TILLAGE AND COVER CROPPING EFFECTS ON SOIL PROPERTIES AND CROP PRODUCTION

BY

IVAN A. DOZIER

THESIS

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Master's Committee:

Asst. Professor María B. Villamil, Chair
Professor Emerson D. Nafziger
Associate Professor Adam S. Davis

ABSTRACT

Cover crops (CCs) have been heralded for their potential to retain nutrients in the field and improve soil properties, but their adoption within the Midwestern Corn-Belt remains limited. We assessed the effects of integrating five sets of CCs into corn-soybean rotations under no-till and chisel till systems compared with fallow controls on soil attributes and crop yields after one complete rotation cycle. The experimental layout was a split split-block where whole plot treatments (phase of the rotation and year) had a Latin square design and sub plot treatments accommodated 4 replications each split in the N_S direction into levels of tillage (NT, no-till vs. Till, chisel till) and further split into sub-subplot treatments of CC rotations (R) arranged in the W-E direction across tillage treatments. Crop yields, CC stand counts in late fall, and spring biomass samples were taken from actively growing CCs each year. Studied soil attributes included bulk density (BD), water aggregate stability (WAS), and penetration resistance (PR), as well as chemical properties of soil organic matter (SOM), total carbon stocks (TCs), pH, plant available nitrogen (TIN, NO3-N and NH4-N), available phosphorus (P), and exchangeable potassium (K). Compared to winter fallows, crop yields and soil attributes under corn-soybean rotations that included CCs did not show any significant change after one cycle of production. Our results show that the inclusion of CCs does not cause significant drops in crop yield in either till or no till systems while there is potential for N scavenging when including overwintering CCs in the corn soybean rotations.

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INTRODUCTION

Global population continues to rise, and with it, global food demand. In order to achieve the crop yields necessary to meet this demand, certain intensive management practices such as increased fertilization and progression towards monocultures are becoming more common, resulting in environmental concerns (Power and Follett, 1987; Tilman et al., 2001). Monocultures can also lead to greater risk for erosion and harmful pests, and given time will eventually begin to decrease yields (Power and Follett, 1987). Increased use of N fertilizer can result in nitrate leaching, which pollutes water supplies, leading to hypoxic zones and contaminated drinking water (Goolsby, 2000).

The Midwestern Corn Belt is one of the most productive regions in the world, and includes much of the state of Illinois. In Illinois, production has maintained a steady rise, with the state producing an average of 180 bu/acre (11300 kg/ha) of corn, and 56 bu/acre (3800 kg/ha) from soybeans in 2014, making the grain production a multi-billion dollar industry in the state alone (USDA NASS, 2011). Yields are also rising, noticeably heightened from the 151 bu/acre (10200 kg/ha) corn and 44 bu/acre (3000 kg/ha) soybean averages across the state at the turn of the century in 2000 (USDA NASS, 2011). This natural productivity makes Illinois one of the most likely regions to adopt intensive agricultural practices to boost yields without immediately seeing the possible negative side-effects. However for high productivity to continue the initial quality must be maintained, making the pursuit of conservative management practices or methods to offset the side-effects of intensive management all the more important in this region of the world (Doran et al., 1994).

Many soil-building practices that were commonplace in the past such as diverse crop rotations have fallen out of popularity as American society has shifted towards grain production.

As the topic of “healthy” soil continues to develop, many such practices such as reduced tillage are being researched for possible reinstatement into modern agricultural production (Hill, 1990). Another such practice is the integration of an actively growing plant between annual crop rotations to provide the benefits of additional plant growth, also known as cover cropping.

Cover crop (CC) adoption has been limited in the Midwest region despite the reputed benefits (Singer et al. 2007). According to survey results from the Conservation Technology Information Center (CTIC SARE, 2014) most operations in the Midwest that use a cover cropping system do so in tandem with no-till practices or organic production, to help mitigate potential negative effects with these particular systems in comparison with traditional tillage or non-organic methods, respectively.

The concept of CCs has been around for a long time, and the advantages of the practice have been widely documented, albeit highly variable. By growing during the traditionally fallow winter period, CCs can improve soil structure and prevent erosion in an isolated agriculture system. At a larger scale, CCs have also been used to benefit the environment by limiting soil erosion, preventing N leaching and phosphorus runoff into aquatic systems, increasing ecosystem diversity, and acting as carbon sequestration sinks (Decker et al., 1994).

Excess fertilizer applications can result in nutrient leaching or runoff, wherein extra fertilizer that is not taken up by the intended plant recipient is transported throughout the soil, eventually winding up in the water. Mobile chemicals can remain in the groundwater, or move on into local stream and river systems. This contamination can cause eutrophication of surface water, leading to hypoxic zones and disruption of local ecosystems (Goolsby, 2000; Rabalais et al., 2002). Cover crops can help prevent these problems by taking up chemicals such as nitrate directly, or absorbing them through already contaminated water (Thorup-Kristensen et al., 2003;

Kaspar et al., 2012). These chemicals can also enter the water supply directly when soil is washed away by wind or water. With roots to anchor the soil in place, CCs can reduce erosion and thus slow this additional mechanism of water pollution (Kaspar et al., 2001).

Incorporating one or more varieties of CCs, can contribute to local diversity by introducing new species into what is commonly a one or two species grain rotation. In this manner, local systems can be one step closer to a natural polyculture, thus reaping the benefits of increased ecosystem diversity (Power and Follett, 1987; Doran et al., 1993). The living material that a CC provides also shows potential for carbon sequestration. Just as dying plant material can provide nutrients through direct and scavenging mechanisms (Ranells and Wagger 1996; Varvel and Wilhelm, 2010) it can also provide carbon to increase the soil organic carbon pool, or at least reduce its rate of depletion through sequestration, which has a number of benefits (Kuo et al., 1997; West and Post, 2002). In addition to effects by the growing CC, residual effects such as improved soil structure and water holding capacity are general advantages of increased soil organic matter, thus extending the time period of beneficial CC inputs (Amézketa, 1999; Varvel and Wilhelm, 2010).

The mechanisms by which soil is affected by CCs can be heavily dependent upon the method of tillage that is instituted. Many Midwestern farmers still use conventional tillage; however no-till is a growing practice for soil conservation (Horowitz et al., 2010). The effects of CCs have been well documented in no-till systems. Rye, vetch, and clover have been shown to increase yields in no-till corn (Frye et al., 1985), and these same crops have a history of being utilized for the N scavenging benefits (Ebelhar et al., 1984). These same CCs, excluding clover, were found to benefit the water aggregate stability as well, highlighting the effect on soil physical properties (Villamil et al., 2006). No-till systems also raise a need for specialized CC results to mitigate the potential downsides to lack of cultivation. No-till soils have been shown to have higher N and C content than tilled soils (Olson et al., 2014; Zuber et al. 2015), so the impact of these nutrient sequestration abilities from CCs may be less pronounced (Arshad et al. 1990). Instead, the key downsides to no-till production are soil compaction, weed control, higher soil moisture, and lower soil temperature (Teasdale, 1996; Diaz-Zorita et al. 2004), all factors that could be potentially modified by inclusion of a CC.

Under conventional tillage, CCs have shown mixed results. The inclusion of CC with more intensive tillage practices have shown non-significant results (Sainju et al., 2002; Olson et al., 2010), or results that fail to paint a conclusive trend (Munawar et al., 1990). Tillage breaks down crop residues into the soil facilitating the oxidation of organic matter, aeration, and release of nutrients. These short term changes brought about by tillage may mirror some of the effects that CCs are used for, whereas bulk density and root inhibition are more prevalent risks under no-till systems. (Hill, 1990)

The active root growth of an overwintering plant can aid in the soil's resistance to erosion, and vastly improve overall soil structure (Haynes and Beare, 1997; Williams and Weil, 2004). Soil stability can also be improved, meaning less soil runoff even after the CC is gone (Doran et al., 1994). The root growth also serves to create pore space and aerate the soil, which is an especially important factor in the relief of compacted soils (Chen and Weil, 2010). As a result of these structural improvements, CCs often result in a cash crop yield boost under compacted or poorly structured soils (Decker et al., 1994; Williams and Weil, 2004).

