Corn Residue, Tillage, and Nitrogen Rate Effects on Soil Carbon and Nutrient Stocks in Illinois

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Abbreviations: SOC, soil organic carbon; TC total carbon; TN total nitrogen; P, available phosphorus; K, exchangeable potassium; EC, electrical conductivity; RR, residue removal; T, tillage; Nr, fertilizer N rates.

Abstract

Removal of crop residues for use as ethanol production feedstock might deplete soil carbon and nutrient pools in site- and management-specific ways. We investigated the effect of residue removal (RR), tillage (T), and N fertilizer rate (Nr) after five years of continuous corn (*Zea mays* L.) on total soil carbon (TC) and nutrient stocks at four sites within Illinois. The experimental design was a split-split plot arrangement of treatments in a randomized complete block design with four replications, and all treatments remained in the same place each year. Main plots consist of one of three levels of corn residue removal (RR: full, partial, and none); split plots were two tillage systems (T: chisel tilled and no-till) and split-split plots were four N fertilizer rates (Nr: 67, 134, 201, and 268 kg N ha⁻¹). The highest TC stocks were found under no-till without residue removal; removing any residue under no-till lowered TC to the levels found under chisel tillage. Removing residue in tilled soils produced higher TC values similar to the levels found with no residue removal and no-till. Residue removal tended to lower P and lowered K and EC in the surface 15cm soil. Tillage decreased the N and K stocks in the surface soil. Increasing the rate of N fertilizer lowered P, K, and pH, generally in an increasing, curvilinear manner, but the response of EC was concave, increasing at the highest N rate used. These responses were closely related to corn grain yields, indicating that the amount of nutrient removed by harvest of grain and residue and the amount of residue retained after harvest affect TC and nutrient stocks in Illinois soils. This information will help producers and policy makers to make better decisions regarding the feasibility of harvesting corn residue, and on agronomic practices that might accompany residue removal in order to prevent soil nutrient depletion.

1. Introduction

Maize crop residues are considered the leading candidate feedstock for cellulosic ethanol production in the U.S. due to their high volume and availability within concentrated areas of production in the Midwestern U.S. (Graham et al., 2007; James et al., 2010; U.S. DOE, 2011; Karlen and Huggins, 2014). The first cellulosic ethanol conversion facility with corn stover as the feedstock started production in September 2014 (POET-DSM, 2014) with more facilities underway in the Midwest region (Advanced Ethanol Council, 2012). To accompany this development, the 2014 Farm Bill authorized the Biomass Crop Assistance Program to provide financial incentives to producers for residue harvest (Agricultural Act of 2014).

Despite the availability of corn residue, producers and researchers equally have raised concerns about the sustainability of this practice due to its potential to decrease soil productivity (Wilhelm et al., 2007; Karlen et al., 2011a,b; Tyndall et al., 2011; Karlen and Huggins, 2014). Tyndall et al. (2011) conducted a survey among Iowa farmers to identify constraints to adoption of residue harvest within their cropping systems. Producers fear that residue harvest could compromise crop yield in the short term through loss of fertility, and in the long term via increased erosion and soil organic matter losses (Tyndall et al., 2011). Recent literature reviews have highlighted the vital role of residues in a wide range of agricultural functions and the potentially detrimental consequences of removal from their agricultural systems (Wilhelm et al., 2004; Blanco-Canqui and Lal, 2007; Moebius-Clune et al., 2008; Blanco-Canqui, 2010; Karlen and Huggins, 2014). Researchers have cautioned that for residue removal to be sustainable it should be managed to avoid compromising the provision of ecosystem services, crop yields and soil productivity, closely related to the maintenance of soil organic carbon (SOC) and nutrient pools (Johnson et al., 2013). Residue left in the field in warmer, drier regions benefits crop yields and soil productivity by preserving water, lowering soil temperature, increasing soil organic matter and

