Published online September 20, 2006

No-Till Corn/Soybean Systems Including Winter Cover Crops: Effects on Soil Properties

M. B. Villamil, G. A. Bollero,* R. G. Darmody, F. W. Simmons, and D. G. Bullock

ABSTRACT

The use of winter cover crops (WCC) such as hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.), in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation provides long-term benefits that are generally overlooked. There is a particular lack of information regarding the effects of WCC on soil physical and chemical properties. The objective of this study was to assess the effects of four crop sequences (C/S, corn-fallow/soybean-fallow; C-R/S-R, corn-rye/soybean-rye; C-R/S-V, corn-rye/soybean-vetch; and C-R/S-VR, corn-rye/soybean-vetch and rye) under no-till on several soil physical and chemical properties. Soil chemical properties included soil organic matter (SOM), pH, total nitrogen (TN), nitrates (NO_3–N), and available phosphorus (P). The analyzed soil physical properties analyzed were: water-aggregate stability (WAS), bulk density (D_b), penetration resistance (PR), total porosity (TP), pore-size distribution, water retention properties, and saturated hydraulic conductivity (K_{sat}). The experimental design was a split-split-plot where whole-plot treatments (sampling period) had a Latin square design and subplot treatments (crop sequences) were arranged in a randomized complete block design with four replications. Compared with winter fallow, crop sequences that included WCC provided substantial benefits from the soil productivity standpoint. Specifically, the use of the C-R/S-V or C-R/S-VR increased SOM down to 30 cm. All WCC sequences improved WAS with increases of 9, 13, and 17% for C-R/S-R, C-R/S-V, and C-R/S-VR, respectively. Winter cover crop sequences reduced D_b and PR of the soil surface and increased total and storage porosity along with plant available water. While the C-R/S-V sequence was the most effective in reducing soil NO_3–N, the C-R/S-R sequence was the most effective in fixing soil P.

Concerns regarding environmental quality and long-term productivity of agroecosystems call for the adoption of management strategies that safeguard soil, air, and water resources. Winter cover crops in association with no-till and crop rotation appears to be the most promising conservation practice (Drury et al., 1999). In Illinois, about 11 million acres of each corn and soybean were planted in the year 2000, with no-till corresponding to 17 and 42% of the respective planted areas (CTIC, 2002). Only 1 and 3% of the corn and soybean acreages follow WCC (USDA/ERS, 2000). This low percentage of adoption is attributable to many factors not new to crop residue management (CRM) practices (USDA/ERS, 2003). Yet information availability and government cost-sharing seem to be the most important factors in shaping farmer's adoption of (CRM) practices (Carter, 1994; Long, 2003). In Illinois or even in the U.S. Midwest region, there is a particular lack of information regarding the effects on soils of no-tilled cropping systems including WCC.

Although prevention of soil erosion has been the traditional role of WCC in agriculture, WCC have gained renewed attention due to the many other environmental services they provide. Winter cover crops have the capacity to prevent NO_3–N contamination and P enrichment of water thereby safeguarding water quality (Brandi-Dohrn et al., 1997; Eckert, 1991). In addition, WCC can fix atmospheric CO_2, sequestering C as part of the SOM decreasing the CO_2 contribution to the greenhouse effect (Reicosky and Forcella, 1998).

Winter cover crops can maintain or increase soil C and N (Kuo et al., 1997; Sainju et al., 2003) and these effects are largely responsible for the changes in physical properties associated with their use (Reeves, 1994). The enhancement of soil structure with WCC is reflected through reduced soil D_b and PR (Latif et al., 1992), increased TP and aeration porosity (Ess et al., 1998), enhanced water infiltration and K_{sat} (Folorunso et al., 1992; McVay et al., 1989), and improved WAS of the surface soil (McVay et al., 1989; Sainju et al., 2003). Nevertheless, the potential of WCC to affect soil properties varies from region to region since WCC exhibit a wide variation in the quality and quantity of biomass yield depending on WCC species, soil factors, environmental conditions, and management options (Kuo et al., 1997; Smith et al., 1987). In addition, many of the previous studies used WCC as green manures, which involve the use of tillage operations in contrast to the use of killed cover crops or dead mulches common with conservation practices.

Crop species vary in their ability to modify soil physical and chemical properties, which is related to the quantity and quality of residues left on the soil and to their rooting patterns and activities (Dexter, 1991; Martens, 2000b; Power et al., 1998). Both WCC and the main crops in the rotation (i.e., corn, soybean, etc.) have the potential to alter soil properties affecting the long-term productivity of the system. The corn–soybean rotation contrasted with continuous monocropping increases the potential yield of both crops (Reeves, 1994), an effect that is called the 'rotation effect'. Although the rotation effect is primarily ascribed to a better control of diseases, pests, and weeds, it has also been related to improved soil physical conditions (Folorunso et al., 1992). When studying crop rotations, it is necessary to identify the period of the rotation when the sampling is performed

M.B. Villamil, G.A. Bollero, and D.G. Bullock, Crop Science Dep., University of Illinois, Urbana, IL 61801; R.G. Darmody and F.W. Simmons, Natural Resources and Environmental Sciences Dep., University of Illinois, Urbana, IL 61801. Received 17 Oct. 2005. *Corresponding author (gbollero@uiuc.edu).

Published in Soil Sci. Soc. Am. J. 70:1936–1944 (2006).
Soil & Water Management & Conservation
doi:10.2136/sssaj2005.0350

Abbreviations: CRM, crop residue management; C-R/S-R, corn-rye/soybean-rye; C-R/S-V, corn-rye/soybean-vetch; C-R/S-VR, corn-rye/soybean-vetch and rye; C/S, corn-fallow/soybean-fallow; D_b, bulk density; DM, dry matter; K_{sat}, saturated hydraulic conductivity; PR, penetration resistance; SOM, soil organic matter; TN, total nitrogen; TP, total porosity; WAS, water-aggregate stability; WCC, winter cover crop.

so as to identify the contribution of each crop on the modification of the soil environment.

The benefits of crop rotations in different U.S. regions are well documented in the literature (Bullock, 1992; Karlen et al., 1994; Reeves, 1994) however there is little information on the effects of rotations and tillage for cropping systems, which include WCC for the U.S. Midwest. Several studies have shown that no-till practices alone have a limited ability to increase organic C levels in cold climates with poorly drained, fine-textured soils (Dick, 1989; Needelman et al., 1999; Wander and Bollero, 1999). It is unknown if the contribution of WCC in no-till will increase SOM and improve related properties. Smith et al. (1987), suggested that these WCC benefits occur only in plowed systems. Moreover, WCC benefits may be less in the U.S. Midwest where the growing season is shorter and there is less biomass accumulation compared to southern regions (Reeves, 1994).