Many of the above situations that are remedied by CCs are an issue restricted to poorer soils, atypical outside of isolated spots in Illinois and the Midwest in general. However, there are circumstances in which production in Illinois could still benefit from a cover cropping practice, as well as a number of generalized benefits that could be applied to all soils, both poor and productive. Under a traditional Illinois corn/soy rotation that was not tilled, CCs were shown to catch plant available nitrogen (N) and phosphorus (P), as well as improve soil water aggregate stability (WAS), bulk density (BD), and penetration resistance (PR) (Villamil et al., 2006; 2008). These measurements are proxies of erosion resistance, compaction, and root growth potential, respectively, and together serve as a collection of overall soil quality indicators. Even after the quality status has been established, a well-structured soil can act as a buffer, resisting further degradation and maintaining itself in the long term (Doran et al., 1994).

In addition to environmental factors and soil physical properties, the chemical composition of the soil also stands to be enhanced through CCs. Nitrogen is perhaps the most important nutrient required for plant growth, and perhaps the most promising advantage of CCs is their ability to scavenge this vital nutrient. Both plants and people have a heavy reliance on N, however the element is tied up in many forms throughout its extremely dynamic cycle. Understanding the N cycle and its role in agriculture is of the upmost importance for modern production, and can help explain the mechanisms behind a cover crop’s ability to provide nutrients to a cash crop. Nitrogen is available naturally as the most abundant gas in our breathable air. However, despite the prevalence of N, only certain forms of the element are available for plant uptake.

Nitrogen exists in many forms. When unavailable to plants, N exists in an immobilized state, bound with organic material. Plants can uptake N after mineralization, residual nitrate, and direct application of fertilizer (Meisinger et al., 1990). To test the levels of N is a soil, measurements of total inorganic N, in the forms of nitrate (NO3) and ammonium (NH4), are tested and used as the primary indicator of N content (Mulvaney, 1996).

The mechanism behind N scavenging involves the use of a growing plant to uptake excess N that may exist in the soil. In the case of a CC, the growing plant will use the N and then release it back into the soil upon the plant's death. This allows the N to be returned to the soil at a time when it is more likely to be taken up by the cash crop, and less likely to be removed through leaching or erosion. These effects are seen more effectively in CCs that produce a greater degree of root biomass over-winter, such as grasses like cereal rye (Sainju et al., 1998). Legume CCs supply N though a by N fixation; this alternative method of N supply can serve to benefit yields, or supply additional N to areas of low fertility (Decker et al., 1994; Sainju et al., 1998).

In general, CCs have been used for the aforementioned effects on soil and environment; however, each species of CC has unique characteristics and provides specific benefits. This makes selection of CC varieties an important aspect of implementation as CC species should be chosen based on the specific issues and characteristics of an individual field. The thick, fibrous roots and ability to produce biomass make grass CCs a very popular choice. Not only can these grasses absorb N in the upper layers of the soil to preserve it in their biomass, but the roots can also decompose and significantly boost soil organic matter (Brandi-Dohrn et al., 1997; Kuo et al., 1997). This combination has also been shown to increase subsequent grain yield. (Kaspar et al., 2012). The more roots that are produced, the more effective the CCs appear to be at reducing leaching and associated losses of N compared to other CC varieties (Sainju et al., 1998; Kaspar et al., 2012). Grass CCs are also appealing due to their potential to supply forage, and a more resistant mulch than legumes due to higher C/N ratio and lignocellulosic content (Munawar, 1990; Wagger and Mengel, 1993). Legume crops such as vetch and clover are primarily used for their ability to fix N and provide N to a growing corn crop (Fisk et al., 2001). This direct production of N can also benefit the water system from an environmental perspective, as N added into the soil by a growing crop can potentially lower fertilizer needs and thus the associated risks of nutrient leaching and runoff.

Brassica crops such as radishes can create macropores within the surface soil with their thick roots and can also penetrate deep into the soil via taproot (Lehrsch and Gallian, 2010). Deep rooted Brassicas such as rapeseed can alleviate compaction in layers of the soil profile that other CCs cannot reach (Chen and Weil, 2009). This deep rooting system also results in augmented nutrient use efficiency, by picking up nutrients tied up in the subsoil that would otherwise go unutilized (Dean and Weil, 2009).

The list of potential CC advantages would certainly seem to actuate the practice worthy of widespread adoption; however there are still many barriers to overcome. A recent survey (CTIC SARE, 2014) polled farmers on their barriers to CC adoption, in addition to the requirement for advanced knowledge, nearly half of the respondents avoided the practice due to the time and labor required. Over one third of both current CC users and non-users were also concerned about the costs associated with CC planting and management. Another potential barrier is the lack of increases in cash crop yield following a cover crop, which could threaten potential adoption despite the positive influence on soil and environment. A meta-analysis of CC effects conducted by Miguez and Bollero (2005), indicates no significant corn yield increases when using grass CCs yet boosts in corn yield were present when legumes and mixtures preceded the corn crop. Variability from species selection, management practices, method and timing of growth suppression, along with weather and soil environments evaluated have contributed to mixed results in regards to CC effects on yields, reflecting the complexity of cover cropping and the main deterrent to widespread adoption of the practice.

To ensure the profitability of a CC, it is of paramount importance to suppress the CC growth to prevent competition with the cash crop. By selecting CCs that are not winter hardy, no additional work is needed to suppress the CC, as they are suppressed naturally by frigid temperatures prior to the cash-crop growing season. Timing the termination of the CC is essential not only for limited interference with the cash crop, but it is also an important factor governing soil temperature and moisture (Unger and Vigil, 1998; Wagger and Mengel, 1993). A growing CC will uptake water and could dry out the soil, whereas killed plants can add moisture through mulching effects. Timing of suppression can also play an important factor when utilizing CCs for the purposes of pest management (Dabney et al., 2001), or for the use of regulating soil temperature through shading (Snapp et al., 2005). The method of suppression is equally important since the efficiency varies according to environmental and plant related factors. Traditional methods of cover crop suppression include “plowing-under” using standard cultivation equipment (Brandi-Dohrn et al., 1997; Singer 2007) and the application of burndown herbicides (i.e. glyphosate). Rolling and crimping the cover crop tissues is also a common option for those who have such specialized equipment yet timing is essential to prevent escapes. Rolling and glyphosate methods have been paired to achieve maximum termination (Price et al., 2009).

Weather can also play a significant factor in not only the growth of the CC itself but also the potential for observed benefits. Precipitation has a substantial effect of soil erosion and potential for nutrient leaching (Schreiber, 1999). In addition, temperature can also play a factor on the transformations of N within the soil (Cookson et al., 2002). The average winter temperature in Illinois is below 2 degrees Celsius (NOAA, 2015). The cold temperature and daily fluctuation could not only have an effect on plant-available soil N, but could initiate a premature winter kill that removes the cover from the field before it has a chance to instigate significant effects, as kill date also is an important factor in the assessment of CC impacts (Clark et al., 1997; Cookson et al., 2002).

The objectives of this study are to monitor soil properties and crop yields in corn soybean rotations including 5 sets of CC under both conventional and no-till practices to evaluate the potential for CC advantages, as well as overall feasibility of widespread adoption in the highly productive Midwest region. We hypothesize that rotations including CCs will show evidence of nutrient scavenging and improvements in soil organic matter, bulk density, water aggregate stability, and penetration resistance through increased input of residues and root activities when compared to winter fallow systems. These anticipated findings will likely only be seen under appropriate temperatures, which can have a significant effect on CC performance (Cookson et al., 2002). With this in mind, more prominent results are anticipated for overwintering CCs due to their longer growing season, as well as in plots subjected to no-till treatment, as many of the physical effects of CCs can also be caused by tillage, albeit temporarily.