nutrient pools, and improving aggregation and stability in order to decrease wind and water erosion. In temperate regions with more fertile soils and more rainfall, however, leaving high amounts of residue in the field may not represent such an advantage, particularly under continuous corn production (Coulter and Nafziger, 2008). High levels of residue in the field interferes with planting and emergence by a combination of factors that include reduced soil temperature and higher water content, both of which can delay field operations and vegetative development after planting. In addition, high-residue systems show increased weed infestation, more N immobilization due to the high C/N ratio of corn stover, and more inoculum for many common corn diseases (Mann et al. 2002). To formulate decision support systems for producers interested in this residue management alternative, the amount of residues available for removal should be carefully determined taking into account the combined effects of soil type and topography, climatic conditions, crop rotation, tillage options, and fertilization practices. This information is critical in the Midwest region to discern in what systems residue harvest is possible, or even beneficial, and at what rates. In a recent report highlighting the achievements of the Sun Grant Regional Partnership, Karlen et al. (2014) summarized the effect of three levels of residue harvest on grain yield and nutrient removal from several sites around this maize-intensive region. The authors found that, in general, moderate harvest of the corn stover resulted in a slight increase in grain yield at 50% of the sites. Average grain yields under no-till were significantly lower than yields under conventional tillage when stover was left in the field, but not when it was harvested. Though the report represents a valuable contribution to the understanding of the effects of residue removal the high variability of the data and the different treatments evaluated at each site has so far precluded an in depth analysis of these trends. Of the experimental sites established within this regional partnership, only the sites in Illinois (Coulter

and Nafziger, 2008) and Minnesota (Linden et al., 2000; Clapp et al., 200; Dolan et al., 2006) provide information on factors that are likely to interact with residue removal, such as tillage options, and fertilizer nitrogen (N) additions. Specifically for Illinois, Coulter and Nafziger (2008) reported on the effect of three residue removal rates (no removal, partial, full), tillage (chisel, no-till) and four N rates (67 to 258 kg N ha⁻¹) on corn yield under continuous corn production across four sites and two consecutive years. In environments with lower rainfall and lighter-textured soil, corn grain yield responded negatively to residue removal and N fertilization only under no-till, likely due to increased water retention that increased the crop response to N. On heavier-textured soils with abundant rainfall, yields were similar between chisel plow and no-till with full residue removal, yet yields were higher with tillage with no or partial removal of residues. In addition, residue removal lowered N fertilizer requirements across tillage systems in these productive environments, probably due to a decline in N immobilization (Coulter and Nafziger, 2008). Building on this previous research, we proposed here to explore the effects of residue removal rates, tillage, and N fertilization on total carbon (TC) and nutrient pools within two depths at four experimental sites around Illinois, after five years since the initiation of the experiments. Results from this research can assist Illinois farmers interested in harvesting corn stover for biofuel production to make better decisions to ensure maintenance of soil productivity in their operations.

2. Materials and Methods

2.1 Field sites and experimental layout

Field experiments were established in the fall of 2005 following uniformly-cropped corn at four University of Illinois Crop Sciences research centers located near DeKalb (41°55′ N, 88°45′ W), Monmouth (40°54′ N, 90°38′ W), Perry (39°46′ N, 90°44′ W), and Urbana, IL (40°6′ N, 88°12′