We hypothesize that the introduction of WCC in a corn–soybean rotation under no-till management will have a positive impact on soil properties over the long term as compared with winter fallowing. In addition, it is likely that the different sampling periods (i.e., after corn or soybean) will have different effects on soil properties and must be addressed. The objectives of this research were, (i) to evaluate the cumulative effect of each of four rotations (C/S; C-R/S-R; C-R/S-V; C-R/S-VR) on soil physical and chemical properties; and (ii) to identify soil properties that are affected by the sampling period that may play a role in the 'rotation effect' observed in many studies.

MATERIALS AND METHODS

Four crop sequences, three of which include a WCC of hairy vetch, cereal rye, and hairy vetch-cereal rye biculture respectively, were evaluated in a corn/soybean no-till system. The crop sequence of corn/soybean with winter fallowing was used as a control.

The study was performed at Urbana, IL, in 2002 and 2003. The experimental plots were established in 1998. Two adjacent fields were used each year. Both fields had previously been in a no-till corn–soybean rotation for at least 5 yr. The experimental area is on Flanagan (Fine, smectitic, mesic, Aquic Argiudolls) silt loam soils with a slope of about 2%. Flanagan series consists of dark colored, somewhat poorly drained soils, developed in 100- to 150-cm of loess over loam till under prairie vegetation. Permeability is moderate and surface runoff is slow to medium (Soil Survey Staff, 2001).

Each year, a rye-WCC was drilled into corn stubble while rye-WCC, vetch-WCC, and the biculture vetch-rye-WCC were drilled into soybean stubble. The planting dates for WCC were 31 Oct. 2001 and 25 Sept. 2002. The seeding rate was 90 kg ha^{-1} for rye and 34 kg ha^{-1} for hairy vetch. For the vetch-rye biculture, the seeding rate was 68 and 28 kg ha^{-1} for rye and vetch, respectively. Hairy vetch seed was inoculated with *Rhizobium leguminosarum* var. *viciae* (Urbana Labs, St. Joseph, MO). Winter cover crops were killed with glyphosate (N-(phosphonomythyl) glycine) at 1.1 kg a.i. ha^{-1} in the spring before planting the main crops. The rye-WCC was killed approximately 2 wk before planting corn and soybean, the biculture rye-vetch-WCC was killed 1 wk before planting corn, while the vetch-WCC was killed just before planting corn. Corn and soybean were planted on 1 May 2002 and 29 Apr. 2003. Nitrogen fertilizer was applied each year to corn as ammonium sulfate at an average rate of 135 kg N ha^{-1} at planting. Neither P nor K fertilizer were applied.

Soil Sampling and Analysis

Sampling was conducted during the spring of 2002 and 2003, before planting either corn or soybean, and following the completion of three production cycles in each plot. Each soil sampling was done after a rain event to ensure uniform water content and as close to field capacity as possible. We did this so that if differences in soil properties were detected, they would be residual in nature (Logsdon et al., 1993) and not due to the effect of temporary differences in water use by the crop sequence. The gravimetric water content at the different sampling times range from 70 to 74% (17–18 g g^{-1}) of field capacity for these soils.

Two soil subsamples per plot to 30-cm depth were taken with a Giddings sampler (40.8-mm diam., Giddings Machine Co., Fort Collins, CO) for D_b and soil chemical analysis. The cores were then cut to obtain 0- to 5-, 5- to 10-, 10- to 15-, and 15- to 30-cm subsamples, and stored in plastic bags. After weighing the subsamples and measuring the water content gravimetrically, D_b values were obtained (USDA/NRCS, 2004) and the results averaged for each plot and depth. The same samples were composited, air-dried, sieved through 2-mm sieve and analyzed for SOM (loss on ignition, LOI) following Davies (1974) procedure. Determinations of pH (1:1 soil/water), TN (dry combustion), NO_3–N (colorimetry), and available P (Bray-1) were made following the procedures in the Soil Survey Laboratory Methods manual (USDA/NRCS, 2004). Soil pH ranged between 5.4 and 6.5, in agreement with the pH values estimated for the Flanagan series by the Soil Survey Staff (2001). Potassium levels were not measured in this study but estimations for the region can be found in Wander and Bollero (1999).

Profile soil PR (kPa) was recorded with a Rimik CP-20 cone penetrometer (Agridry Rimik, Queensland, Australia) with a cone basal area of 1.2 cm^2 and cone angle of 30°. Five subsamples, each consisting of three sub-subsamples, were recorded at each plot and the results averaged at the selected depths of 0 to 5, 5 to 10, 10 to 15, 15 to 30 cm to get one measurement per plot per depth considered. Gravimetric water content was determined simultaneously and later used as a covariate in the statistical analysis of PR.

One sample from the center of each plot was taken with shovel down to a depth of 15 cm for the determination of WAS (g g^{-1}). The sample was divided into three incremental subsamples, 0 to 5, 5 to 10, and 10 to 15 cm. Two 25-g subsamples of each depth were used to determine WAS on the 1- to 2-mm aggregate-size fraction following the standard procedure developed by Kemper and Rosenau (1986). In addition, three subsamples of intact soil cores (7.6-cm diam. by 7.6-cm height) per plot were taken at 3- to 10-cm depth and used to determine K_{sat} (mm d^{-1}) by the constant head method (Reynolds, 1993) and water retention properties. These undisturbed soil cores were collected in stainless steel rings using a centered, hammer-driven sampler, at a 10-cm soil depth (top of the core). The core barrel, forming part of the coring tool, is detachable and it allows for the use of removable cylinders that once filled and leveled, were tightly covered with plastic foil, stored in individual boxes, and sent to the laboratory. (The first 3 cm of the soil are always discarded using this sampler.)