MATERIALS AND METHODS

Site Characterization and Management

This study was established in 2012 at the Crop Sciences Research and Education Center (South Farms) of the University of Illinois at Urbana (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). Drummer silty clay loam (fine-silty, mixed, superactive, mesic, Typic Endoaquoll), Flanagan silt loam (fine, smectitic, mesic, Aquic Argiudoll), and Catlin silt loam (Fine-silty, mixed, superactive, mesic, Oxyaquic Argiudoll) consist of dark colored soils developed under prairie in 40-60in of loess over silty clay loam till on mostly nearly level to very gently sloping topography in upland positions. Flanagan is somewhat poorly drained and Catlin is moderately to well drained, occupying the higher landscape positions. Drummer soils are poorly drained soils that occupy the lower landscape positions. 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 May 17 in 2013 and May 21 in 2014 and harvested on October 17 and November 3 in 2013 and 2014, respectively. Soybean was planted on June 7 2013 and May 21 2014, and harvested on October 14 and 30 in 2013 and 2014, respectively. Volunteer corn plants were removed from soybean plots in July. Tillage was conducted via chisel plow 20-25cm deep in the fall after harvest, with secondary tillage occurring in the spring with field cultivator. No tillage was carried out on the no-tilled plots.

Cover crops were broadcasted by hand into standing cash crop to simulate aerial seeding ion September 16 and 17 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 and hairy vetch; 67.2 kg/ha for spring oats; and 100 kg/ha for cereal rye. Cover crops were chemically suppressed with glyphosate (N-(phosphonomythyl) glycine) at 1.12 kg a.i./ha at the time of biomass sampling in mid-April, about a month before cash crop planting each year.

Soil Sampling and Analyses

Soil samples were collected during the first week of May in 2014 and 2015 after CCs were terminated 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 0-15, 15-30, and 30-45cm. Three soil core samples were taken with a tractor-mounted soil sampler (Amity Tech, Fargo, ND) to 45cm 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 4.3cm, and was cut into three 15cm increments for lab determinations at successive depths. Soil was oven-dried at 105 °C to measure gravimetric water content at each depth, concurrently with soil bulk density (BD, Mg/m^3)using the core method (Blake and Hartge, 1986). Field moist soil was analyzed for available N (N-NO_3 and N-NH_4, in mg/kg) using KCl extraction (1:5 ratio soil to 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 2mm 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 1-2mm 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).

Samples were sent to a commercial laboratory (Brookside laboratories Inc, New Bremen, OH) for the determination of available P (mg/kg), exchangeable K (mg/kg), and soil organic matter (%). According to this commercial lab procedures, available P was determined following Bray-1 extraction, and K following Mehlich-III extraction. Soil organic matter was determined by loss on ignition (Soil and Plant Analysis Council, 1992), and the results adjusted according to equations developed by Konen et al. (2002) for these soils. Bulk density values were used to convert SOM in % to a basis of weight per unit area, or total carbon stocks (TCs, Mg/ha) for each 15cm depth increment.

Fall stand counts of CCs (plants/m^2) were taken during the first week of November each year using a 0.25m^2 quadrat to estimate growing CC populations prior to winterkill. Spring biomass samples were collected on April 25 2014, and again on April 27 2015 using a 0.5m side square thrown randomly into the plots three times. Overwintering biomass samples (g/m^2) were cut at ground level and oven-dried at 60 degrees C and weighed. Yields of the cash crop were taken using a plot combine and adjusted to 15% and 13% moisture basis for corn and soybeans, respectively.

Experimental Design and Statistical Analysis

The experiment aimed to test the effects of tillage and corn-soy rotations including CCs on soil properties and crop yields. A diagram of the experimental layout is shown in Figure 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 years for each field of corn and soybeans to complete the rotation. With no true replications of field and years, both factors field (F) and year (Y) act as blocks for the effect of rotation phase which is consistent with a Latin square design. Whole-plot treatments where phases of the rotations (P) where phase 1 corresponds to the spring sampling following soybean and CCs (or fallow), and phase 2 to the spring sampling following corn and CCs (or fallow), respectively. Sub-plot treatments of tillage (T) and rotations (R) were arranged in a split block design with four replications [B(F)]. Whole plots accommodated 4 reps each split in the N_S direction into levels of tillage (T: NT, no-till vs. Till, chisel till) and further split into sub-subplot treatments of CC rotations (R) arranged in the W-E direction across tillage treatments. There were 6 levels of CC rotations R: 1) CT: Soybean _ fallow/ corn _ fallow; 2) SclCso: Soybean _ red clover/ corn _ spring oats; 3) ShvCr: Soybean _ hairy vetch/ corn _ cereal rye; 4) SrCr: Soybean _ annual ryegrass/ corn _ annual ryegrass; 5) SrdCrd: Soybean _ radish/ corn _ radish; and 6) SrpCrp: Soybean _ rape/ corn _ rape.

Factors phase (P), tillage (T), rotations (R), and depth (D) were considered fixed while years (Y), fields (F), and replications [B(F)] were considered random. The statistical model follows:

P + Y + F + Error(1) + T + T*P + B(F) + Error(2) + R+ R*P + R*T + R*T*P + Error(3) + D + P*D + T*D + R*D + P*T*D + P*R*D + T*R*D + P*T*R*D + Error(4)

Error(1): P*Y*F as in a Latin square (Y and F are not testable as in two random blocking factors)

Error(2): P*T*Y*B(F)

Error(3): P*T*R*Y*B(F), and Error(4): residual.

The resulting models were analyzed 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 but soil organic carbon (SOC) and pH, were analyzed with the lognormal distribution (`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 (D) 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, 2006). When appropriate, `lsmeans` were separated using the `pdiff` option of `lsmeans` setting the probability of Type I error at 0.05(α), and using a Bonferroni correction (`adjust=bon`) linked to the degrees of freedom adjustment (`adjdfe=row`) included in the model statement. The corresponding general SAS code results:

```
title 'variable';
proc glimmix data=thesis ;
class Y F P rep T R D;
model variable= P|T|R|D/ ddfm=kr;
random F*Y*P rep(F) P*T*Y*rep(F) P*T*R*Y*rep(F);
random _residual_ /subject=P*T*R*Y*rep(F) type=arh(1);
lsmeans P T R P*R D/adjdfe=row adjust=bon; run;
```

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 soybean (phase 1) and corn (phase 2). The **`corr`** procedure of SAS 9.4 was used to evaluate the relationship between soil variables.

RESULTS

As illustrated in Figures 2 and 3, weather played an important role in CC emergence and growth both years. Table 1 shows the probability values associated with the different sources of variation in the statistical analysis of CC fall counts and spring biomass. A statistically significant effect of the interaction of P x R was found for both CC fall counts ($p<0.0001$) and spring biomass ($p<0.0001$) (Table 1) reflecting differences in plant density and biomass for the overall CC rotations (R) within each phase of the rotations, i.e following soybean or following corn. This was expected based on the different seeding rates of the CCs as well as their different overwintering potential in our region. Shown in figure 3, above-ground biomass yield was measurable at some point during each CC phase, with the exception of the control and radish. However, the lack of aboveground biomass in the radish rotation is not unusual, as the radish was expected to winter-kill and the prominent growth of radishes come from the taproot's below-ground biomass. The most biomass was produced by cereal rye used during phase 2 (following corn and before soybean crop) in the ShvCr rotation, averaging 86 g/m2 with the hairy vetch averaging 5 g/m2 of biomass. Annual ryegrass was the only other CC to produce substantial aboveground biomass during both growing seasons with 6 g/m2 following corn and 14 g/m2 of biomass following soybean (phase 1). These grass varieties also produced the highest plant densities, significantly higher than any other treatment. However the data collected showed extreme variability on emergence and survival even for the same species (Fig. 3) and it was especially variable 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 the CC implementation which coupled with the extreme weather conditions over late fall and winter during both years increased the variability for both establishment (fall counts) and survival (spring biomass). In the months of November and December, following CC planting, precipitation amounts were below normal during 2013 and 2014 (Fig. 2). Reduced soil moisture was a likely cause for establishment and early growth challenges across some CCs due to the crucial role of seed imbibition and incorporation into the soil via rainfall. Temperature also plays a significant role in CC activity. Once again, conditions were below average for the months of November and December, providing another source of stress for growing CCs resulting in complete suppression of legumes and brassica CCs in late fall both years with uneven survival of the overwintering species (Fig. 2 and 3).

