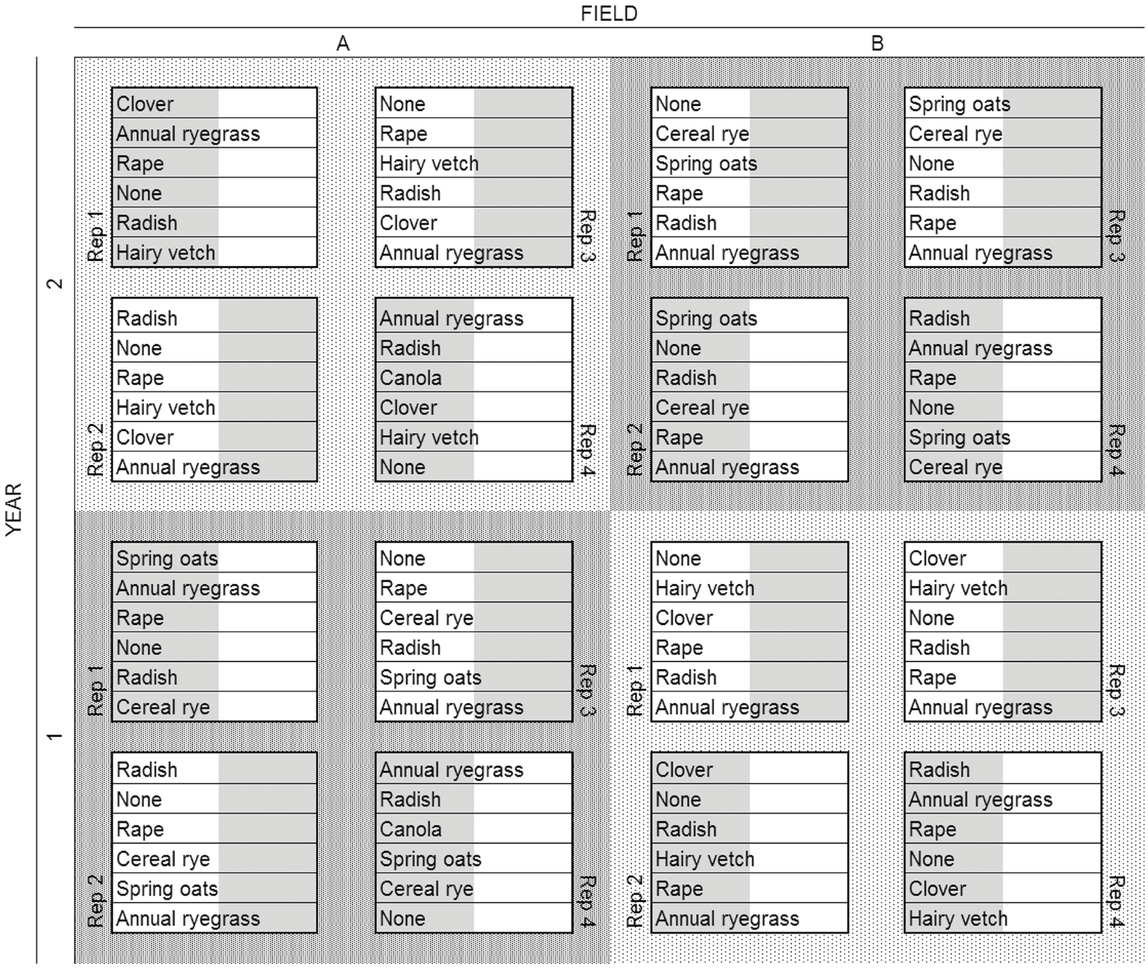
## Experimental Design and Statistical Analysis

The experiment aimed to test the effects of tillage and corn–soybean rotations including CCs on soil properties and crop yields. A diagram of the experimental layout is shown in Fig. 1. The experimental design was a split split-block where whole-plot treatments of phase of the rotation (P) had a Latin square design in time of factor years (Y) and field (F) since it took 2 yr for each field of corn and soybean to complete the rotation. With no true replications of F and Y, both factors F and Y act as blocks for the effect of rotation phase which is consistent with a Latin square design. Whole-plot treatments were rotation phase (P), where phase 1 corresponds to the spring sampling following corn the previous year and CCs (or fallow), and phase 2 to the spring sampling following soybean the previous year and CCs (or fallow). Subplot treatments of tillage (T) and cover crop rotations (Rcc) were arranged in a split block design with four replications [B(F)]. Each whole plot was 92 m long by 25 m wide. Whole plots accommodated four reps 18 by 25 m each, and split into levels of tillage (T: NT vs. Till). Tillage plots of each cash crop were split into sub-subplot treatments of CCs, 3 by 12.5 m and each comprising a cash crop–CC rotation that was maintained across years. There were six levels of CC rotations, Rcc, as follows: (1) CT, Corn _ fallow/Soybean _ fallow; (2) CsoScl, Corn _ spring oat/Soybean _ red clover/; (3) CcrShv, Corn _ cereal rye/Soybean _ hairy vetch; (4) CarSar, Corn_ annual ryegrass/Soybean _ annual ryegrass; (5) CrdSrd, Corn _ radish/Soybean _ radish; and (6) CrpSrp, Corn _ rape/Soybean _ rape.