W). Soil types were Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) at DeKalb and Urbana; Muscatine silt loam (fine-silty, mixed, superactive, mesic Aquic Argiudolls) at Monmouth; and Clarksdale silt loam (fine, smectitic, mesic Udollic Endoaqualfs) at Perry. All soils are somewhat poorly drained, with a slope between 0 and 1%. Mean annual precipitation ranges from 890 to 914 mm, and the mean annual temperature from 10.6 to 11.1°C. At each site, the experimental design was a split-split plot arrangement in a randomized complete block with four replications, and all treatments remained in the same place each year (Coulter and Nafziger, 2008). Main plots consist of one of three levels of corn residue removal (RR: full, partial, and none) in early November after grain harvest, with full removal accomplished by chopping stalks and raking them off the plots, and partial removal done by raking without chopping stalks. Split plots were two tillage systems (T: chisel tilled and no-till). Primary tillage was conducted with a chisel plow to a depth of 25cm during the fall and after crop harvest each year. Split-split plots were four N fertilizer rates (Nr: 67, 134, 201, and 268 kg N ha⁻¹) side dressed as 28% urea-ammonium nitrate (UAN) solution at the third leaf stage. Split-split plots were eight, 76-cm rows (6.1 m) wide by 8.1 to 13.1 m long, depending on location. Residue removal and tillage treatments were implemented in the fall of 2005, and N fertilizer treatments commenced in 2006. Detailed description of treatment implementation and plot management is available in Coulter and Nafziger (2008).

Based on several periodic measurements, we estimated residue removal for the full and partial removal treatments at 90 and 50 percent, respectively. We used a harvest index of 0.52, and combined residue nutrient content reported by Sindelar et al. (2013) with grain and stover yields in that same study (Sindelar et al., 2012) to estimate N, P, and K content of stover at 5.13, 0.23, and 5.66 kg Mg⁻¹, respectively. These were multiplied by stover dry weight and times removal

rates to give estimated nutrient removal over the 5-year period preceding soil sampling. Samples were taken at maturity in these trials, and so represent maximum values for N and K, which would be expected to decline as residue weathers in the field after harvest. In the current study, residue removal normally followed harvest by several weeks to a month, and it's likely that this lowered removal values.

2.2 Soil sampling and lab procedures

Soil sampling was conducted following harvest after the fifth year of establishment to assess the effect of residue removal, tillage and N rate effects on total carbon (TC) and nutrient stocks. Three samples per sub-subplot were taken with hand-held soil probes 20 mm in diameter, to a depth of 30 cm, and cores were divided into 0-15 and 15-30 cm depth segments. Samples were air-dried and sieved to <2 mm before analysis by standard methodology recommended for the North Central Region (NCR, 1998). Soil pH and EC were determined 1:1 in water. Air dried soil sieved to pass a 0.25-mm screen was used for determinations of available P (Bray 1), and extractable K (atomic absorption). Air-dried, finely-ground samples were used to determine TC and total nitrogen (TN) by dry combustion on a Costech Elemental Analyzer (Model ECS 4010, Costech Analytical Technologies, Inc. CA). Two subsamples were taken with a slide-hammer probe with a 5cm core diameter in each sub-subplot and at each depth to obtain bulk density values (Mg/m^3) via the core method (Blake and Hartge, 1986) to then convert TC and nutrient concentrations (TN, P, and K) to a basis of weight per unit area (Ellert and Bettany, 1995).

2.3 Statistical analysis

Data was analyzed using the MIXED procedure of SAS software version 9.4 (SAS Institute Inc., 2013). Residue removal (RR), tillage (T), and N rates (Nr) were considered fixed effects, while

replicates (blocks within sites and sites) were considered random effects. Significance of random effects was calculated with a Wald Z test statistic using the COVTEST option in the MIXED procedure. Depth (D) was analyzed using a repeated measures technique with variance-covariance structure VC, variance components, selected on the basis of the lowest Akaike's Information Criteria (Littell et al., 2006). Exact p-values from the analysis of variance for each studied variable are reported in Table 1. Pre-planned estimates were used for mean comparison purposes setting the probability of Type I error or alpha level (α) at 0.05. Linear, quadratic and higher order trends among group means were evaluated using orthogonal polynomial contrasts when N rate effects were found to be significant. In addition, selected non-orthogonal contrasts were used to investigate differences in specific treatment groupings. Plots were created using Sigma Plot 12.5 (Systat Software, 2013) and least significant difference (LSD) values at $\alpha=0.05$ are included to facilitate visualization of treatment differences. Statistical model and SAS codes are available upon request from the authors.