Table 2 shows the exact probability values (p-values) associated with the different sources of variation in the analysis of soil properties across the two years of the experiment. None of the CC rotations (R) were different from the fallow control for the measured soil physical properties of PR, BD and WAS.

Table 3 illustrates the back transformed mean values of soil physical properties. Depth was the only source of variation significant across physical properties ($p<0.0001$). As expected, values associated with soil porosity increased with depth. Penetration resistance had a 779 kPa difference between the top and bottom soil layers, and BD increased by 0.13 Mg/m^3 from the soil surface to a depth of 45 cm. Water aggregate stability, which is typically greater in surface soil layers, also increased with depth. There was no difference between the 0-15 cm and 15-30 cm depths but increased by 9% in 30-45 cm, the lowest measured layer.

Probability values (p-values) associated with the different sources of variation in the analysis of soil chemical properties across the two years of the experiment are found in Table 2. Soil organic matter was significantly affected by R ($p<0.0012$), with significantly greater SOM in the ShvCr rotation compared to the SclCso or SrCr rotations. However, despite the significant effect on SOM, TC stock was not affected by rotation. Additionally, the effect of tillage was statistically significant for both SOM ($p<0.0490$) and TCs ($p<0.0220$), with 0.06% higher SOM and 1.64 Mg/ha higher TC stock under tilled plots versus the no-till.

The soil pH was measured and found to be slightly acidic, not uncommon for agricultural land in the area. Table 4 shows SrdCrd was found to have a statistically significant effect on pH ($p<0.0107$), where soil under radishes was found to be more acidic than other treatments. Significant differences in pH under SrdCrd were measured with 0.13 units more acidic than under ShvCr, which had the next most acidic value, and 0.16 more acidic than the control.

Effects on soil TIN were analyzed to estimate CC scavenging ability. Total inorganic nitrogen analyzation included independent categories of nitrate and ammonia, as well as the sum of the two forms of inorganic N. In crop rotations with overwintering CC biomass, lower soil N values were expected, as that N would be tied up within the plant and thus not detected via soil test. Table 2 shows the interaction of P x R was statistically significant for TIN ($p<0.0001$) and also exhibits this level of significance for nitrate alone. The lower soil N value for the ShvCr rotation compared to all other treatments indicates the strong possibility of scavenged N as a result of this CC treatment (Table 4). The ShvCr rotation showed 10.12 mg/kg less TIN compared to the control following soy and with the majority of the difference (9.99 mg/kg) from nitrate.

Phosphorus and potassium levels were also measured to evaluate the scavenging abilities of CCs for these nutrients with depth significant for both, but the only other significant effect was tillage ($p<0.0497$) on K (Table 2). Potassium was statistically significantly higher in tilled plots versus no-till, with K levels in tilled plots 4.16 mg/kg greater than no-till. As expected, depth was also highly significant for all chemical properties ($p<0.0001$), and values for every measured chemical property decreased with depth.

There was a no statistically significant effect on cash crop yields from cover crops. Shown in table 5, cash crop yields were statistically significantly affected by only tillage ($p<0.0044$) and only for soybean crops. Soybeans were found to yield 295 kg/ha less when grown on tilled plots as compared to no-till.

DISCUSSION

Previous research shows the difficulty of achieving significant results with CCs in Illinois in short-term experimental plots (Acuna and Villamil, 2014; Welch et al., 2015), which is further exemplified by the lack of significant results in regards to soil physical properties. However, even in a span of just two years, certain CCs provided noticeable effects on soil chemical composition, illustrating not only a possibility for benefits for short-term cover-cropping, but more specifically, the potential for nutrient scavenging. Biomass data from CCs indicates the overwintering ability and crop hardiness of the grass varieties used in this study, as well as their potential for N scavenging. All CC treatments produced measurable density numbers, indicating that although many did not overwinter, CC growth was still taking place to instigate soil changes via root growth and eventual plant decomposition prior to biomass sampling.

Higher values of BD and PR are indicative of unfavorable conditions, which would become more apparent at greater depth and further from the nutrient-rich surface. Higher BD and PR values could be indicative of compaction, however in this case, the levels found are not considered limiting for root growth as values are well below critical (Arshad et al. 1990). The lack of significance from CC rotations is likely due to the poor biomass survival of CC during this 2 year study. Yet benefits to the soil microbial activity and aggregation potential via above and below ground supply of residues and exudates could potentially accrue in these highly fertile soils resulting in lower values for BD and PR in the long term (Rosolem et al., 2002). These remains to be explored since our WAS results showed again no indication of CC influence (Table 2). Cover crops were not seen to provide a boost to stability through root growth and influence on the soil microbial community through root exudates and nutrient supply, once again likely due to the fairly short time frame in which the CCs could have influenced the soil

(Amezketa, 1999; Diaz-Zorita et al., 2002). Both BD and WAS were expected to be higher under no-till (Zuber et al., 2015), but there was no difference in these variables. WAS is typically greater near the soil surface as the SOM is higher in the part of the soil profile; as WAS is related to the amount of SOM, it would be expected to see greater WAS near the surface, especially in the relatively undisturbed NT soils (Amezketa, 1999).

Despite the lack of significance in the physical properties associated with SOM, significant results were seen in both SOM and TC stock. Higher SOM in the ShvCr rotation could suggest an effect from the use of multiple CCs rather than a single species, or simply the immediate returns from high amounts of biomass. However, the ScloCso rotation also featured more than one CC species and featured statistically significantly lower SOM than the ShvCr rotation. Additionally, the rotation SrCr including annual ryegrass, though also producing considerable biomass, had statistically significantly lower SOM than the ShvCr rotation. These rotation effects were only found to be significant on SOM, and were not statistically significant when analyzed as TC stocks which reflects these SOM differences where mainly due to the lack of consideration of the tillage affect in altering slightly the volume of the soil under consideration. Tillage was a statistically significant factor affecting for both SOM and TCs with higher values under tilled plots as opposed to NT. This effect could be a short-term result of residues that have not yet broken down to release C into the soil under no-till, and is expected to stabilize over time (Villamil et al., 2015).

Plant roots can influence soil pH in the short term through the uptake of nutritive ions, which changes the ionic balance of the soil, which results in the alteration of pH due to not only the change in soil ionic composition, but also the release of hydrogen and hydroxide ions in order to keep the nutrient absorption process chemically balanced. Additionally, due to the intended life cycle of a CC, decomposing plant material could contribute to a short-term pH fluctuation, due to deposition of organic acids, as well as by-products associated with the decomposition process (Haynes, 1990). Both of these facets for CC/pH interaction likely played a role, as the control had the highest pH of any plot. The rotation SrdCrd with radishes as the prominent species showed statistically significant lower pH than the control plots. Though radishes were not expected to overwinter, these effect on pH is likely due to the effect of decomposing plant material.

Lower amounts of TIN in the ShvCr rotation shows potential for N scavenging across these two CC species (Table 4). The strong effect of this rotation suggests the added potential for overwintering CC varieties to absorb more N from a longer growth period. The timing at which CCs were terminated also plays an important role regarding soil N. The time, method, and weather conditions surrounding CC termination can influence C:N ratios of the decomposing CC residues as well as the microbial community, both of which play a role in the amount of N that is made plant-available (Unger and Vigil, 1998). This could mean that some of the CC varieties that did not exhibit statistically significant differences had already started returning their N to the soil. Evidence of P scavenging, though possible, was not witnessed in any significant capacity during the term of this study.

Additionally, evidence for nutrient scavenging of K was not witnessed, however there was a higher amount of K in tilled plots. Long-term tillage practices suggest that over time, K accumulates under no-till rather than till, the opposite of what was witnessed in this study (Franzluebbers and Hons, 1996). However, because the results from this study are short-term and K content in residues comparatively high to other essential nutrients, it is possible that increased residue breakdown from tillage may have caused this short-term boost (Kumar and Goh, 2000).