Factors phase (P), T, Rcc, and sampling depth (D) were considered fixed while Y, F, and replications [B(F)] were considered random. Resulting mixed models were implemented using the glimmix procedure of SAS software version 9.4 (SAS Institute, Cary, NC). Due to lack of normality of model residuals most soil properties, with the exception of SOM and pH, were analyzed with a lognormal distribution link function (dist = logn) within the model statement along with the Kenward–Rogers adjustment of degrees of freedom (ddfm = kr) to account for model complexity and potential missing data (Gbur et al., 2012). Water content at the time of sampling was used as a covariate in the analysis of soil penetration resistance. Depth was analyzed using a repeated measures approach with variance–covariance structure of heterogeneous autoregressive [type = arh(**1**)] for each soil variable consistently selected on the basis of the lowest Akaike's Information Criteria (Littell et al., 2006). When appropriate, lsmeans were separated using the pdiff option of lsmeans setting the probability of Type I error at 0.05($\alpha$), and using a Bonferroni correction (adjust = bon) linked to the degrees of freedom adjustment (adjdfe = row) included in the model statement. Most double and triple interaction effects between D and the factors P, T, or Rcc were not statistically significant (with $p > 0.50$) except for those in the analysis of TIN and its constituents, $NO_3$–N and $NH_4$–N, yet their adjusted mean comparisons at a same depth for a given P or T were not significant as well (data not shown). Therefore, to visually simplify the tables, the probability values associated with the results of double and triple interactions of factors P, T, or Rcc with D, are not shown for any of the soil variables analyzed. Similar models and adjustment of degrees of freedom in glimmix were used in the analysis of crop yields conducted by phase of the rotation (P) to obtain the yields of each cash crop. Statistical model and SAS codes are available on request from the authors.

## RESULTS AND DISCUSSION

The fall of 2013 was dry and the fall of 2014 was wet; both years had below-normal temperatures in November (Fig. 2). The establishment of CCs was decreased by dry conditions in 2013, and while establishment was better in 2014, minimum temperatures of –3.7 C on 25 Oct. 2013 and of –4.4 C on 2 Nov. 2014 killed



**Rotation phase legend (P)**

▩ **P1**, Following corn harvest and before soybean planting

░ **P2**, Following soybean harvest and before corn planting

**Tillage legend (T)**

▨ **Till**, Spring tillage done before planting

☐ **NT**, No-till planting

| **Rotation** | Cover crop that follows crop | |
|---|---|---|
| **Legend** | Corn | Soybean |
| **CT** | None | None |
| **CsoScl** | Spring oats | Clover |
| **CcrShv** | Cereal rye | Hairy vetch |
| **CarSar** | Annual ryegrass | Annual ryegrass |
| **CrdSrd** | Radish | Radish |
| **CrpSrp** | Rape | Rape |

Fig. 1. Schematic representation of the experimental layout showing the arrangement of the factors phase of the rotation (P), tillage (T), and corn–soybean rotations including cover crops (Rcc), along with the three blocking criteria used in the study, field, year, and blocks (Reps) within each field.

or injured small plants of most CC species, resulting in low biomass the following spring (Fig. 3). The interaction of P × Rcc was significant for both CC fall counts and spring biomass (Table 1), reflecting differences in plant density and biomass for the CCs that follow each crop, corn or soybean. This was expected based on the different seeding rates of the CCs as well as their different overwintering potential in our region. However, emergence and survival data were highly variable even for the same species (Fig. 3), especially for the grass species considered winter hardy (i.e., cereal rye and annual ryegrass). The seeding method was likely an important contributor to the low success of CC establishment, and coupled with the unfavorable weather conditions in the fall and winter of both years (Fig. 2), increased the variability for both establishment and survival (Fig. 3).

Despite problems with establishment and survival, aboveground biomass yield of CCs was measurable during each rotation, with the exception of radish and rape. Rape was expected to survive the winter, but it did not survive the low temperature during its establishment, and the record-low temperatures during the winter of 2013–2014 probably completed its demise. Radishes were expected to winter-kill, but as was the case with other species, they likely did not survive into the winter. Cereal rye planted following corn and before soybean produced the largest amount of biomass, averaging 86 g/m$^2$, and hairy vetch planted following soybean in this same CC rotation averaged 5 g/m$^2$ of biomass. Annual ryegrass was the only other CC to produce substantial aboveground biomass during both growing seasons, with 6 g/m$^2$ following corn and 14 g/m$^2$ following soybean. Both grass species, along with spring oat seeded following corn had the highest plant densities in the fall (Fig. 3A).

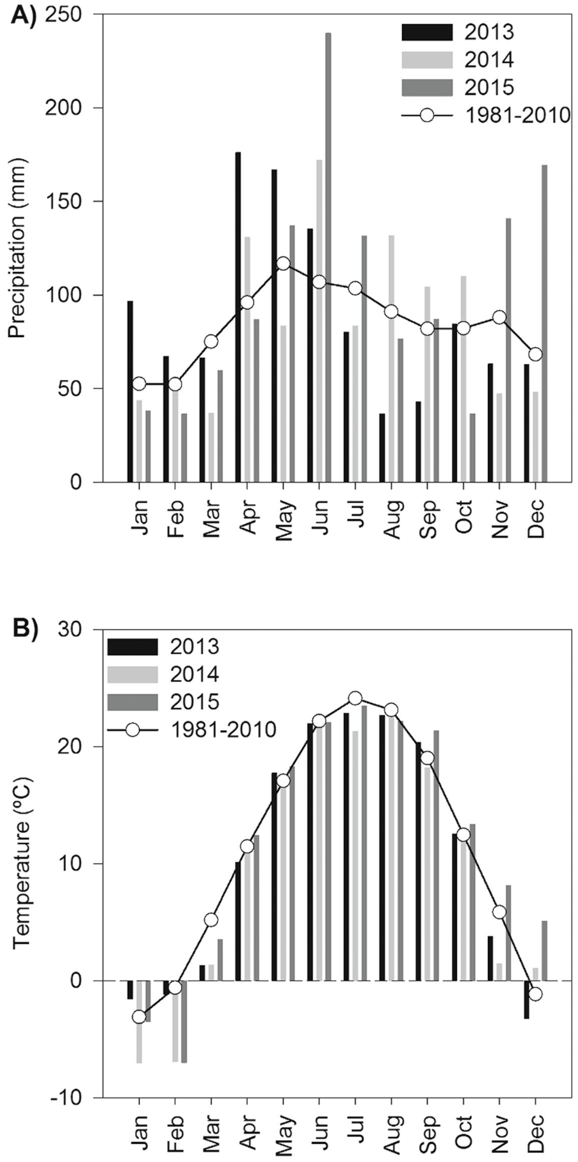


Fig. 2. (A) Precipitation (mm) and (B) temperature (°C) from 2013 to 2015 during the CCs (September–April) and soybean and corn growing seasons (May–November) along with their respective normal for the 1981 to 2010 period. Source: Midwest Regional Climate Center (2015).