3. Results

3.1 Analyses of variance

Table 1 shows the exact probability values associated with the different sources of variation in the analysis of variance for TC, TN, available P, and exchangeable K stocks along with soil pH and electrical conductivity (EC) across four sites after five years of initiation of experiments. Residue removal affected K and EC levels across both sampling depths, and interacted with N rates to affect soil available P (statistically significant RRxNr). On the other hand, residue removal effect on TC depended upon the tillage option (statistically significant RRxT interaction) yet it had no influence on TN, or pH (Table 1). As a main effect, tillage (T)

influenced TN, and K (Table 1) while N rates had statistically significant effects on exchangeable K, pH and EC of the soils. All soil variables measured showed a statistically significant effect of depth of sampling, with higher TC, TN, P and K stocks, lower pH, and higher EC values in the topsoil. No double interaction effects were detected for tillage and N rates (TxNr) indicating there is no evidence that the fertilizer alter the trends found under the two tillage options. Likewise, no interaction among the three factors of residue removal, tillage and N rates (RRxTxNr) was detected in this study. The statistically significant two-way interactions with depth (RRxD, TxD, and NrxD) found for some of the soil variables indicate a response that varies with the depth studied, and will be reported within the next sections. No triple- or four-way interactions among treatments were identified in the present study (Table 1).

Estimated total residue production over 5 years ranged from 33 Mg ha⁻¹ at the low N rate to 47 Mg ha⁻¹ average across the two highest N rates. Removing part or all of the residue removed 87 and 160 kg N ha⁻¹, 4 and 7 kg P ha⁻¹, and 96 and 176 kg K ha⁻¹, respectively, at the lowest N rate. Averaged over the highest two N rates, nutrient removal averaged across the two highest two N rates with partial and full residue removal were 124 and 226 kg N ha⁻¹, 5 and 10 kg P ha⁻¹, and 136 and 239 kg K ha⁻¹, respectively.

3.2 Total Carbon and Total Nitrogen

The effects of the interaction of residue removal and tillage (statistically significant RRxT) reported on Table 1 for TC stocks resulted from a drop in TC with either partial or full residue removal under no-till practices compared to no residue removal (Table 2). The effect of residue removal is different when it occurs under chisel tillage where there is no change on soil TC with partial removal of residue compared to no residue removal. Interestingly, under full residue

removal, TC stock showed an increasing trend with tillage and a stock value that was not different than the TC stocks found under no residue removal in no-tilled situations (Table 2). No effects of residue removal rates were detected for TN stocks yet the use of chisel tillage over no-till practices reduced TN stocks in the surface soil (Tables 2 and 3).

3.3 Available P

Residue removal, tillage or their interaction RRxT did not affect the available P stocks (Table 1 and 3) yet this nutrient responded to N fertilizer rates and the shape of these responses depended upon the level of residue removal (RRxNr interaction present, Table 1). Orthogonal contrasts showed that both linear and quadratic components affected the response of available P to N rate, while differences in P stock level among residue removal rates and N rate combinations were due to slight variations in the shape of the cubic response of residue removal with increasing N rates (Figure 1). The statistically significant interaction of tillage and depth of sampling (TxD) found for available P stocks (Table 1) reflects higher stocks in the surface soil compared to the deeper layer yet stocks are similar between tillage options at both depths studied (Table 3).

3.4 Exchangeable K

Stocks of exchangeable K clearly responded to the independent or main effects of each of the three studied factors of residue removal (RR), tillage (T), and fertilizer N rates (N) (Table 1) that interacted with depth in each case (statistically significant RRxD, TxD, and NrxD) reflecting more pronounced or slightly different shape of the response in the surface 15cm than deeper in the soil (Table 1). Partial or full residue removal decreased the K stocks in the surface soil with a less pronounced effect in the deeper soil layer (Figure 2). No-tilled soils had significantly higher levels of soil exchangeable K compared to chisel tilled situations yet this effect was limited to

the surface soil layer (Table 2). Increasing fertilizer N rates reduced the K stocks in the soil yet this response differed by soil depth, with K levels showing a linear decrease with increasing N rate in the surface soil but a curvilinear response in the deeper layer (Figure 3).