For water retention properties, a tension table was used to measure the water retained at 0 (saturation), −1, −2, −3, −4, −5 (air porosity), −6, −8, −10, −12, −16, −20, −24, and −31 kPa (field capacity-residual air porosity), whereas a pressure plate was used to measure the water content at −50, −100, −500, −1000, and −1500 kPa (permanent wilting point) (Topp et al., 1993). Pore-size distribution was analyzed on the same samples by the water desorption method using the following equation to calculate the diameter (D) of the smallest pore drained at a specific potential (kPa) (Carter and Ball, 1993),

$$D(\mu\mathrm{m}) = \frac{300}{(\mathrm{kPa})} \quad [1]$$

The volume of water removed between two specific pore-size diameters equals the volume of pore space for that pore size range. Pores were classified using the classification developed by Greenland (1977), that recognizes macro- or transmission pores (>50 μm of epd [equivalent pore diameter]), meso- or storage pores (50–0.5 μm), and micro- or residual pores (<0.5 μm). These pore-size ranges were calculated through the difference in water retained between 0 (saturation) and −6 kPa (macro), −6, and −500 kPa (meso), and −500 kPa (micropores). Total porosity was obtained by adding the percentages of pores in each size range. Occluded porosity was obtained form the difference between the total porosity estimated from the bulk and particle densities and the total porosity resulting from the sum of different pore sizes. From each of the cores sampled in 2002, 50 g of oven dry soil was passed through 2-mm sieve to analyze for particle-size distribution. Percentage by weight of sand was determined by sieving and percentages of silt and clay were obtained by the hydrometer method (Gee and Bauder, 1986). Additional characterization of the sand size (very coarse 2- to 1-mm; coarse 1- to 0.5-mm; medium 0.5- to 0.25-mm; fine 0.25- to 0.10-mm; and very fine 0.1- to 0.05-mm sand) fraction was performed with a set of five utrasonic sieves with corresponding openings of 1, 0.5, 0.25, 0.10, and 0.05 mm (ATM Sonic Sifter, ATM Corp., Milwaukee, WI). This further characterization of sand separates is important in our experiment since the fields are located south of a sandy hill and there were concerns that slight differences in sand content, or even in one of the sand fractions, will be affecting our results. The experimental design was successful in isolating that variability. The textural class of the soils is silt loam and experimental units are highly homogeneous in particle-size distribution (Table 1).

Experimental Design and Statistical Analysis

The experimental layout is shown in Fig. 1. The experimental design was a split split-plot where whole-plot treatments had a Latin square design and subplot treatments were arranged in a randomized complete block design with four replications. Whole-plot treatments were sampling periods where Period 1 corresponds to the sampling after corn/rye or corn/fallow, and Period 2 to the sampling after soybean/WCC or soybean/fallow. Whole-plots were 36 m wide by 80 m long. Since each year each field is in a different period of the rotation, field, and year acted as blocks for the effect of sampling period. The first subplot treatments were four crop sequences: C/S; C-R/S-R; C-R/S-V; C-R/S-VR. Treatments were randomized in 9 m wide by 20 m long plots, which accommodated 12 rows of corn planted at 76 cm. The second subplot treatments involved the analyzed depths. Factors period, year, field, sequences, depth, and tension are considered fixed while blocks are considered random. The resulting models were analyzed using the MIXED procedure of SAS (SAS Institute, 2002). Dependent variables that were measured at several depths (or tensions) on the same experimental units were analyzed using a repeated measures approach (Littell et al., 2002). All pairwise comparisons were used with $\alpha = 0.10$ (Carmer and Walker, 1988). The variables P, TN, NO_3–N, PR, and K_{sat} required transformations to normalize the data that were obtained using the ADXTRANS macro in SAS (SAS Institute, 2002). A square root transformation was used for P, while a logarithm ($\log_{10}$) transformation was used for TN, NO_3–N, and PR, and a natural logarithm (ln) transformation was applied to K_{sat}. Main effects of the independent variables (sampling period, crop sequence, and depth or tension) are included in the discussion and tables. Main effects can be defined as the effect of one independent variable averaged across the levels of the other independent variable(s) (Kuehl, 2000).

RESULTS AND DISCUSSION

Changes in Soil Chemical Properties

Soil Organic Matter

There was a significant main effect of crop sequence ($p < 0.0017$) on SOM. Crop sequences C-R/S-V or C-R/S-VR significantly increased SOM within the entire depth compared to C-R/S-R or C/S (Table 2). These results reflect not only the potential difference in residue quality and quantity between rye and vetch but also the need for an N source by soil microorganisms and fauna for breakdown and incorporation of residues into SOM. It is well known that rye produces a greater amount of residues both above- and belowground with a much higher C/N ratio than does hairy vetch (Ranells and Wagger, 1997). However, our study suggests that without the vetch as N supplier, the rye residue is not transformed into SOM. On the same plots this study was performed, rye in the biculture produced greater dry matter (DM) yields per unit area than the respective monoculture with an average across years of 0.5 Mg ha^{-1} more DM when grown in biculture (data from Miguez, 2004). In addition, the lower C/N ratio of rye in biculture (Ruffo

Table 1. Mean values of particle-size separates as affected by the main effect of crop sequence at Urbana, IL.

	Sand size fraction‡						Silt size fraction‡			
Crop sequence†	VCoS	CoS	MS	FS	VFS	Total	CoSi	FSi	Total	Clay
	g kg^{-1}									
C/S	1.2	3.1	10.5	10.1	2.4	27.3	22.5	36.0	58.7	14.1
C-R/S-R	1.2	3.4	10.7	10.3	2.4	27.8	21.8	35.6	57.4	14.6
C-R/S-V	1.1	3.1	10.5	10.7	2.6	27.8	22.5	36.1	58.7	13.5
C-R/S-VR	1.2	3.1	9.8	8.9	2.5	25.4	22.5	37.3	59.9	14.8
SE§	0.2	0.4	1.4	1.2	0.3	3.1	0.9	1.8	2.5	0.8

† Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ VCoS, very coarse sand; CoS, coarse sand; MS, medium sand; FS, fine sand; VFS, very fine sand; CoSi, coarse silt; and FSi, fine silt.
§ SE, standard error of the mean values.