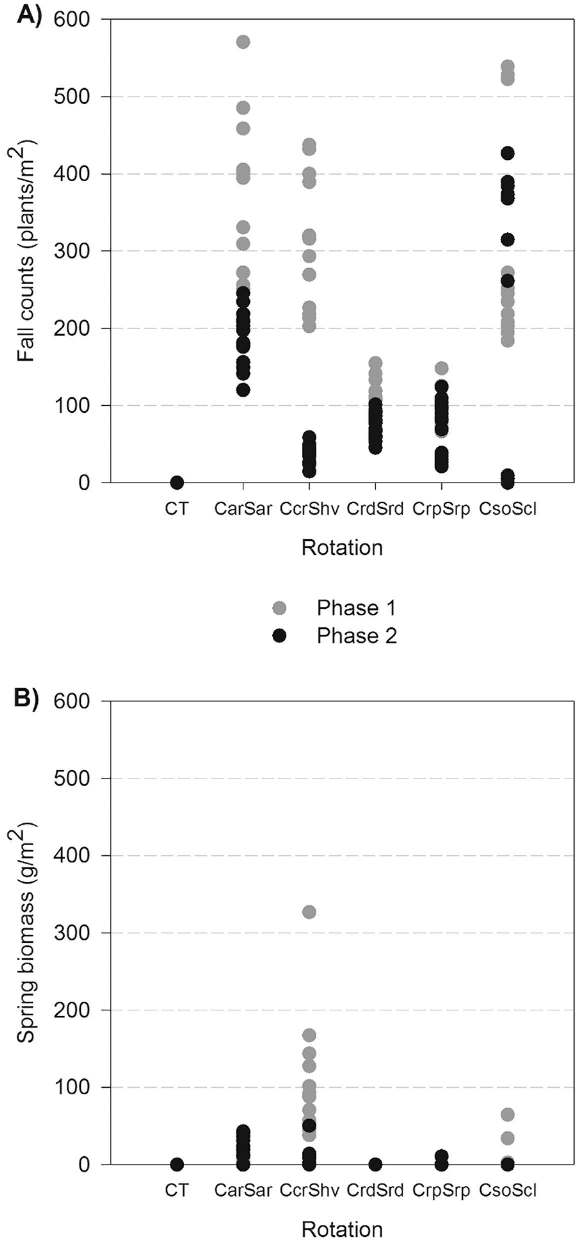


Fig. 3. (A) Fall counts (plants/m$^2$) and (B) spring biomass (g/m$^2$) of specific cover crops in the corn–soybean rotations over the 2 yr of the study and for each phase of the rotation (P). Data points represent each experimental unit instead of their treatment means to show the actual spread of the data.

Table 1. Probability values ($p$ values) associated with the sources of variation in the analysis of cover crop density (plants/$m^2$) in late fall and cover crop biomass in early spring (g/$m^2$) that represents the biomass of the species that overwintered.

| Sources of variation | df | Late fall density | Spring biomass |
|---|---|---|---|
| | | plants/$m^2$ | g/$m^2$ |
| Phase (P) | 1 | 0.1546 | 0.0008 |
| Tillage (T) | 1 | 0.3117 | 0.3176 |
| P × T | 1 | 0.9561 | 0.9111 |
| Rotations (Rcc) | 4 | <0.0001 | <0.0001 |
| P × Rcc | 4 | <0.0001 | <0.0001 |
| T × Rcc | 4 | 0.8558 | 0.8734 |
| P × T × Rcc | 4 | 0.7171 | 0.9925 |

Table 2 shows the probability values ($p$ values) associated with the different sources of variation, that is, P, T, Rcc, and their interaction effects (P × T, P × Rcc, T × Rcc, and P × T × Rcc), as well as D in the statistical analysis of soil properties of PR, BD, WAS, SOM, and TCs, pH, TIN (and its constituents $NO_3$–N and $NH_4$–N), along with available Pa, and exchangeable K, determined in the spring time across the rotation cycle. There was a statistically significant effect of D for all properties measured, reflecting the changes in these properties from the surface down, associated with surface deposition of residues and increased aeration and associated microbial activities when compared with the deeper soil layers under study. After one cycle of cropping and cover crops, the soil physical properties PR, BD, and WAS showed narrow ranges and did not differ by P, T, or Rcc (Table 3). Recorded PR and BD increased with D, consistent with the mulching effect of residue accumulation or tillage incorporation of residue in the surface. The PR values reported here are considered optimal for crop production, below the PR threshold range of 2000 to 4000 kPa suggested as restrictive for root growth (Hamblin, 1985), and we also found BD values lower than BD considered to restrict roots in silt loam soils (Kaufmann et al., 2010). Similar WAS values, a measure of the soil susceptibility to erosion, were recorded for the top 30 cm of the soil, with values increasing in the deeper soil layer (Table 3). Increased soil aggregate strength and higher WAS found in D is likely associated with the higher clay content of the BA horizon of the dominant Drummer soil, increasing the physical protection of soil aggregates.