3.5 Soil pH and EC

Soil pH was not affected by residue removal or tillage practices or their combination treatments (Table 1 and 3) yet it was statistically and negatively affected by increasing fertilizer N rates in the surface soil layer. The statistically significant N rate interaction with depth (NrxD) indicated that the negative linear response to N rate did not extend to the deeper soil layer (Table 1).

Partial or full residue removal rates lowered the EC in the surface soil compared to the EC under no residue removal, but did not affect EC within the deeper soil layer. On the other hand, EC values showed no response to N rate in the surface soil, but a negative (concave) quadratic trend in the deeper soil layer (data not shown). The statistically significant interaction effect of tillage and depth of sampling (significant TxD) found for EC (Table 1) reflects higher EC in the surface soil compared to the deeper layer yet the magnitudes are similar between tillage options at both depths studied (Table 3).

4. Discussion

While maize crop residues are an important potential source of biomass, their removal also means some loss of nutrients for the soil, and this might negatively affects SOC, fertility and long term productivity, regardless of the soil type and ecosystem. The response of soil to residue removal is assumed to be site-dependent, and a number of reports have estimated and modelled the effects of residue removal on SOC and other soil properties in different soils from temperate regions (Wilhelm et al., 2004; Blanco-Canqui and Lal, 2009; Muth et al., 2012; Bonner et al.

2014; Johnson et al. 2014). Impacts of stover removal in temperate regions under no-till management are considered to be greater in sloping silt loam soils than in flat glaciated soils of similar texture (Blanco-Canqui and Lal, 2009). Previous research with continuous corn in Iowa showed that maintenance of soil organic matter levels requires about 2 tons/ha yr of corn residue left on the soil surface prior to plowing each fall (Larson et al., 1972); this is less than half the residue produced under high-yield conditions, but may equal or exceed residue amounts produced by low-yielding corn. Today, amounts and tissue integrity of residue produced by current corn hybrids are much higher than those of hybrids found four decades ago (Yanni et al., 2011). In a recent report from the SunGrant Regional Partnership, Johnson et al. (2014) empirically estimated a minimum residue return rate required to sustain SOC levels at numerous locations of about 3.9 ± 2.2 Mg/ha yr, yet the authors warn against universal targets on which to base harvest recommendations at a given site. An important consideration is that there is a limited number of residue removal studies that had investigated other agronomic strategies that producers manage and that may affect SOC and nutrient balance, such as tillage and N fertilization. This knowledge gap makes any generalization from research plots to farm environment, risky, yet the results from this current study can actually succeed in providing those numbers for Illinois producers with continuous corn production.

Our results show that the response of soil TC stocks to residue removal depends on the tillage practice used, and that these responses are limited to the surface soil layer reflecting the stratification associated with topsoil addition of residues and nutrients, especially under conservation tillage systems (Wilhelm et al., 2004; Dolan et al., 2006). It is possible that we are seeing a trend toward more separation in TC resulting from residue removal and tillage, but that more time is needed for TC levels to stabilize under these systems. Still, it is not clear why

tillage under full residue removal would show higher TC levels than those under tillage with residue present. We hypothesize that the full removal of residue in these highly fertile soils allows for a faster turnover of the soil carbon due to the higher temperature and reduced water content that commonly limits carbon cycling in this environments particularly under no-till conditions (Needelman et al. 1999). Yet this might be a temporary effect which indicates the need to further evaluate these trends to see if they are continuing in the same direction.