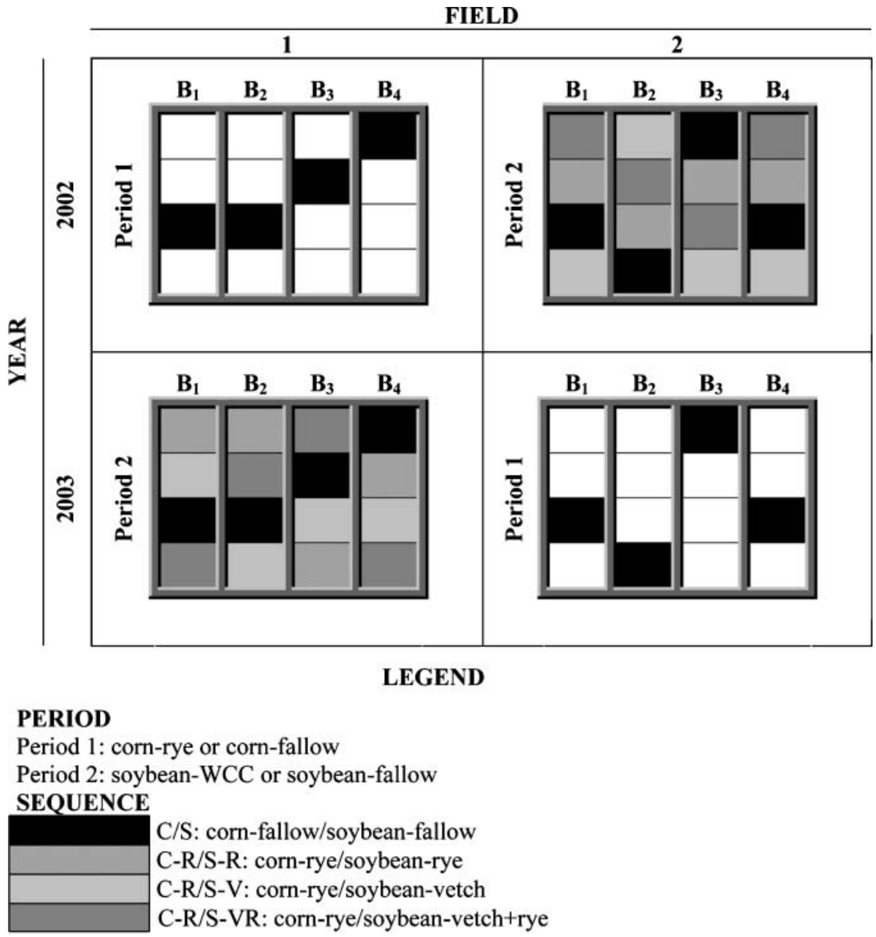

Fig. 1. Schematic representation of the experimental layout showing arrangement of the factors period and sequence and the three blocking criteria used in the study, field, year, and blocks within each field.

and Bollero, 2003b) allows decomposition to proceed at a faster rate compared with rye monoculture, while moderating the rapid mineralization potential of hairy vetch. The magnitude of the difference in SOM between C-R/S-V and C/S was 2.5 kg Mg soil^{-1} ($p < 0.0175$), which represents an increase of about 10 kg ha^{-1} of SOM for the C-R/S-V sequence. This difference in SOM is even larger with C-R/S-VR, about 3.8 kg Mg soil^{-1} ($p < 0.0005$), which translates into an extra 15 kg ha^{-1} of SOM.

Total Nitrogen and Soil Nitrate

No significant differences of the main effects or interactions in TN were detected (data not shown). The lack of WCC-effect on TN was also reported by Mendes et al. (1999), Liebig et al. (2002), and Sainju et al. (2003). This can be attributed to the slow change over time of the labile and recalcitrant pools of soil N that constitutes TN (Sainju et al., 2003). In addition, TN contents may have a delayed response to conservation tillage systems, particularly to no-till (Al-Kaisi et al., 2005).

Soil nitrate (NO_3–N) was significantly affected by the sampling period × crop sequence × depth interaction ($p < 0.05$). This interaction is due to significant differences in soil NO_3–N among crop sequences for sampling Period 1 (corn) compared with sampling Period 2 (soybean) (Table 3). Soil NO_3–N concentrations for sampling Period 2 (soybean) were lower than for sampling Period 1 (corn). The use of N fertilizer in corn accounts for differences between periods. For sampling Period 1 (corn) only the C-R/S-V sequence showed a significant reduction in soil NO_3–N within 5- to 15-cm of depth. The observed effect can be linked to the combined effect of increased NO_3–N uptake by the previous corn crop due

Table 2. Soil organic matter (SOM) as affected by sampling period, crop sequences and depth at Urbana, IL.

Depth	Sequence			
	C/S	C-R/S-R	C-R/S-V	C-R/S-VR
cm	kg Mg soil^{-1}			
	Period 1 (corn)			
0–5	42	44	45	47
5–10	33	35	36	38
10–15	31	33	34	36
15–30	35	36	37	37
	Period 2 (soybean)			
0–5	40	44	46	47
5–10	32	34	35	35
10–15	33	33	33	33
15–30	37	38	37	40
Main effect	35a†	36a	38b	39b

Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).

† Within sequences, means followed by the same letter are not significantly different at $p = 0.1$ based on preplanned comparisons.

Table 3. Soil nitrate (NO_3–N) as affected by sampling period, crop sequences, and depth at Urbana, IL.

Depth	Crop Sequence†							
	C/S		C-R/S-R		C-R/S-V		C-R/S-VR	
cm	$\log_{10}$ mg NO_3–N kg soil^{-1} (mg NO_3–N kg soil^{-1})							
	Period 1 (corn)							
0–5	1.0a‡	(27.7)	1.0a	(23.1)	1.0a	(21.8)	0.9a	(21.5)
5–10	1.1b	(24.8)	1.0b	(29.1)	0.6a	(17.5)	0.9ab	(28.6)
10–15	1.1b	(32.7)	0.8b	(26.7)	0.3a	(15.9)	0.8b	(29.9)
15–30	1.0a	(17.6)	0.9a	(26.7)	0.7a	(17.4)	0.8a	(20.1)
	Period 2 (soybean)							
0–5	0.9a	(13.3)	0.6a	(9.2)	0.7a	(9.3)	0.6a	(9.5)
5–10	0.8a	(11.1)	0.7a	(14.6)	0.6a	(12.9)	0.6a	(8.5)
10–15	0.4a	(4.1)	0.3a	(15.4)	0.6a	(11.2)	0.3a	(15.6)
15–30	0.8a	(12.2)	0.7a	(13.0)	0.5a	(9.8)	0.6a	(10.4)

† Crop sequences: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ Between sequences at a given depth and for each period, means followed by the same lowercase letter are not significantly different at $p = 0.1$ based on pre-planned comparisons.

to rapid N mineralization by hairy vetch, and the subsequent N scavenging ability of the rye cover crop. Together the processes resulted in a decrease in soil NO_3–N under the crop sequence involving C-R/S-V when compared with the other crop sequences. This is in agreement with the works of Ruffo and Bollero (2003a), Ruffo et al. (2004), and Crandall et al. (2005).