Table 4 shows the mean values and the results of the mean separation procedure (when appropriate) of the soil properties of SOM, pH, TIN, $NO_3$–N, $NH_4$–N, Pa, and K determined within phases of the rotations (P), under tillage options (T) and Rcc, at successive D. A clear nutrient and pH stratification in depth was identified ($p < 0.0001$), typically related to greater additions of organic residues and greater activity of micro and macro fauna and roots in the topsoil. In the analysis of SOM (Table 2) the statistical significance extended to the main effects of the factors Rcc ($p < 0.0012$) and T ($p < 0.0490$) as well. Once we explored the source of the Rcc effect in Table 4, we determined that it was associated with higher levels of SOM in the CcrShv rotation compared to the CsoScl or CarSar rotations, yet none of the rotations differed from the controls (CT) without CC. Once the SOM is expressed as stocks (TCs in Tables 2 and 4), however, the statistical significance of this finding decreases substantially ($p < 0.0594$) indicating that the observed differences in SOM could be associated with small variations in the soil bulk density among those specific rotations.

Table 2. Probability values ($p$ values) and numerator degrees of freedom (df) associated with the sources of variation in the statistical analysis of soil penetration resistance (PR, kPa), bulk density (BD, Mg/$m^3$), water aggregate stability (WAS, %), soil organic matter (SOM, %), total carbon stocks (TCs, Mg/ha), soil pH, total inorganic nitrogen (TIN, $NO_3$–N, and $NH_4$–N, mg/kg), available phosphorus (Pa, mg/kg), and exchangeable K (mg/kg), determined on each phase of the rotation (P) during the spring each year.

| Source of Variation | df | PR | BD | WAS | SOM | TCs | pH | TIN | $NO_3$–N | $NH_4$–N | Pa | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase (P) | 1 | 0.4252 | 0.7916 | 0.8381 | 0.5445 | 0.2655 | 0.7166 | 0.8821 | 0.8775 | 0.9368 | 0.6413 | 0.8729 |
| Tillage (T) | 1 | 0.7600 | 0.9044 | 0.8022 | 0.0490 | 0.0220 | 0.1163 | 0.0873 | 0.2699 | 0.2502 | 0.2377 | 0.0497 |
| P × T | 1 | 0.9688 | 0.8637 | 0.7868 | 0.2125 | 0.3957 | 0.4392 | 0.9150 | 0.3163 | 0.0857 | 0.5499 | 0.8855 |
| Rotation (Rcc) | 5 | 0.2010 | 0.3526 | 0.2705 | 0.0012 | 0.0594 | 0.0107 | <0.0001 | <0.0001 | 0.4703 | 0.0592 | 0.3622 |
| P × Rcc | 5 | 0.3614 | 0.1718 | 0.0603 | 0.6502 | 0.6370 | 0.5004 | <0.0001 | <0.0001 | 0.2684 | 0.8995 | 0.7773 |
| T × Rcc | 5 | 0.6458 | 0.5398 | 0.8844 | 0.4389 | 0.2749 | 0.4792 | 0.9235 | 0.7769 | 0.8786 | 0.4225 | 0.3622 |
| P × T × Rcc | 5 | 0.3583 | 0.6773 | 0.7738 | 0.6885 | 0.5423 | 0.7638 | 0.1600 | 0.3264 | 0.6387 | 0.3602 | 0.1667 |
| Depth (D) | 2 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

Table 3. Back transformed mean values of soil penetration resistance (PR, kPa), bulk density (BD, Mg/m$^3$), and water aggregate stability (WAS, %) determined within phases of the rotations (P) under tillage options (T) and rotation treatments (Rcc), at successive depths (D). Within a column and within a given factor or combination of factors, means followed by the same letter are not statistically different ($\alpha$ = 0.05).

| P† | T‡ | Rcc§ | D | *n* | PR | BD | WAS |
|---|---|---|---|---|---|---|---|
| | | | cm | | kPa | Mg/m$^3$ | % |
| P1 | | | | 288 | 1271 | 1.36 | 77 |
| P2 | | | | 288 | 1326 | 1.34 | 77 |
| | Till | | | 288 | 1304 | 1.35 | 77 |
| | NT | | | 288 | 1292 | 1.35 | 77 |
| | | CT | | 96 | 1261 | 1.36 | 77 |
| | | CsoScl | | 96 | 1312 | 1.34 | 77 |
| | | CcrShv | | 96 | 1335 | 1.34 | 78 |
| | | CarSar | | 96 | 1301 | 1.33 | 75 |
| | | CrdSrd | | 96 | 1298 | 1.35 | 78 |
| | | CrpSrp | | 96 | 1283 | 1.35 | 77 |
| P × Rcc | | | | | | | |
| P1 | | CT | | 48 | 1250 | 1.39 | 75 |
| | | CsoScl | | 48 | 1274 | 1.35 | 78 |
| | | CcrShv | | 48 | 1333 | 1.34 | 80 |
| | | CarSar | | 48 | 1257 | 1.33 | 75 |
| | | CrdSrd | | 48 | 1263 | 1.36 | 79 |
| | | CrpSrp | | 48 | 1251 | 1.37 | 76 |
| P2 | | CT | | 48 | 1273 | 1.34 | 78 |
| | | CsoScl | | 48 | 1351 | 1.33 | 77 |
| | | CcrShv | | 48 | 1338 | 1.34 | 76 |
| | | CarSar | | 48 | 1346 | 1.34 | 75 |
| | | CrdSrd | | 48 | 1334 | 1.34 | 76 |
| | | CrpSrp | | 48 | 1316 | 1.33 | 78 |
| | | | 0–15 | 192 | 925c | 1.27b | 74b |
| | | | 15–30 | 192 | 1385b | 1.38a | 74b |
| | | | 30–45 | 192 | 1707a | 1.39a | 83a |

† Phases of the rotations (P): P1, spring following corn; P2, spring following soybean.