Chemical properties all decreased with depth, an expected result for a number of reasons. Decomposition of residues as well as nutrient inputs all occur at the surface, so it is expected that all chemical properties will decrease moving away from the topsoil. Additionally, the soil microbial community is most active at upper layers due to access to air, water, nutrients, and growing plant roots.

Crop yields of corn were not significantly different in rotations or tillage treatments (Table 5) yet soybean yields were significantly higher under no-till during the length of the study. Compared to winter fallows, crop yields and soil attributes under corn-soybean rotations that included CCs did not show any significant change after one cycle of production. Our results show that the inclusion of CCs does not cause significant drops in crop yield in either till or no till systems while there is potential for N scavenging when including overwintering CCs in the corn soybean rotations.

CONCLUSION

This study illustrates the short-term effects of CCs in a corn-soybean rotation, most notably what specific effects can be seen across several common CC varieties. Data suggests that CCs are ineffective at improving soil structure in the short term, as evidenced by a lack of significance in BD, PR, and WAS results. For use as nutrient scavengers, the presence of overwintering biomass appears to be the strongest possible indicator of effective scavenger species. Grass CCs also produced the most aboveground overwintering biomass, suggesting their hardiness in cold regions. However, the overall lack of significance in cash crop yields illustrate that CC do not pose a risk to yields, though claims of a yield increase also do not seem feasible, at least in the short term.

The lack of significance regarding soil properties in the interactions with the variable of tillage shows that there is potential motivation for CC adoption regardless of tillage practice. Lack of significance in CC varieties could be an indicator that non-hardy covers may not be the best choice for an area with cold winters such as Illinois, however due to the limited time scale, it is not enough to discount any claims of long-term benefit, or use in more mild growing seasons, weather-wise.

Future Research

Though grasses and legumes were interchanged depending on the cash crop, only one CC species at a time was present in the plots. In order to fully reap the benefits of multiple varieties at time, or simply to mitigate risk of certain varieties, two or more species could be applied in a CC mix. Now that this study has highlighted the effects of several key species, those plants could be combined in various amalgamations in future research to see how the varieties act together, rather than separate.

This study was conducted in fertile Midwestern soils, and so these CCs may have different effects depending on location and climate. Additionally, the unique weather conditions of central Illinois proved to be a barrier in CC establishment. Not only does this highlight the need for cooperative research between agriculture and meteorology, but also brings to focus the need for practical research on timing of management practices in association with geographical variables. In addition to timing, there are also many methods for CC management, application, and termination, which could affect CC growth and subsequent effects.

Finally, this research is part of a larger study spanning more years and location sites. This paper shows the potential for immediate benefits from CC adoption, but long-term effects across numerous sites in Illinois has yet to be seen to answer whether CCs have a place as permanent fixtures in Corn-Belt rotations, and what impact this long-term adoption will have on soil, crops, and the environment.

TABLES AND FIGURES

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

Sources of variation	df	Late fall density (plants/m^2)	Spring biomass (g/m^2)
P	1	0.1546	0.0008
T	1	0.3117	0.3176
P x T	1	0.9561	0.9111
R	4	<.0001	<.0001
P x R	4	<.0001	<.0001
T x R	4	0.8558	0.8734
P x T x R	4	0.7171	0.9925

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 N (TIN, N-NO_3, and N-NH_4, mg/kg), available phosphorus (P, mg/kg), and exchangeable K (mg/kg), determined during the spring each year.

Source of Variation	df	PR	BD	WAS	SOM	TCs	pH	TIN	NO3-N	NH4-N	P	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 x 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 (R)	5	0.2010	0.3526	0.2705	0.0012	0.0594	0.0107	<.0001	<.0001	0.4703	0.0592	0.3622
P x R	5	0.3614	0.1718	0.0603	0.6502	0.6370	0.5004	<.0001	<.0001	0.2684	0.8995	0.7773
T x R	5	0.6458	0.5398	0.8844	0.4389	0.2749	0.4792	0.9235	0.7769	0.8786	0.4225	0.3622
P x T x R	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	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.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 (R), 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 (α=0.05).

P[§]	T[¶]	R[§§]	D	n	PR (kPa)	BD (Mg/m^3)	WAS (%)
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
		SclCso		96	1312	1.34	77
		ShvCr		96	1335	1.34	78
		SrCr		96	1301	1.33	75
		SrdCrd		96	1298	1.35	78
		SrpCrp		96	1283	1.35	77
P x R							
P1		CT		48	1250	1.39	75
		SclCso		48	1274	1.35	78
		ShvCr		48	1333	1.34	80
		SrCr		48	1257	1.33	75
		SrdCrd		48	1263	1.36	79
		SrpCrp		48	1251	1.37	76
P2		CT		48	1273	1.34	78
		SclCso		48	1351	1.33	77
		ShvCr		48	1338	1.34	76
		SrCr		48	1346	1.34	75
		SrdCrd		48	1334	1.34	76
		SrpCrp		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, after soy harvest; P2, after corn harvest; [¶] Tillage options (T): Till, chisel tilled; NT, no-tilled; [§§] Rotation reference (R), CT: Soybean _ fallow/ corn _ fallow; SclCso: Soybean _ red clover/ corn _ spring oats; ShvCr: Soybean _ hairy vetch/ corn _ cereal rye; SrCr: Soybean _ annual ryegrass/ corn _ annual ryegrass; SrdCrd: Soybean _ radish/ corn _ radish; and SrpCrp: Soybean _ rape/ corn _ 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, N-NO$_3$+N-NH$_4$, mg/kg), available phosphorus (P, mg/kg), and exchangeable K (mg/kg), determined within phases of the rotations (P), under tillage options (T) and rotation treatments (R), 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 (α=0.05).