Soil Available Phosphorus

There were significant main effects of depth ($p < 0.0001$) and crop sequence ($p < 0.0035$) on soil available P (Table 4). All sequences but C-R/S-R showed values higher than the maximum P test levels (32 mg Kg) recommended for corn and soybean production in Illinois (Hoeft and Peck, 2004). Soil available P significantly decreased with depth. This stratification of P and other nutrients has also been reported by Franzluebbers and Hons (1996) and Crozier et al. (1999) for no-till management systems compared with conventional tillage. As explained by the researchers, redistribution of P with no-till is probably a direct result of surface-placement of crop residues that leads to accumulation of SOM and microbial biomass, in association with lack of soil mixing. Furthermore, the lack of significant crop sequence × depth interaction indicates that the P stratification occurred regardless of crop sequence.

Significantly lower soil P concentrations were found in the C-R/S-R and C-R/S-VR sequences than in the C/S sequence (Table 4). The C-R/S-V sequence had an intermediate P level. Reductions of available soil P with the use of legume WCC have also been reported by Hargrove (1986), Groffman et al. (1987), and McVay et al. (1989), and with grass WCC by Eckert (1991), and Kabir and Koide (2002). Similarly, in our study the lower P levels with C-R/S-R and C-R/S-VR are likely due to immobilization of this nutrient in the cover crop biomass, which is advantageous from an environmental point of view since it reduces the potential for P runoff loss.

Changes in Soil Physical Properties

Water Aggregate Stability

Significant main effects of sampling period ($p < 0.066$), sequence ($p < 0.027$), and depth ($p < 0.0001$) on WAS were determined (Table 5). Water aggregate stability was significantly higher for Period 2 (soybean) than for Period 1 (corn). This result is likely due to the differences in the quality of residues added and the root morphology and chemical composition of their exudates between sampling periods. On the contrary, Martens (2000b) reported a decrease in WAS after the soybean phase in a corn–soybean rotation. Martens (2000a; 2000b) attributed the diminished WAS after soybean to the chemical composition of the crop residues. However, the root activities of the leguminous crops are associated with higher microbial biomass, increased aggregation, and WAS than non-legumes (Haynes and Beare, 1997). It is possible that in our study the positive root influences on soil aggregation overcame the unfavorable biochemical composition of the soybean residues. The lack of an interaction effect between period and crop sequence also confirms that the increase in WAS followed the same pattern in all the rotations in Period 2, including the fallow, which in each period represents the effect of the main crop (corn or soybean) alone.

Water-aggregate stability was significantly higher under crop sequences with WCC (Table 5). Soil organic matter and root mass affect WAS (Haynes and Beare,

Table 4. Main effects of factors sequence and depth on available phosphorous (P).†

Factor	Levels	P‡	
Sequence	C/S	5.9c§	(36.4)
	C-R/S-R	5.3a	(29.6)
	C-R/S-V	5.8bc	(34.4)
	C-R/S-VR	5.5ab	(31.2)
Depth, cm	0–5	6.9d	(48.3)
	5–10	5.5c	(31.6)
	10–15	5.3b	(29.1)
	15–30	4.7a	(23.1)

† Crop sequences: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ Transformed [mg P kg soil^{-1}]$^{1/2}$, and untransformed (mg P kg soil^{-1}) mean values.
§ Within column and for each factor, means followed by the same lowercase letter are not significantly different at $p = 0.1$ based on pre-planned comparisons.

Table 5. Water aggregate stability (WAS, g g^{-1}) as affected by the main effects of sampling period, crop sequence, and depth at Urbana, IL.

Factor	Levels	WAS
Period	1	40a‡
	2	43b
Sequence†	C/S	38a
	C-R/S-R	41b
	C-R/S-V	43b
	C-R/S-VR	44b
Depth, cm	0–5	51c
	5–10	43b
	10–15	31a

† Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ Within column and for each factor, means followed by the same lowercase letter are not significantly different at $p = 0.1$ based on pre-planned comparisons.

1997). The increase in SOM explains the enhanced WAS in the crop sequences that included vetch. The C-R/S-R sequence did not increase SOM but higher WAS is probably related to greater root mass of grass WCC. Greater SOM content at the surface in association with higher activities of microorganisms, fauna, and roots may account for the observed reduction in WAS with increased depth, which followed the same pattern between periods and across crop sequences.

Bulk Density

There was a significant crop sequence × depth ($p < 0.093$) interaction on D_b (Table 6). Bulk density significantly increased with depth for all crop sequences. However, these increases were more pronounced with the use of WCC than with winter fallowing. While the average increment of D_b in depth for fallow was 8.5%, WCC increments in D_b averaged 15%. Alternating cycles of wetting and drying due to root activities in soils with WCC account for these differences in depth (Bronick and Lal, 2005). Crop sequences including WCC caused a 7% reduction in soil D_b within the 0- to 5-cm depth. Within 5 to 10 cm only the sequence with vetch produced a substantial decrease in D_b while deeper in the soil profile no significant effect was detected for any rotation. The observed drop in D_b values with the use of WCC is likely due to the extra amount of residues available in the soils under those rotations in contrast to winter fallow. Even when these residues are not mechanically mixed into the soil, but rather are left on the surface, soil D_b decreases as organic materials are slowly incorporated into the surface soil during degradation and by the soil fauna (Kladivko, 1994). We speculate that the C-R/S-V sequence provided greater microbial and fauna activities and consequently faster residue decomposition, which ultimately was responsible for lower D_b at the 5- to 10-cm depth. However, an increase in D_b occurred at 15- to 30-cm depth for the C-R/S-V sequence. This increase has been also reported by Wagger and Denton (1989) and is attributed to water depletion by vetch, which is killed later in the spring compared with the other WCC.

No-tilled soils under rotation with WCC (e.g., C-R/S-V and C-R/S-VR) are at much less risk of compaction since there are frequent additions of biomass, which maintain and increase SOM. Indeed the reduction of D_b of the surface soil that we can achieve with the use of WCC, particularly with sequences including vetch, is a highly desirable condition due to its implications for aeration, water infiltration, seed establishment, and root development.