‡ Tillage options (T): Till, chisel tilled; NT, no-tilled.

§ Rotation reference (Rcc), CT, Corn _ fallow/Soybean _ fallow; CsoScl, Corn _ spring oat/Soybean _ red clover/; CcrShv, Corn _ cereal rye/Soybean _ hairy vetch; CarSar, Corn_ annual ryegrass/Soybean _ annual ryegrass; CrdSrd, Corn _ radish/Soybean _ radish; and CrpSrp, Corn _ rape/Soybean _ rape.

Table 4. Mean values of soil organic matter (SOM, %), total carbon stocks (TCs, Mg/ha), soil pH, and back transformed means of total inorganic nitrogen (TIN, $NO_3$–N+$NH_4$–N, mg/kg), available phosphorus (Pa, mg/kg), and exchangeable K (mg/kg), determined within phases of the rotations (P), under tillage options (T) and rotation treatments (Rcc), at successive depths (D). Within a column and within a given factor or combination of factors, means followed by the same letter are not statistically different ($\alpha$ = 0.05).

| P† | T‡ | Rcc§ | D | *n* | SOM | TCs | pH | TIN | $NO_3$–N | $NH_4$–N | Pa | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | cm | | % | Mg/ha | | mg/kg | mg/kg | mg/kg | | |
| P1 | | | | 288 | 2.13 | 43.52 | 5.60 | 21.65 | 13.74 | 5.53 | 3.89 | 68.59 |
| P2 | | | | 288 | 2.00 | 39.13 | 5.67 | 19.38 | 12.60 | 6.12 | 3.05 | 70.93 |
| | Till | | | 288 | 2.09a | 42.15a | 5.59 | 19.57 | 12.69 | 5.58 | 3.69 | 71.87a |
| | NT | | | 288 | 2.03b | 40.51b | 5.68 | 21.44 | 13.63 | 6.06 | 3.22 | 67.71b |
| | | CT | | 96 | 2.05ab | 41.88 | 5.70a | 21.72 | 15.09 | 5.60 | 3.51 | 69.56 |
| | | CsoScl | | 96 | 2.03b | 40.61 | 5.61ab | 22.67 | 15.37 | 5.81 | 3.54 | 71.55 |
| | | CcrShv | | 96 | 2.11a | 42.21 | 5.71a | 17.06 | 9.46 | 5.96 | 3.82 | 70.82 |
| | | CarSar | | 96 | 2.01b | 40.26 | 5.65ab | 18.64 | 11.26 | 5.65 | 3.02 | 69.94 |
| | | CrdSrd | | 96 | 2.08ab | 41.27 | 5.54b | 23.31 | 15.41 | 6.26 | 3.45 | 67.42 |
| | | CrpSrp | | 96 | 2.09ab | 41.72 | 5.62ab | 20.25 | 13.62 | 5.63 | 3.39 | 69.31 |
| P × Rcc | | | | | | | | | | | | |
| P1 | | CT | | 48 | 2.10 | 44.60 | 5.66 | 24.06a | 16.69a | 5.31 | 4.06 | 67.78 |
| | | CsoScl | | 48 | 2.12 | 42.58 | 5.58 | 25.28a | 16.88a | 5.89 | 3.85 | 70.93 |
| | | CcrShv | | 48 | 2.18 | 44.62 | 5.74 | 13.94b | 6.70b | 5.39 | 4.40 | 68.22 |
| | | CarSar | | 48 | 2.06 | 41.84 | 5.58 | 21.60a | 14.22a | 5.13 | 3.29 | 69.97 |
| | | CrdSrd | | 48 | 2.13 | 43.24 | 5.48 | 26.66a | 17.36a | 6.33 | 3.89 | 66.06 |
| | | CrpSrp | | 48 | 2.16 | 44.25 | 5.59 | 21.08a | 14.42a | 5.20 | 3.93 | 68.71 |
| P2 | | CT | | 48 | 2.00 | 39.17 | 5.74 | 19.61ab | 13.63ab | 5.89 | 3.03 | 71.38 |
| | | CsoScl | | 48 | 1.95 | 38.65 | 5.63 | 20.32ab | 14.00ab | 5.73 | 3.25 | 72.17 |
| | | CcrShv | | 48 | 2.04 | 39.80 | 5.68 | 20.88ab | 13.35ab | 6.60 | 3.32 | 73.51 |
| | | CarSar | | 48 | 1.96 | 38.68 | 5.72 | 16.08ab | 8.92ab | 6.21 | 2.77 | 69.92 |
| | | CrdSrd | | 48 | 2.02 | 39.30 | 5.60 | 20.37ab | 13.68ab | 6.19 | 3.06 | 68.81 |
| | | CrpSrp | | 48 | 2.01 | 39.19 | 5.65 | 19.46ab | 12.86ab | 6.10 | 2.92 | 69.92 |
| | | | 0–15 | 192 | 2.36a | 44.77a | 5.52b | 27.48a | 17.92a | 8.37a | 10.67a | 100.71a |
| | | | 15–30 | 192 | 2.09b | 43.22b | 5.53b | 18.27b | 11.71b | 5.48b | 3.02b | 56.55b |
| | | | 30–45 | 192 | 1.73c | 36.00c | 5.86a | 17.13b | 10.86b | 4.29c | 1.27c | 59.59c |

† Phases of the rotations (P): P1, spring following corn; P2, spring following soybean.

‡ Tillage options (T): Till, chisel tilled; NT, no-tilled.

§ Rotation reference (Rcc), CT, Corn _ fallow/Soybean _ fallow; CsoScl, Corn _ spring oat/Soybean _ red clover/; CcrShv, Corn _ cereal rye/Soybean _ hairy vetch; CarSar, Corn_ annual ryegrass/Soybean _ annual ryegrass; CrdSrd, Corn _ radish/Soybean _ radish; and CrpSrp, Corn _ rape/Soybean _ rape.