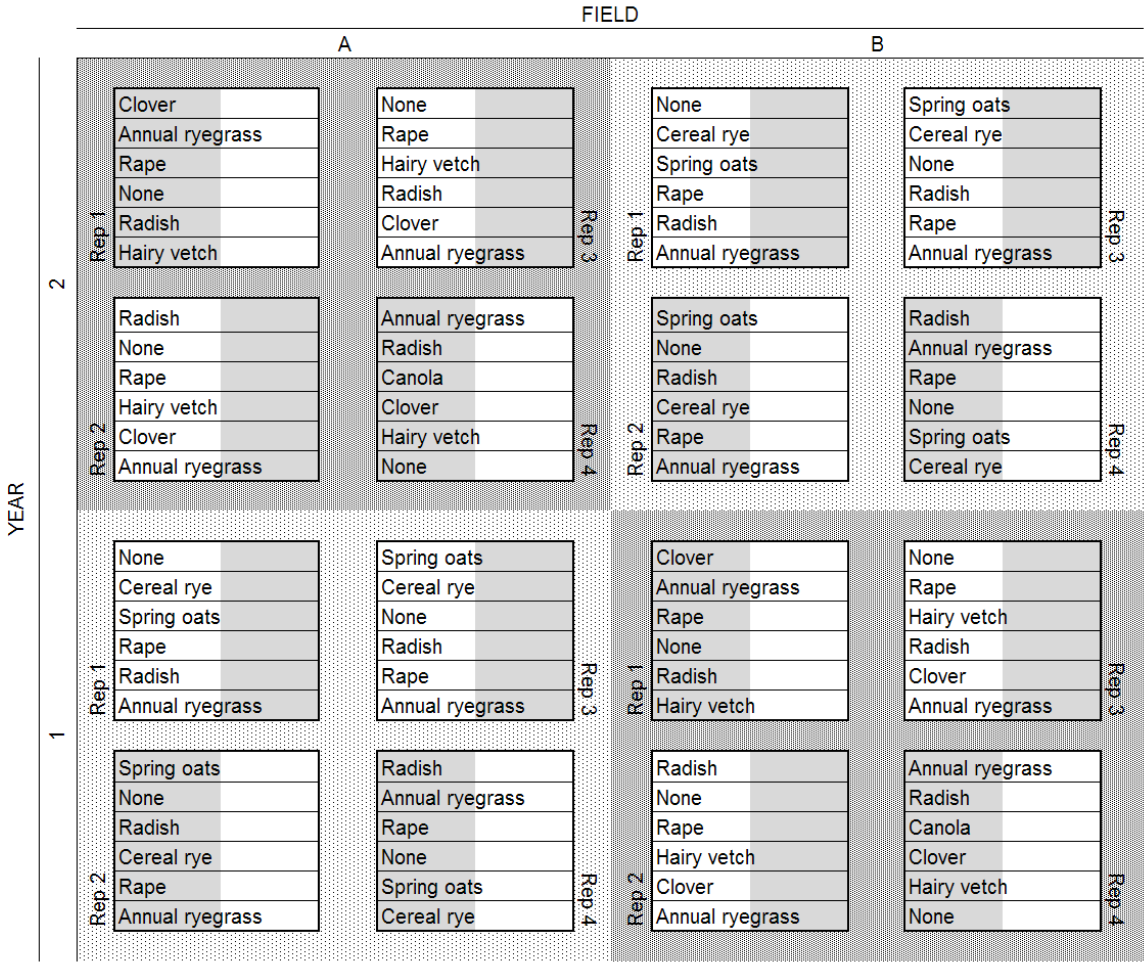
P[§]	T[¶]	R[§§]	D	n	SOM (%)	TCs(Mg/ha)	pH	TIN	NO3-N	NH4-N	P(mg/kg)	K(mg/kg)
P1				288	2.13	43.52	5.61	21.65	13.74	5.53	3.89	68.59
P2				288	2.00	39.13	5.67	19.38	12.60	6.12	3.05	70.93
	Till			288	2.09a	42.15a	5.60	19.57	12.69	5.58	3.69	71.87a
	NT			288	2.03b	40.51b	5.67	21.44	13.63	6.06	3.22	67.71b
		CT		96	2.05ab	41.88	5.71a	21.72	15.09	5.60	3.51	69.56
		SclCs		96	2.03b	40.61	5.61ab	22.67	15.37	5.81	3.54	71.55
		ShvC		96	2.11a	42.21	5.68a	17.06	9.46	5.96	3.82	70.82
		SrCr		96	2.01b	40.26	5.65ab	18.64	11.26	5.65	3.02	69.94
		SrdC		96	2.08ab	41.27	5.55b	23.31	15.41	6.26	3.45	67.42
		SrpC		96	2.09ab	41.72	5.62ab	20.25	13.62	5.63	3.39	69.31
P x R												
P1		CT		48	2.10	44.60	5.66	24.06a	16.69a	5.31	4.06	67.78
		SclCs		48	2.12	42.58	5.58	25.28a	16.88a	5.89	3.85	70.93
		ShvC		48	2.18	44.62	5.74	13.94b	6.70c	5.39	4.40	68.22
		SrCr		48	2.06	41.84	5.58	21.60a	14.22a	5.13	3.29	69.97
		SrdC		48	2.13	43.24	5.48	26.66a	17.36a	6.33	3.89	66.06
		SrpC		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
		SclCs		48	1.95	38.65	5.63	20.32ab	14.00ab	5.73	3.25	72.17
		ShvC		48	2.04	39.80	5.68	20.88ab	13.35ab	6.60	3.32	73.51
		SrCr		48	1.96	38.68	5.72	16.08ab	8.92ab	6.21	2.77	69.92
		SrdC		48	2.02	39.30	5.60	20.37ab	13.68ab	6.19	3.06	68.81
		SrpC		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	27.48	17.92	8.37	10.67a	100.71a
			15-30	192	2.09b	43.22b	5.53b	18.27	11.71	5.48	3.02b	56.55b
			30-45	192	1.73c	36.00c	5.86a	17.13	10.86	4.29	1.27c	59.59c

[§] Phases of the rotations (P): P1, after soy harvest; P2, after corn harvest; [¶] Tillage options (T): Till, chisel tilled; NT, no-tilled; [§§] Rotation reference (R), CT: Soybean _ fallow/ corn _ fallow; SclCso: Soybean _ red clover/ corn _ spring oats; ShvCr: Soybean _ hairy vetch/ corn _ cereal rye; SrCr: Soybean _ annual ryegrass/ corn _ annual ryegrass; SrdCrd: Soybean _ radish/ corn _ radish; and SrpCrp: Soybean _ rape/ corn _ rape.

Table 5. Soybean and corn crop yields (kg/ha) under different tillage options and rotation treatments. Probability values (p-values) associated with the different sources of variation for each crop are presented below.

T[¶]	R[§]	n	Soybean (kg/ha)		Corn (kg/ha)	
			mean	SEM[§§]	mean	SEM
T						
Till		48	3482b	300.9	12060	2313.9
NT		48	3777a		11473	
R						
	CT	16	3661	302.9	11980	2319.2
	SclCso	16	3621		12002	
	ShvCr	16	3667		11811	
	SrCr	16	3650		10943	
	SrdCrd	16	3590		12028	
	SrpCrp	16	3587		11837	
T x R						
Till	CT	8	3467	308.4	12536	2355.0
	SclCso	8	3421		12415	
	ShvCr	8	3513		11921	
	SrCr	8	3595		10673	
	SrdCrd	8	3478		12397	
	SrpCrp	8	3417		12420	
NT	CT	8	3855		11425	
	SclCso	8	3821		11589	
	ShvCr	8	3820		11701	
	SrCr	8	3705		11213	
	SrdCrd	8	3702		11658	
	SrpCrp	8	3757		11254	
Sources of variation		df	p-value		p-value	
T		1	0.0044		0.5107	
R		5	0.8748		0.4159	
T x R		5	0.2094		0.4385	

[¶] Tillage options (T): Till, chisel tilled; NT, no-tilled; [§] Rotation reference (R), CT: Soybean _ fallow/ corn _ fallow; SclCso: Soybean _ red clover/ corn _ spring oats; ShvCr: Soybean _ hairy vetch/ corn _ cereal rye; SrCr: Soybean _ annual ryegrass/ corn _ annual ryegrass; SrdCrd: Soybean _ radish/ corn _ radish; and SrpCrp: Soybean _ rape/ corn _ rape. [§§] SEM, standard error of the mean value



Phase legend

▩	Rotation phase 1: Following soybean harvest (before corn planting)
░	Rotation phase 2: Following corn harvest (before soybean planting)

Tillage legend

▒	Spring tillage done before planting
☐	No-till planting

Rotation	Cover crop that follows crop	
Legend	Soybean	Corn
CT	None	None
SclCso	Spring oats	Clover
ShvCr	Cereal rye	Hairy vetch
SrCr	Annual ryegrass	Annual ryegrass
SrdCrd	Radish	Radish
SrpCrp	Rape	Rape

Figure 1. Schematic representation of the experimental layout showing the arrangement of the factors phase of the rotation (P), tillage (T), and CS rotations including CCs (R) and the three blocking criteria used in the study, field (F), year (Y), and blocks (Reps) within each field.