Table 6. Bulk density (D_b) as affected by crop sequence and depth at Urbana, IL.

Depth	Sequence† C/S	C-R/S-R	C-R/S-V	C-R/S-VR
	Mg m^{-3}			
0–5	1.32aB‡	1.24aA	1.23aA	1.23aA
5–10	1.40bB	1.38bAB	1.35bA	1.36bAB
10–15	1.45bcAB	1.46cAB	1.50dB	1.43cA
15–30	1.45cA	1.44cA	1.42cA	1.39bcA

† Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).

‡ Within depths and for each column, means followed by the same lowercase letter are not significantly different at $p = 0.1$ based on preplanned comparisons. Between sequences, means followed by the same uppercase letter at a given depth are not significantly different at $p = 0.1$ based on preplanned comparisons.

Penetration Resistance

Results for PR measurements were consistent with soil strength values reported for no-tilled soils throughout Illinois (Hussain et al., 1998; Wander and Bollero, 1999). There was a significant sampling period × crop sequence interaction effect on PR ($p < 0.072$). This interaction effect is due to differences in the response of PR to the C-R/S-V sequence at the two sampling periods (Table 7). In addition, C-R/S-V sequence had a significantly higher PR in sampling Period 2 (soybean) than in sampling Period 1 (corn). The lack of significance between sampling periods for the C/S sequence allows us to ascribe the observed rise in PR solely to the effect of the C-R/S-V sequence. Rye WCC was killed every year approximately 2 wk before planting corn or soybean and the biculture suppressed 1 wk ahead planting but vetch was killed at planting. At the time of soil sampling, vetch was in an active growth stage while rye was already killed. We speculate that the longer period of active growth in the field produced higher water demands by the vetch WCC which in turn, caused an intensification of the wetting-drying cycles in the underlying soil. This stimulation of the wetting-drying cycles led to a closer contact between particles, which translated into increases in PR in this study (Angers and Caron, 1998).

There was a significant crop sequence × depth interaction effect on PR ($p < 0.093$) (Table 7). All crop sequences including WCC reduced soil PR at the surface 0 to 5 cm compared with C/S, and this effect was more pronounced under the C-R/S-R sequence ($p < 0.0001$). The C-R/S-R sequence caused about a 19% reduction on PR in the first 5 cm of the soil profile, the C-R/S-V sequence effect was about 8% and the C-R/S-VR sequence decreased PR by 16%. As with D_b, the observed reduction in PR with the use of WCC is due to the additional residues available in the soils under these rotations as compared with winter fallow (Kladivko, 1994). Treatments did not differ within the 5- to 10-cm depth but within 10 to 15 cm, the C-R/S-VR sequence produced a significant increase in PR as compared with that of fallow ($p < 0.09$). In the 15- 30-cm soil layer, both rotations with legume WCC significantly increased PR. This effect was also observed by Drury et al. (1999).

Porosity, Pore-Size Distribution, and Water Retention Properties

The introduction of WCC sequences decreased D_b and therefore significantly increased total soil porosity of the soil surface (Table 8). Enhanced total porosity in the horizon has been correlated with SOM content, root number, and abundance and diversity of earthworms (Lamande et al., 2003; Rasse et al., 2000; Schmidt et al., 2003). Changes in pore-size distribution are reflected in

Table 7. Penetration resistance (PR) as affected by sampling period, crop sequence, and depth at Urbana, IL.

Depth	Sequence† C/S		C-R/S-R		C-R/S-V		C-R/S-VR	
	$\log_{10}$ kPa (kPa)							
cm	Period 1							
0–5	3.1	(1412)	3.0	(1032)	3.0	(1006)	3.1	(1203)
5–10	3.3	(1840)	3.2	(1653)	3.2	(1741)	3.2	(1781)
10–15	3.2	(1744)	3.2	(1746)	3.3	(1859)	3.3	(1867)
15–30	3.2	(1629)	3.2	(1744)	3.2	(1756)	3.3	(1821)
Main effect	3.2aA‡	(1656)	3.2aA	(1544)	3.2aA	(1591)	3.2aA	(1668)
	Period 2							
0–5	3.1	(1337)	3.0	(1198)	3.2	(1510)	3.0	(1094)
5–10	3.3	(1835)	3.2	(1784)	3.3	(2102)	3.3	(1997)
10–15	3.2	(1739)	3.3	(1838)	3.3	(2016)	3.3	(2144)
15–30	3.2	(1624)	3.2	(1845)	3.3	(2060)	3.3	(2034)
Main effect	3.2aA‡	(1634)	3.2aA	(1666)	3.3bB	(1922)	3.2abA	(1817)

† Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ Within sequences and sampling period, means followed by the same lowercase letter are not significantly different at $P = 0.1$ based on pre-planned comparisons. Between sampling periods, means followed by the same uppercase letter are not significantly different at $p = 0.1$ based on pre-planned comparisons.

significant increases in the volume of transmission pores (macropores) with the use of the C-R/S-R sequence ($p < 0.029$), and the volume of storage pores (mesopores) with the use of any WCC sequences as compared with the C/S sequence (Table 8). In addition, WCC sequences showed a significant reduction of occluded porosity compared with C/S ($p < 0.019$).

The observed increase in transmission pores with the C-R/S-R sequence resulted in better soil aeration expressed as both air porosity (at −5 kPa) and residual air porosity (at −31 kPa). Changes in soil macro- and mesoporosity are translated into increases in water retention properties with the inclusion of WCC. Plant available water capacity (PAW) was significantly higher under WCC sequences ($p < 0.0026$). Sequences including WCC showed a significant increase in the volume of water held between saturation (0 kPa) and field capacity (−31 kPa) compared with the C/S sequence. This effect was even more distinct with C-R/S-VR ($p < 0.003$).

Saturated Hydraulic Conductivity

There was a significant effect of the sampling period on K_{sat} measurements ($p < 0.003$). The measured K_{sat} values were 45 and 381 mm d^{-1} in sampling Periods 1 (corn) and 2 (soybean), respectively. Differences in rooting patterns and amount and quality of residue left in the field between corn and soybean and the greater stimulation of faunal activity following legume crops (Mackay and Kladivko, 1985) may account for the observed increase in K_{sat} in sampling Period 2 (soybean). Crop sequences did not influenced soil K_{sat}. The large variability of K_{sat} data and consequent lack of significant differences among treatments is frequently reported in the literature and is related to limitations of the soil core method used for K_{sat} estimation, which is considered the reference method of analysis (Reynolds et al., 2000).