Table 5. Averaged soybean and corn crop yields (kg/ha) under different tillage (T) and rotation treatments (Rcc) and combinations of treatments (T × Rcc). Probability values (*p* values) associated with the different sources of variation for each crop are presented below. Within a column and within a given factor or combination of factors, means followed by the same letter are not statistically different ($\alpha = 0.05$).

| | | | Soybean | | Corn | |
|---|---|---|---|---|---|---|
| T† | Rcc‡ | *n* | Mean | SEM§ | Mean | SEM |
| | | | kg/ha | | | |
| T | | | | | | |
| Till | | 48 | 3482b | 300.9 | 12060 | 2313.9 |
| NT | | 48 | 3777a | | 11473 | |
| Rcc | | | | | | |
| | CT | 16 | 3661 | 302.9 | 11980 | 2319.2 |
| | CsoScl | 16 | 3621 | | 12002 | |
| | CcrShv | 16 | 3667 | | 11811 | |
| | CarSar | 16 | 3650 | | 10943 | |
| | CrdSrd | 16 | 3590 | | 12028 | |
| | CrpSrp | 16 | 3587 | | 11837 | |
| T × Rcc | | | | | | |
| Till | CT | 8 | 3467 | 308.4 | 12536 | 2355.0 |
| | CsoScl | 8 | 3421 | | 12415 | |
| | CcrShv | 8 | 3513 | | 11921 | |
| | CarSar | 8 | 3595 | | 10673 | |
| | CrdSrd | 8 | 3478 | | 12397 | |
| | CrpSrp | 8 | 3417 | | 12420 | |
| NT | CT | 8 | 3855 | | 11425 | |
| | CsoScl | 8 | 3821 | | 11589 | |
| | CcrShv | 8 | 3820 | | 11701 | |
| | CarSar | 8 | 3705 | | 11213 | |
| | CrdSrd | 8 | 3702 | | 11658 | |
| | CrpSrp | 8 | 3757 | | 11254 | |
| Sources of variation | | df | *p* value | | *p* value | |
| T | | 1 | 0.0044 | | 0.5107 | |
| Rcc | | 5 | 0.8748 | | 0.4159 | |
| T × Rcc | | 5 | 0.2094 | | 0.4385 | |

† Tillage options (T): Till, chisel tilled; NT, no-tilled.

‡ Rotation reference (Rcc), CT, Corn _ fallow/Soybean _ fallow; CsoScl, Corn _ spring oat/Soybean _ red clover/; CcrShv, Corn _ cereal rye/Soybean _ hairy vetch; CarSar, Corn_ annual ryegrass/Soybean _ annual ryegrass; CrdSrd, Corn _ radish/Soybean _ radish; and CrpSrp, Corn _ rape/Soybean _ rape.

§ SEM, standard error of the mean value.

Tillage affected both SOM and TCs levels, with higher values under tilled plots as opposed to NT. Several studies have reported opposite results, showing increased SOM and TCs under long-term NT compared to tillage practices (West and Post, 2002; Kumar et al., 2012), even under Illinois conditions (Villamil et al., 2015; Villamil and Nafziger, 2015; Zuber et al., 2015). Yet all these later studies reported results from experimental plots with more than 5 yr since treatment establishment whereas the current study has been in place for 3 yr and one complete production cycle in each field. Perhaps tillage in these soils triggers temporary increases in SOM by allowing faster residue turnover due to the higher temperature and reduced water content that commonly limits C cycling in these environments, particularly under NT conditions (Needelman et al., 1999). Further research is needed to evaluate the stability of these observed measures.

Soil pH was not affected by the phase of the rotation (P) or the tillage practices (T) yet we found a statistically significant effect of the rotation (Rcc, $p < 0.0107$) (Table 2). Values range from 5.52 to 5.86 (slightly acidic) typical for agricultural land in the region, though below the range considered optimal (6–6.5) for corn and soybean production (Fernandez and Hoeft, 2009). The source of the significance for the Rcc effect on soil pH, shown by the mean separation results in Table 4, was the lower pH measured in the rotation with radishes (CrdSrd, pH 5.55) compared to the control (CT, pH 5.71) or the rotation that included hairy vetch and rye (CrShv, pH 5.68). Despite the lack of aboveground biomass growth of radishes (CrdSr), this rotation had an acidifying effect on the soil that might have resulted from the oxidation of the volatile components of sulfides and disulfides, arising from the microbial decomposition of the radish root tissues (Belle et al., 2015), clearly ongoing at the time of sampling each year.

Measured levels of soil TIN ($NO_3$–N+$NH_4$–N) were due to mineralization of SOM, residual $NO_3$–N from the N fertilization of the corn crop, and differences among CCs resulting from their scavenging abilities and length of their growing season. There was a statistically significant effect of Rcc in soil TIN, specifically $NO_3$–N levels, that depended on the P as well, rendering a significant interaction term Rcc ′ P ($p < 0.0001$), after one complete cycle of production of the corn–soybean rotations (including two CC growing seasons or two fallow terms). Levels of TIN and $NO_3$–N were the highest in the spring after corn harvest (phase 1) though the lowest levels we found were also during this phase, with the CcrShv rotation; all TIN and $NO_3$–N levels determined during phase 2, that is, in the spring following soybean, were intermediate. There was about 10 mg/kg less TIN (mostly $NO_3$–N) during phase 1 of the CcrShv rotation, likely because N was taken up by the growing cereal rye CC within this rotation. None of the other CCs in the study had any effect on TIN (Table 4); this is likely associated with the low and highly variable levels of spring biomass production even for those CCs expected to overwinter in our region such as hairy vetch, spring oat, annual ryegrass, and rape (Fig. 3). These results agree with previous studies in Illinois (Villamil et al., 2006; Acuña and Villamil, 2014) and highlight the superior performance of cereal rye as a N scavenger within corn–soybean rotations despite its restricted growing season and its variable growth under different environmental conditions.