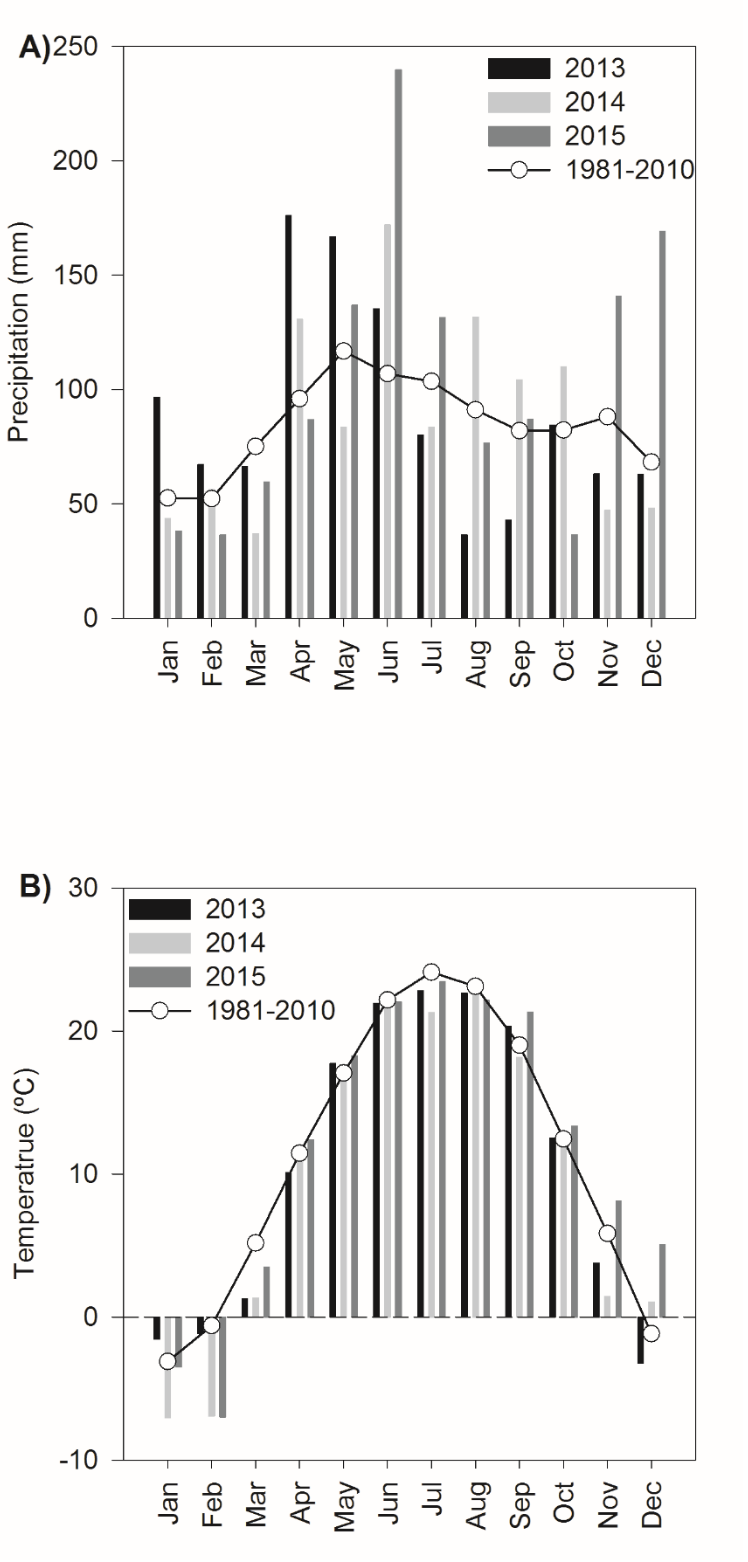


Figure 2. (A) Precipitation (mm) and **(B)** temperature (°C) from 2013 to 2015 during the CC(Sept to Apr) and soybean and corn growing seasons (May to Nov) along with their respective normal for the 1981-2010 period. Source: Midwest Regional Climate Center, 2015.

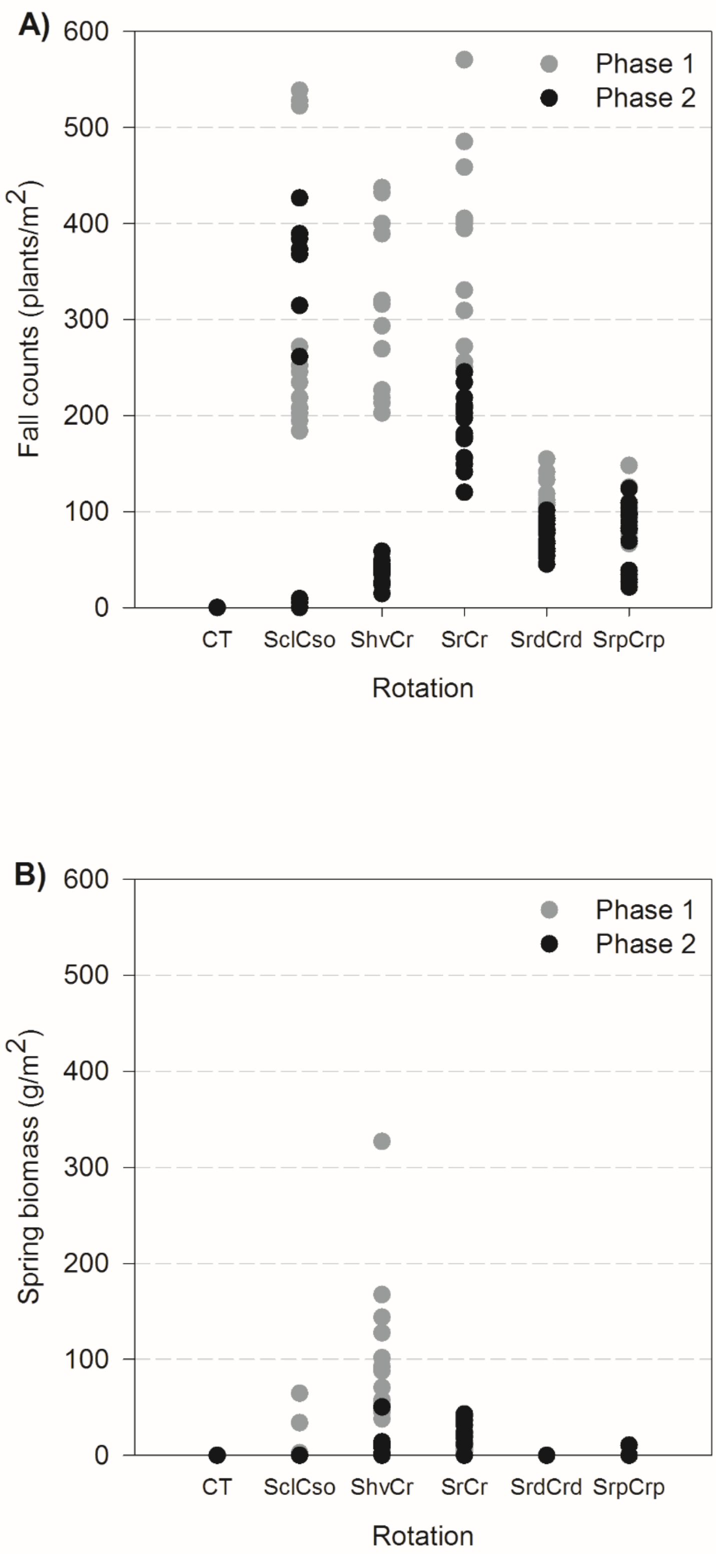


Figure 3. (A) Fall counts (plants/m^2) and **(B)** spring biomass (gr/m^2) of CCs in the CS rotations (R) over the two years of the study and for each phase of the rotation (P).

REFERENCES

Acuña, J.C.M. and M.B. Villamil. 2014. Short-term effects of CCs and compaction on soil properties and soybean production in Illinois. Agron. J. 106: 860-870.

Amézketa, E. 1999. Soil aggregate stability: A review. J. Sustain. Agric. 14: 83-151.

Arshad, M.A., M. Schnitzer, D.A. Angers and J.A. Ripmeester. 1990. Effects of till vs no-till on the quality of soil organic-matter. Soil Biol. Biochem. 22: 595-599.

Blake, G.R. and K.H. Hartge. 1986. Bulk Density. In: A. Klute, editor, Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI.

Brandi-Dohrn, F.M., R.P. Dick, M. Hess, S.M. Kauffman, D.D. Hemphill and J.S. Selker. 1997. Nitrate leaching under a cereal rye cover crop. J. Environ. Qual. 26: 181-188.

Chen, G. and R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331: 31-43.

Clark, A.J., A.M. Decker, J.J. Meisinger and M.S. McIntosh. 1997. Kill date of vetch, rye, and a vetch-rye mixture: I. Cover crop and corn nitrogen. Agron. J. 89: 427-434.