Tillage is the single most important practice reducing nutrient stocks in the surface soil yet N fertilization could be used as a tool to moderate the P and K responses since it works closely with residue removal in shaping the response of available P in the soil. Averaged over tillage treatments, available P and exchangeable K levels in the top 15 cm of soil – 4.61 and 22.8 g/m² or 46.1 and 228 kg/ha, respectively – are within the adequate range for P but are slightly suboptimal for K (Fernandez and Hoeft, 2009). Because the harvesting of corn residue removes some K from the cropping system, we anticipated the finding that exchangeable K stocks might decrease with residue removal. Likely, the increased K removal (lower K stock level) as N rate increased is indirectly due to the increase grain and residue yield at higher N rates; the different pattern of the response observed in the deeper soil layer may be due to the commonly observed increased crop uptake of K when limiting nutrients such as N, become increasingly available with higher N rates (IPNI, 1998). Soil exchangeable K was also higher within the surface soil layer under no-till situations, a response also observed by Karlen et al. (2013) and attributed to the stratification of soil properties commonly observed in these systems.

All soil pH values measured were within appropriate ranges for corn production (Fernandez and Hoeft, 2009). Surface soil pH showed a negative linear trend with increasing N rate, likely due to the acidifying effects of residue decomposition and fertilization near the soil surface. Soils had

lower pH values in the surface layer compared to the deeper layer, with no differences due to tillage. Similarly, EC values, all of which were much lower than the 980 mS/cm considered the threshold for salinity problems (Smith and Doran, 1996), were higher in the surface than in the deeper soil layer, and were not affected by tillage treatments. Both H^+ and EC would be expected to increase with additions of fertilizer N, and are higher in the surface soil because within these production systems, N is applied at a shallow depth and it is not moved deeper by tillage.

These results are closely reflecting the effect of residue removal, tillage and fertilization practices on corn yields (Coulter and Nafziger, 2008; unpublished data of the authors since 2007). In poorly-drained, productive soils of Illinois, with annual corn yield averages of 10 Mg/ha or more, removing residue increase yield regardless of tillage, but more under no-till than when tilled. The positive quadratic response to N fertilizer rate is also accentuated with tillage, though the magnitude of this response varies with weather conditions. Thus we see that residue and its removal have effects that extend well beyond those of short-term changes in soil C, N, and other nutrient levels, and include such things as effects on soil temperatures and soil water retention that are unrelated to small changes in C and nutrient stocks.

5. Conclusions

Under the temperate weather, high yielding, and high fertility soil conditions of Illinois, residue removal, with or without tillage, appears to represent little threat to soil productivity, at least over a period of five years, and as long as removed nutrients are replenished. By increasing grain and biomass yield, higher N rates increased estimated nutrient uptake and stover content, thereby increasing the amount nutrients removed when residue was removed. Removing all of the residue at the highest yield levels removed only 10 kg of $P\ ha^{-1}$ over 5 years, and so the drop in

soil P with full residue removal and as N rate increased was due to factors other than removal of P along with residue. Actual removal of N and K were likely overestimated because of weathering after harvest in the current work, but maximum removal levels exceeded 200 kg ha⁻¹ over five years may be enough to influence soil K levels. Yet a longer term evaluation of these practices is required to generate responsible recommendations regarding residue removal rates integrated with tillage and fertilization options if corn crop residue is to provide a major feedstock to support a sustainable bioenergy industry.

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Figure captions

Figure 1. Interaction effects of residue removal and N rate on available P across four Illinois locations after five years of treatment. The bar indicates the size of the least significant difference (LSD) among treatment means at $\alpha=0.05$.

Figure 2. Residue removal effects on soil exchangeable K at both studied depths across four Illinois locations after five years of treatment. The bar indicates the size of the least significant difference (LSD) among treatment means at $\alpha=0.05$.

Figure 3. Nitrogen rate effects (N rate) on soil exchangeable K at both studied depths across four Illinois locations after five years of treatment. The bar indicates the size of the least significant difference (LSD) among treatment means at $\alpha=0.05$.

TABLES

Table 1. Probability values and numerator degrees of freedom (Df) associated with the different sources of variation in the analysis of variance for TC, TN, available P, and exchangeable K stocks along with soil pH and electrical conductivity (EC) across four sites after five years of initiation of experiments.