Rotations with CCs, or the interaction effect of Rcc with tillage, Rcc × T, did not affect soil available P or exchangeable K (Table 2). Both nutrients showed a strong stratification in D, with higher levels in the surface compared to the deeper soil layers studied. There was a statistically significant effect of T on K levels ($p < 0.0459$) with Till having some 4 mg/kg more exchangeable K than NT plots (Table 4). The K content in residues is relatively high compared to that of other essential nutrients, and increased residue breakdown under tillage might have led to this increase (Kumar and Goh, 1999).

Both 2014 and 2015 were favorable growing seasons, with corn and soybean yields over the production cycle of 12.6 and 3.8 Mg/ha, respectively (Table 5). While crop yields were not affected by either Rcc, or their interaction with T, a significant effect of T was found for soybean yields ($p < 0.0044$), with NT soybean yielding some 0.3 Mg/ha more than the Till soybean. This agrees with other findings from the northern Midwest region (Pedersen and Lauer, 2004; Temperly and Borges, 2006), but we recognize that soybean yield responses to T is influenced by seasonal distribution of precipitation and temperature, as well as by soil drainage characteristics.

## CONCLUSIONS

Compared to no CC, corn–soybean rotations that included CCs other than cereal rye did not show any significant change on soil attributes after one cycle of production. Including cereal rye after corn harvest within the corn–soybean rotation decreased available soil N by about 42% but no other CC affected soil N. We found that tillage increased SOM and exchangeable K within these systems, though further research is needed to evaluate the stability of these detected changes. We found that including CCs did not affect cash crop yields in either T or NT systems, but tillage decreased the yield of soybean during our production cycle. This investigation thus showed little response to CCs over the short term, but this does not speak clearly to the benefits that might accrue from long-term use of CCs in U.S. Corn Belt rotations.

## ACKNOWLEDGMENTS

Funding for this project was provided by the Illinois Nutrient Research and Education Council (IL-NREC), Award No. 2013-03556-01 "Agronomic and Environmental Assessment of Cover Crops in Illinois." We are also indebted to the IL-NREC for supporting Mr. Dozier's master degree within the context of this project. We acknowledge with gratitude the assistance of Mr. Dennis Bowman, and Mr. Jeffrey Warren for cover crop seeding and overall plot maintenance at the Urbana site. We are thankful to Mr. Samuel Kato and the many undergraduate workers who provided essential help with field tasks and laboratory determinations.

## REFERENCES

Acuña, J.C.M., and M.B. Villamil. 2014. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agron. J. 106:860–870. doi:10.2134/agronj13.0370

Belle, A.J., S. Lansing, W. Mulbry, and R.R. Weil. 2015. Methane and hydrogen sulfide production during co-digestion of forage radish and dairy manure. Biomass Bioenergy 80:44–51. doi:10.1016/j.biombioe.2015.04.029

Blake, G.R., and K.H. Hartge. 1986. Bulk density. In: A. Klute, editor, Methods of soil analysis: Part 1 Physical and mineralogical methods. SSSA and ASA, Madison, WI.

Chen, G., and R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331:31–43. doi:10.1007/s11104-009-0223-7

Cherr, C.M., J.M.S. Scholberg, and R. McSorley. 2006. Green manure approaches to crop production: A synthesis. Agron. J. 98:302–319. doi:10.2134/agronj2005.0035

CTIC-SARE. 2016. Report of the 2014-15 Cover Crop Survey (previous surveys available int eh same webpage). Joint publication of the Conservation Technology Information Center and the North Central Region Sustainable Agriculture Research and Education Program. http://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2013-14-Cover-Crops-Survey-Analysis (accessed 18 Mar. 2016).

David, M.B., L.E. Drinkwater, and G.F. Mclsaac. 2010. Sources of nitrate yields in the Mississippi River Basin. J. Environ. Qual. 39:1657–1667. doi:10.2134/jeq2010.0115

David, M.B., and L.E. Gentry. 2000. Anthropogenic inputs of nitrogen and phosphorus and riverine exports for Illinois, USA. J. Environ. Qual. 29:494–508. doi:10.2134/jeq2000.00472425002900020018x

Dean, J.E., and R.R. Weil. 2009. Brassica cover crops for nitrogen retention in the Mid-Atlantic Coastal Plain. J. Environ. Qual. 38:520–528. doi:10.2134/jeq2008.0066

Fernandez, F.G. and R.G. Hoeft. 2009. Managing soil pH and crop nutrients. Illinois agronomy handbook. Univ. of Illinois. http://extension.cropsciences.illinois.edu/handbook/ (accessed 14 Apr. 2017). Chapter 8.

Gbur, E.E., W.W. Stroup, K.S. McCarter, S. Durham, L.J. Young, M. Christman et al. 2012. Analysis of generalized linear mixed models in the agricultural and natural resources sciences. ASA, SSSA, and CSSA, Madison, WI.

Hamblin, A.P. 1985. The influence of soil structure on water movement, crop root growth, and water uptake. Adv. Agron. 38:95–158. doi:10.1016/S0065-2113(08)60674-4

Illinois EPA. 2015. Illinois Nutrient Loss Reduction Strategy (INLRS). Illinois Environ. Protection Agency. http://www.epa.illinois.gov/Assets/iepa/water-quality/watershed-management/nlrs/nlrs-final-revised-083115.pdf (accessed 19 Sept. 2016).