CTIC-SARE. 2014. Report of the 2013-14 Cover Crop Survey. Joint publication of the Conservation Technology Information Center and the North Central Region Sustainable Agriculture Research and Education Program. Available at: http://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2013-14-Cover-Crops-Survey-Analysis (verified 03/18/2016).

Cookson, W.R., I.S. Cornforth and J.S. Rowarth. 2002. Winter soil temperature (2-15 degrees C) effects on nitrogen transformations in clover green manure amended or unamended soils; a laboratory and field study. Soil Biol. Biochem. 34: 1401-1415.

Dabney, S.M., J.A. Delgado and D.W. Reeves. 2001. Using winter COVER CROPs to improve soil and water quality. Commun. Soil Sci. Plant 32: 1221-1250.

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.

Decker, A.M., A.J. Clark, J.J. Meisinger, F.R. Mulford and M.S. McIntosh. 1994. Legume Cover cropcontributions to no-tillage corn production. Agron. J. 86: 126-135.

Diaz-Zorita, M., J.H. Grove, L. Murdock, J. Herbeck and E. Perfect. 2004. Soil structural disturbance effects on crop yields and soil properties in a no-till production system. Agron. J. 96: 1651-1659.

Doran, J.W., D.C. Coleman, D.F. Bezdicek and B.A. Stewart. 1994. Defining soil quality for a sustainable environmentSoil Science Society of America, WI.

Ebelhar, S.A., W.W. Frye and R.L. Blevins. 1984. Nitrogen from legume cover crops for no-tillage corn. Agron. J. 76: 51-55.

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Harwood, J.M. Squire, et al. 2001. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93: 319-325.

Franzluebbers, A.J. and F.M. Hons. 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. Soil Till. Res. 39: 229-239.

Frye, W.W., W.G. Smith and R.J. Williams. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. J. Soil Water Conserv. 40: 246-249.

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. American Society of Agronomy, Soil Science Society of America, Crop Science Society of America, Madison (WI).

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach and R.P. Hooper. 2000. Nitrogen flux and sources in the Mississippi River Basin. Sci. Total Environ. 248: 75-86.

Haynes, R.J. 1990. Active ion uptake and maintenance of cation-anion balance - a critical-examination of their role in regulating rhizosphere pH. Plant Soil 126: 247-264.

Haynes, R.J. and M.H. Beare. 1997. Influence of six crop species on aggregate stability and some labile organic matter fractions. Soil Biol. Biochem. 29: 1647-1653.

Hill, R.L. 1990. Long-term conventional and no-tillage effects on selected soil physical-properties. Soil Sci. Soc. Am. J. 54: 161-166.

Horowitz, J., R. Ebel, and K. Ueda. 2010. "No-till” farming is a growing practice. Washington, DC: USDA Economic Research Service, Economic Information Bulletin No. 70. Available at: http://www.ers.usda.gov/media/135329/eib70.pdf (verified 03/14/2016).

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.

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. Soil Science Society of America, American Society of Agronomy, 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.

Kumar, K. and K.M. Goh. 2000. Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. Adv. Agron. 68: 197-319.

Kuo, S., U.M. Sainju and E.J. Jellum. 1997. Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61: 145-152.

Lehrsch, G. and J. Gallian. 2010. Oilseed radish effects on soil structure and soil water relations. J. Sugar Beet Res. 47: 1-21.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger and O. Schabenberger. 2006. SAS for Mixed Models. 2nd ed. SAS Institute.

Liu, A., B.L. Ma and A.A. Bomke. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Sci. Soc. Am. J. 69: 2041-2048.

Meisinger, J.J., P.R. Shipley and A.M. Decker. 1990. Using winter cover crops to recycle nitrogen and reduce leaching. In: J. P. Mueller and M. G. Wagger, editors, Conservation Tillage for Agriculture in the 1990's. Special Bulletin 90-1. North Carolina State University, Raleigh, NC p. 1-6.

Midwest Regional Climate Center. 2015. Cli-MATE. MRCC Application tools environment. Illinois State Water Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign. Available at: http://mrcc.isws.illinois.edu/CLIMATE/ (verified 03/14/2016).

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.

Mulvaney, R.L. 1996. Nitrogen—Inorganic Forms. In: D. L. Sparks, A. L. Page, P. A. Helmke and R. H. Loeppert, editors, Methods of Soil Analysis Part 3—Chemical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI.

Munawar, A., R.L. Blevins, W.W. Frye and M.R. Saul. 1990. Tillage and cover crop management for soil water conservation. Agron. J. 82: 773-777.

NOAA, National Oceanic and Atmospheric Administration. 2015. National Centers for Environmental Information. Climate at a Glance: Time Series. Available at: http://www.ncdc.noaa.gov/cag/time-series/us (verified 03/14/2016).

Olson, K.R., M.M. Al-Kaisi, R. Lal and B. Lowery. 2014. Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. Soil Sci. Soc. Am. J. 78: 348-360.

Olson, K.R., S.A. Ebelhar and J.M. Lang. 2010. Cover crop effects on crop yields and soil organic carbon content. Soil Sci. 175: 89-98.

Power, J.F. and R.F. Follett. 1987. Monoculture. Scientific American 256: 79.

Price, A.J., F.J. Arriaga, R.L. Raper, K.S. Balkcom, T. Kornecki and D.W. Reeves. 2009. Comparison of mechanical and chemical winter cereal cover crop termination systems and cotton yield in conservation agriculture. J. Cotton Sci. 13: 238-245.

Rabalais, N.N., R.E. Turner and W.J. Wiseman. 2002. Gulf of Mexico hypoxia, aka "The dead zone". Annu. Rev. Ecol. Syst. 33: 235-263.

Ranells, N.N. and M.G. Wagger. 1996. Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron. J. 88: 777-782.

Rosolem, C.A., J.S.S. Foloni and C.S. Tiritan. 2002. Root growth and nutrient accumulation in cover crops as affected by soil compaction. Soil Till. Res. 65: 109-115.

Sainju, U.M., B.P. Singh and W.F. Whitehead. 1998. Cover crop root distribution and its effect on soil nitrogen cycling. Agron. J. 90: 511-518.

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 Till. Res. 63: 167-179.

Schreiber, J.D. 1999. Nutrient leaching from corn residues under simulated rainfall. J. Environ. Qual. 28: 1864-1870.

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.

Soil and Plant Analysis Council. 1992. Soil Analysis: Handbook of Reference Methods. CRC Press, New York (NY).

Soil Survey Staff, 2012. Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available at http://websoilsurvey.nrcs.usda.gov/ (verified 03/14/2016).

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 (NY).

Teasdale, J.R. 1996. Contribution of CCs to weed management in sustainable agricultural systems. J. Produc. Agric. 9: 475-479.

Thorup-Kristensen, K., J. Magid and L.S. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79: 227-302.

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. Science. 292:281-284.

Unger, P.W. and M.F. Vigil. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53: 200-207.

USDA NASS. 2011. Illinois Agriculture. USDA's National Agricultural Statistics Service Illinois Field Office. Available at: http://www.nass.usda.gov/Statistics_by_State/Illinois/Publications/Farmfacts/farmfact.pdf (verified 03/14/2016).

Varvel, G.E. and W.W. Wilhelm. 2010. Long-term soil organic carbon as affected by tillage and cropping systems. Soil Sci. Soc. Am. J. 74: 915-921.

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.

Villamil, M.B., J. Little and E.D. Nafziger. 2015. Corn residue, tillage, and nitrogen rate effects on soil properties. Soil Till. Res. 151: 61-66.

Wagger, M.G. and D.B. Mengel. 1993. The role of nonleguminous cover crops in the efficient use of water and nitrogen. In: W. L. Hargrove, editor Cropping strategies for efficient use of water and nitrogen. ASA Special Publication 51, Madison, WI. p. 115-127.

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. Agr. Ecosyst. Environ. 216: 322-332.

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.

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.

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.