CONCLUSIONS

The use of WCC in a no-till system has proven to be important in soil chemical and physical characteristics in Illinois. While many studies found the improving effects of WCC to be limited to the soil surface, our study showed that their effects extend deeper into the soil profile. Specifically, the use of the C-R/S-V or C-R/S-VR increased SOM down to 30 cm. In addition, all WCC sequences produced a significant improvement in WAS. Percent WAS increases were 9, 13, and 17% for C-R/S-R, C-R/S-V, and C-R/S-VR, respectively. Winter cover

Table 8. Main effect of crop sequence on pore-size distribution, total (TP) and occluded (OP) porosity, air (AP) and residual air (RAP) porosity, plant available water (PAW), and water retained at lower tensions (W), at 3- to 10-cm depth expressed as percentages (%) of total soil volume.

Sequence†	Pore-size distribution (μm)‡ > 50	50–0.5	< 0.5	TP§	OP¶	AP	RAP	PAW	W
C/S	3.5a#	21.2a	15.0a	39.0a	3.3b	3.2a	6.0a	24.3a	35.2a
C-R/S-R	4.5b	22.4b	14.6a	41.0b	1.8a	4.2b	7.0b	25.3b	36.4b
C-R/S-V	3.9ab	22.4b	14.6a	40.3b	2.5ab	3.7ab	6.1a	25.6bc	36.4b
C-R/S-VR	4.0ab	22.6b	15.4a	41.3b	1.8a	3.9ab	6.1a	26.4c	37.3b
SE††	0.3	0.5	0.7	0.7	0.5	0.3	0.4	0.5	0.6

† Crop sequence: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).
‡ > 50-μm, transmission pores; 50–0.5-μm, storage pores; and < 0.5-μm, residual pores.
§ Calculated by addition of pore sizes.
¶ Obtained from the difference between the TP estimated from the bulk and particle densities and the TP resulting from the sum of pore sizes.
# Within sequences, means followed by the same lowercase letter are not significantly different at $p = 0.1$ based on preplanned comparisons.
†† SE, standard error of the mean values.

crop sequences reduced D_b and PR of the soil surface due to the additional residues and SOM as compared with C/S. There was an increase in TP and fewer occluded pores with WCC use. While the percentages of transmission pores and aeration were higher with C-R/S-R, all of the WCC sequences were effective in increasing storage porosity. Changes in pore-size distribution were also reflected through improved plant available water and increased water retained at lower tensions. Environmental problems regarding water contamination with NO_3–N and eutrophication (P) might also be addressed with extended WCC use. While the C-R/S-V sequence was the most effective in reducing soil NO_3–N, the C-R/S-R sequence was the most effective in trapping soil P.

The investigation of the effects of the sampling period on soil properties allowed us to identify and isolate the effects of the main crops corn and soybean and their entailed agronomical practices. A more widespread use of this kind of approach will help to better understand the interactive effect of rotations and tillage systems for different crops and in different climates and locations. In sampling Period 2 (soybean), only WAS and K_{sat} increased while the other variables were not affected. Likely, these properties are involved in the 'rotational effect' observed in many studies when corn–soybean rotations are contrasted with continuous monocropping.

REFERENCES

Al-Kaisi, M.M., X. Yin, and M.A. Licht. 2005. Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. Agric. Ecosyst. Environ. 105:635–647.

Angers, D.A., and J. Caron. 1998. Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 42:55–72.

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.

Bronick, C.J., and R. Lal. 2005. Soil structure and management: A review. Geoderma 124:3–22.

Bullock, D.G. 1992. Crop rotation. Crit. Rev. Plant Sci. 11:309–326.

Carmer, S.G., and W.M. Walker. 1988. Significance from a statistician's viewpoint. J. Prod. Agric. 1:27–33.

Carter, M.R. 1994. Strategies to overcome impediments to adoption of conservation tillage. p. 1–19. *In* M.R. Carter (ed.) Conservation tillage in temperate agroecosystems. Lewis Publishers. CRC Press, Boca Raton, FL.

Carter, M.R., and B.C. Ball. 1993. Soil Porosity. p. 581–588. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, Fl.

Crandall, S.M., M.L. Ruffo, and G.A. Bollero. 2005. Cropping systems and nitrogen dynamics under a cereal winter cover crop preceding corn. Plant Soil 268:209–219.

Crozier, C.R., G.C. Naderman, M.R. Tucker, and R.E. Sugg. 1999. Nutrient and pH stratification with conventional and no-till management. Commun. Soil Sci. Plant Anal. 30:65–74.

CTIC. 2002. National crop residue management survey. Available online at www.ctic.purdue.edu/CTIC/CTIC.htm (verified 28 June 2006).

Davies, B.E. 1974. Loss-on-ignition as an estimate of soil organic matter. Soil Sci. Soc. Am. Proc. 38:150–151.

Dexter, A.R. 1991. Amelioration of soil by natural processes. Soil Tillage Res. 20:87–100.

Dick, W.A. 1989. Influence of long-term tillage and crop rotation combinations on soil enzyme activities. Soil Sci. Soc. Am. J. 48:569–574.

Drury, C.F., C.S. Tan, T.W. Welacky, T.O. Oloya, A.S. Hamill, and S.E. Weaver. 1999. Red clover and tillage influence on soil temperature, water content, and corn emergence. Agron. J. 91:101–108.

Eckert, D.J. 1991. Chemical attributes of soils subjected to no-till cropping with rye cover crops. Soil Sci. Soc. Am. J. 55:405–409.

Ess, D.R., D.H. Vaughan, and J.V. Perumpral. 1998. Crop residue and root effects on soil compaction. Trans. ASAE 41:1271–1275.

Folorunso, O.A., D.E. Rolston, T. Prichard, and D.T. Louie. 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technol. 5:189–197.

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

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–412. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. SSSA, Madison, WI.

Greenland, D. J. 1977. Soil drainage by intensive cultivation: Temporary or permanent? Philos. Trans. R. Soc. London. Ser. B 281: 193–208.

Groffman, P.M., P.F. Hendrix, and J. Crossley, D.A. 1987. Effects of a winter legume on phosphorus, potassium, calcium and magnesium cycling in a humid subtropical agroecosystem. Agric. Ecosyst. Environ. 18:281–289.

Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agron. J. 78:70–74.

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.

Hoeft, R.G., and T.R. Peck. 2004. Soil testing and fertility. p. 91–131. *In* Illinois agronomy handbook. University of Illinois–Urbana-Champaign, Urbana, IL.

Hussain, I., K.R. Olson, and J.C. Siemens. 1998. Long-term tillage effects on physical properties of eroded soil. Soil Sci. 163:970–981.

Kabir, Z., and R.T. Koide. 2002. Effect of autumn and winter mycorrhyzal cover crops on soil properties, nutrient uptake, and yield of sweet corn in Pennsylvania, USA. Plant Soil 238:205–215.

Karlen, D.L., G.E. Varvel, D.E. Bullock, and R.M. Cruse. 1994. Crop rotations for the 21st century. Adv. Agron. 53:1–45.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425–442. *In* A. Klute (ed.) Methods of soil analysis. Part I. 2nd ed. SSSA, Madison, WI.

Kladivko, E.J. 1994. Residue effects on soil physical properties. p. 123–141. *In* P.W. Unger (ed.) Managing agricultural residues. Lewis Publishers, Boca Raton, FL.

Kuehl, R.O. 2000. Design of experiments: Statistical principles of research design and analysis. 2nd ed. Duxbury Press, Pacific Grove, CA.

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.

Lamande, M., V. Hallaire, P. Curmi, G. Peres, and D. Cluzeau. 2003. Changes of pore morphology, infiltration and earthworm community in a loamy soil under different agricultural managements. Catena 54:637–649.

Latif, M.A., G.R. Mehuys, A.F. Mackenzie, I. Alli, and M.A. Faris. 1992. Effects of legumes on soil physical quality in a maize crop. Plant Soil 140:15–23.

Liebig, M.A., G.E. Varvel, J.W. Doran, and B.J. Wienhold. 2002. Crop sequence and nitrogen fertilization effects on soil properties in the western corn belt. Soil Sci. Soc. Am. J. 66:596–601.

Littell, R.C., W.W. Stroup, and R.J. Freund. 2002. SAS for lineal models. 4th ed. Wiley InterScience.

Logsdon, S.D., J.L. Jordahl, and D.L. Karlen. 1993. Tillage and crop effects on ponded and tension infiltration rates. Soil Tillage Res. 28: 179–189.

Long, L.M. 2003. Conservation practices adoption by agricultural landowners. Ph.D. diss. Northern Illinois University, Dekalb, IL.

Mackay, A.D., and E.J. Kladivko. 1985. Earthworms and rate of breakdown of soybean and maize residues in soil. Soil Biol. Biochem. 17:851–857.

Martens, D.A. 2000a. Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. Soil Biol. Biochem. 32:361–369.

Martens, D.A. 2000b. Management and crop residue influence soil aggregate stability. J. Environ. Qual. 29:723–727.

McVay, K.A., D.E. Radcliffe, and W.L. Hargrove. 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. Soil Sci. Soc. Am. J. 53:1856–1862.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873–881.

Miguez, F.E. 2004. Winter cover crops: Meta-analysis and Illinois field study. M.S. thesis. University of Illinois at Urbana-Champaign, Urbana, IL.

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.

Power, J.F., P.T. Koerner, J.W. Doran, and W.W. Wilhelm. 1998. Residual effects of crop residues on grain production and selected soil properties. Soil Sci. Soc. Am. J. 62:1393–1397.

Ranells, N.N., and M.G. Wagger. 1997. Grass-legume bicultures as winter annual cover crops. Agron. J. 89:659–665.

Rasse, D.P., A.J.M. Smucker, and D. Santos. 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Sci. Soc. Am. J. 64:725–731.

Reeves, D.W. 1994. Cover crops and rotations. p. 125–172. *In* J.L. Hatfield and B.A. Stewart (ed.) Advances in soil science. Crops residue management. CRC Press, Boca Raton, FL.

Reicosky, D.C., and F. Forcella. 1998. Cover crop and soil quality interactions in agroecosystems. J. Soil Water Conserv. 53:224–229.

Reynolds, W.D. 1993. Saturated hydraulic conductivity: Laboratory measurements. p. 589–598. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Reynolds, W.D., B.T. Bowman, R.R. Brunke, C.F. Drury, and C.S. Tan. 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64:478–484.

Ruffo, M.L., and G.A. Bollero. 2003a. Residue decomposition and C and N release rates prediction based on biochemical fractions using principal component regression. Agron. J. 95:1034–1040.

Ruffo, M.L., and G.A. Bollero. 2003b. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agron. J. 95:900–907.

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.

Sainju, U.M., W.F. Whitehead, and B.R. Singh. 2003. Cover crops and nitrogen fertilization effects on soil aggregation and carbon and nitrogen pools. Can. J. Soil Sci. 83:155–165.

SAS Institute. 2002. SAS System for Windows. Release V9.1. SAS Institute, Cary, NC.

Schmidt, O., R.O. Clements, and G. Donaldson. 2003. Why do cereal-legume intercrops support large earthworm populations? Appl. Soil Ecol. 22:181–190.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops, p. 95–139 Adv. Soil Sci., Vol. 7. Springer-Verlag, New York Inc.

Soil Survey Staff. 2001. Soil survey of Champaign County, Illinois [Online]. Available online at http://websoilsurvey.nrcs.usda.gov/app/websoilsurvey.aspx (verified 13 July 2006). University of Illinois Agricultural Experiment Station, Soil Conservation Service, and U.S. Department of Agriculture.

Topp, G.C., Y.T. Galganov, B.C. Ball, and M.R. Carter. 1993. Soil water desorption curves. p. 569–579. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

USDA/ERS. 2000. Production practices for major crops in U.S. agriculture, 1990–97: General crop management practices. Statistical bulletin (SB) No. 969, Washington, DC.

USDA/ERS. 2003. Agricultural resources and environmental indicators: Soil management and conservation. Agricultural Handbook (AHB) No. 722, Washington, DC.

USDA/NRCS. 2004. Soil survey laboratory methods manual. [Online] ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab_Methods_Manual/SSIR42_2004_view.pdf (verified 28 June 2006).

Wagger, M.G., and H.P. Denton. 1989. Influence of cover crop and wheel traffic on soil physical properties in continuous no-till corn. Soil Sci. Soc. Am. J. 53:1206–1210.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961–971.