Jacobson, L.M., M.B. David, and L.E. Drinkwater. 2011. A Spatial analysis of phosphorus in the Mississippi River Basin. J. Environ. Qual. 40:931–941. doi:10.2134/jeq2010.0386

Kaspar, T.C., D.B. Jaynes, T.B. Parkin, T.B. Moorman, and J.W. Singer. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agr. Water Manage. 110:25–33. doi:10.1016/j.agwat.2012.03.010

Kaufmann, M., S. Tobias, and R. Schulin. 2010. Comparison of critical limits for crop plant growth based on different indicators for the state of soil compaction. J. Plant Nutr. Soil Sci. 173:573–583. doi:10.1002/jpln.200900129

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. In: A. Klute, editor, Methods of soil analysis: Part 1 Physical and mineralogical methods. SSSA and ASA, Madison, WI.

Konen, M.E., P.M. Jacobs, C.L. Burras, B.J. Talaga, and J.A. Mason. 2002. Equations for predicting soil organic carbon using loss-on-ignition for north central US soils. Soil Sci. Soc. Am. J. 66:1878–1881. doi:10.2136/sssaj2002.1878

Kumar, K., and K.M. Goh. 1999. Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. Adv. Agron. 68:197–319. doi:10.1016/S0065-2113(08)60846-9

Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012. Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio. Soil Sci. Soc. Am. J. 76:1798–1809. doi:10.2136/sssaj2012.0055

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.

Midwest Regional Climate Center. 2015. Cli-MATE. MRCC Application tools environment. Illinois State Water Survey, Prairie Research Inst., Univ. of Illinois at Urbana-Champaign. http://mrcc.isws.illinois.edu/CLIMATE/ (accessed 14 Mar. 2016).

Miguez, F.E., and G.A. Bollero. 2005. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci. 45:2318–2329. doi:10.2135/cropsci2005.0014

Miguez, F.E., and G.A. Bollero. 2006. Winter cover crops in Illinois: Evaluation of ecophysiological characteristics of corn. Crop Sci. 46:1536–1545. doi:10.2135/cropsci2005.09.0306

Needelman, B.A., M.M. Wander, G.A. Bollero, C.W. Boast, G.K. Sims, and D.G. Bullock. 1999. Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois. Soil Sci. Soc. Am. J. 63:1326–1334. doi:10.2136/sssaj1999.6351326x

Pedersen, P., and J.G. Lauer. 2004. Soybean growth and development response to rotation sequence and tillage system. Agron. J. 96:1005–1012. doi:10.2134/agronj2004.1005

Ruffo, M.L., D.G. Bullock, and G.A. Bollero. 2004. Soybean yield as affected by biomass and nitrogen uptake of cereal rye in winter cover crop rotations. Agron. J. 96:800–805. doi:10.2134/agronj2004.0800

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63:167–179. doi:10.1016/S0167-1987(01)00244-6

Singer, J.W. 2008. Corn Belt assessment of cover crop management and preferences. Agron. J. 100:1670–1672. doi:10.2134/agronj2008.0151

Singer, J.W., S.M. Nusser, and C.J. Alf. 2007. Are cover crops being used in the US Corn belt? J. Soil Water Conserv. 62:353–356.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep et al. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97:322–332.

Soil and Plant Analysis Council. 1992. Soil analysis: Handbook of reference methods. CRC Press, New York.

Soil Survey Staff. 2012. Web soil survey. Natural Resources Conserv. Serv., USDA. http://websoilsurvey.nrcs.usda.gov/ (accessed 14 Mar. 2016).

Strom, S. 2016. Cover crops, a farming revolution with deep roots in the past. New York Times, Feb 7. https://www.nytimes.com/2016/02/07/business/cover-crops-a-farming-revolution-with-deep-roots-in-the-past.html (accessed 14 Apr. 2017)

Temperly, R.J., and R. Borges. 2006. Tillage and crop rotation impact on soybean grain yield and composition. Agron. J. 98:999–1004. doi:10.2134/agronj2005.0215

Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112:58–72. doi:10.1016/j.agee.2005.07.003

USDA NASS. 2016a. Survey. Agricultural chemical use program. USDA NASS. http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.asp (accessed 6 Sept. 2012).

USDA NASS. 2016b. Quick Stats. Survey. Field crops, Illinois. USDA NASS. https://quickstats.nass.usda.gov/ (accessed 23 Sept. 2016).

Villamil, M.B., and E.D. Nafziger. 2015. Corn residue, tillage, and nitrogen rate effects on soil carbon and nutrient stocks in Illinois. Geoderma 253–254:61–66. doi:10.1016/j.geoderma.2015.04.002

Villamil, M.B., G.A. Bollero, R.G. Darmody, F.W. Simmons, and D.G. Bullock. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Sci. Soc. Am. J. 70:1936–1944. doi:10.2136/sssaj2005.0350

Villamil, M.B., F.E. Miguez, and G.A. Bollero. 2008. Multivariate analysis and visualization of soil quality data for no-till systems. J. Environ. Qual. 37:2063–2069. doi:10.2134/jeq2007.0349

Villamil, M.B., J. Little, and E.D. Nafziger. 2015. Corn residue, tillage, and nitrogen rate effects on soil properties. Soil Tillage Res. 151:61–66. doi:10.1016/j.still.2015.03.005

Welch, R.Y., G.D. Behnke, A.S. Davis, J. Masiunas, and M.B. Villamil. 2016. Using cover crops in headlands of organic grain farms: Effects on soil properties, weeds and crop yields. Agric. Ecosyst. Environ. 216:322–332. doi:10.1016/j.agee.2015.10.014

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1930–1946. doi:10.2136/sssaj2002.1930

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68:1403–1409. doi:10.2136/sssaj2004.1403

Zuber, S.M., G.D. Behnke, E.D. Nafziger, and M.B. Villamil. 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron. J. 107:971–978. doi:10.2134/agronj14.0465