Source of variation	Df	TC	TN	P	K	pH	EC
		kg/m ²	kg/m ²	g/m ²	g/m ²	unit less	μS/cm
Residue Removal (RR)	2	0.3044	0.2189	0.1200	<.0001	0.2277	0.0903
Tillage (T)	1	0.0154	0.0179	0.7843	0.0038	0.8114	0.8347
RR x T	2	0.0648	0.1639	0.2281	0.2058	0.3261	0.3885
N rates (Nr)	3	0.8738	0.8152	0.0106	0.0001	<.0001	0.0047
Linear Nr	1	-	-	0.0339	0.0011	<.0001	0.7788
Quadratic Nr	1	-	-	0.0095	0.0024	0.3141	0.0004
Cubic Nr	1	-	-	0.9026	0.4884	0.2022	0.7359
RR x Nr	6	0.2514	0.8515	0.1102	0.2105	0.9225	0.9266
Linear Nr x RR	2	-	-	0.6406	-	-	-
Quadratic Nr x RR	2	-	-	0.5345	-	-	-
Cubic Nr x RR	2	-	-	0.0164	-	-	-
T x Nr	3	0.4448	0.8229	0.1577	0.3685	0.8747	0.7742
RR x T x Nr	6	0.9446	0.8061	0.7304	0.8513	0.3239	0.6586
Depth (D)	1	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
RR x D	2	0.1710	0.3207	0.4418	0.0049	0.9515	0.0048
T x D	1	0.0002	<.0001	0.0805	<.0001	0.4141	0.0438
RR x T x D	3	0.9634	0.6626	0.8444	0.2531	0.4612	0.2369
Nr x D	3	0.9499	0.4141	0.8304	0.0021	0.0004	0.0702
Linear Nr x D	1	-	-	-	0.0075	<.0001	0.2725
Quadratic Nr x D	1	-	-	-	0.0062	0.6397	0.0156
Cubic Nr x D	1	-	-	-	0.7423	0.4353	0.9320
RR x Nr x D	6	0.9508	0.9027	0.9598	0.8093	0.5980	0.4173
T x Nr x D	3	0.4220	0.6715	0.9038	0.6315	0.9567	0.5842
RR x T x Nr x D	6	0.9576	0.7700	0.9916	0.6154	0.9466	0.8882

Table 2. Interaction effects of residue removal and tillage on total carbon (TC) and total nitrogen (TN) stocks, averaged across four Illinois sites five years after treatment establishment, and across four N rates within the top 30 cm of soil. Means within a column with the same lower case letter are not significantly different at $p=0.05$; no letters means no significant response.

Residue removal	Tillage	TC		TN
		kg/m ²		
None	No-till	4.56	a	0.36
None	Chisel tilled	4.10	b	0.32
Partial	No-till	4.26	b	0.34
Partial	Chisel tilled	4.09	b	0.32
Full	No-till	4.27	b	0.34
Full	Chisel tilled	4.29	ab	0.35

Table 3. Interaction effects of tillage and sampling depth on total carbon (TC), total nitrogen (TN), available P, exchangeable K, pH, and electrical conductivity (EC) across four Illinois sites five years after treatment establishment. Means within a column with the same lower case letter are not significantly different at $p=0.05$.

Tillage	D (cm)	TC		TN		P		K		pH		EC	
		kg/m ²				g/m ²						μS/m	
No-till	0-15	4.72	a	0.37	a	4.67	a	24.05	a	6.18	a	106.4	a
Chisel tilled		4.40	b	0.32	b	4.54	a	21.55	b	6.19	a	103.7	a
No-till	15-30	4.01	c	0.35	c	2.85	b	18.58	c	6.32	b	67.3	b
Chisel tilled		3.92	c	0.31	c	3.07	b	18.65	c	6.31	b	70.9	b

FIGURES

Figure 1.

Figure 2.

Figure 3.