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Agriculture, Ecosystems and Environment 105 (2005) 635–647

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils

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Received 20 August 2003; received in revised form 22 July 2004; accepted 4 August 2004

Abstract

Soil organic C (SOC) and total N (TN) contents play a crucial role in sustaining agricultural production systems. Short-term ($\leq$10-year) management effects on SOC and TN dynamics are often complex and variable. Three experiments were conducted to evaluate short-term tillage and cropping system effects on SOC and TN within the 0–30 cm soil depth across Iowa. The first experiment with no-tillage and chisel plowing treatments was established in 1994 on Clarion-Nicollet-Webster (CNW), Galva-Primghar-Sac (GPS), Kenyon-Floyd-Clyde (KFC), Marshall (M), and Otley-Mahaska-Taintor (OMT) soil associations under a corn (*Zea mays* L.)–soybean (*Glycine max* (L.) Merr.) rotation. The second experiment with no-tillage, strip-tillage, chisel plowing, deep ripping, and moldboard plowing treatments was initiated in 1998 on the CNW soil association in a corn–soybean rotation. The third experiment consisting of smooth bromegrass (*Bromus inermis* Leyss.), switchgrass (*Panicum virgatum* L.) and corn–soybean–alfalfa (*Medicago sativa* L.) treatments was established in 1991 on Monona-Ida-Hamburg (MIH) soil association under no-tillage management. Short-term tillage effects on SOC and TN occurred primarily at the 0–15 cm soil depth. Tillage effects did not vary significantly with soil association. No-tillage resulted in greater SOC and TN contents than chisel plowing at the end of 7 years of tillage practices averaged over the CNW, GPS, KFC, M, and OMT soil associations. The increase in SOC and TN with no-tillage was not related to SOC and TN stratification in the soil profile or annual C and N inputs from crop residue, but most likely due to decreased mineralization rate of soil organic matter. However, tillage effects on SOC and TN were negligible at the end of only 3 years of tillage practices on the CNW soil association. Smooth bromegrass and switchgrass systems resulted in greater SOC and TN contents at both 0–15 cm and 15–30 cm soil depths than a corn–soybean–alfalfa rotation after 10 years of management on the MIH soil association. Smooth bromegrass and switchgrass systems increased SOC by 2.3 and 1.2 Mg ha^{-1} yr^{-1} at the 0–15 cm soil depth, respectively. We conclude from these short-term experiments that reducing tillage intensity and increasing crop diversity to include perennial grasses could be effective in improving C and N sequestration in Midwest soils.

Keywords: Cropping system; Smooth bromegrass; Soil organic carbon; Switchgrass; Tillage; Total nitrogen

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doi:10.1016/j.agee.2004.08.002

1. Introduction

Soil organic C (SOC) and total N (TN) contents play a crucial role in sustaining soil quality, crop production, and environmental quality (Bauer and Black, 1994; Doran and Parkin, 1994; Robinson et al., 1994) due to their effects on soil physical, chemical, and biological properties, such as soil water retention, nutrient cycling, gas flux, and plant root growth (Sainju and Kalisz, 1990; Sainju and Good, 1993). Soil, as an open system, can be a net source of CO_2 released to the atmosphere due to elevated SOC mineralization as a result of disruptive agricultural practices. On the other hand, soil can function as a net sink for sequestering atmospheric CO_2 under appropriate soil and crop management, and thus reducing atmospheric CO_2 (Paustian et al., 1992; Lal et al., 1995).

Plant biomass is a source of C and N, which can replenish SOC and TN. Changes in soil conditions (e.g., temperature, moisture, O_2, pH, and nutrient availability) can alter the decomposition rate of plant biomass and the mineralization rate of soil organic matter (Broadbent et al., 1964; Kowalenko et al., 1978; Clark and Gilmour, 1983). Therefore, SOC and TN can be enriched via appropriate soil and crop management practices that either increase organic matter input to the soil, decrease the mineralization rate of soil organic matter, or both (Paustian et al., 2000; Follett, 2001).

It has been well documented that soil can be managed to increase SOC and TN storage from a long-term (>10 years) perspective by implementing conservation soil and crop management practices such as conservation tillage (Havlin et al., 1990; Franzluebbers et al., 1995; Halvorson et al., 2002) and crop rotations (Robinson et al., 1996). However, short-term ($\leq$10 years) management effects on soil C and N dynamics are complex and often variable. After analyzing a large global data set, West and Post (2002) concluded that soil C sequestration was generally increased by no-tillage practices, but had a delayed response, with peaks in years 5–10. This finding agreed with the results reported by Franzluebbers and Arshad (1996), that there may be little to no detectable increase in SOC in the first 2–5 years, but a large increase 5–10 years after switching to conservation tillage. In a study on short-term crop rotation effects on SOC, Campbell et al. (2000) found that measurable gain in SOC could be observed in 6 years or less when weather conditions were favorable.

Conservation tillage systems such as no-tillage, strip-tillage, and chisel plowing have been increasingly used in the Midwest during the past decade due to their profitability and environmental advantages over moldboard plowing. For example, no-tillage systems in the Midwest were used in over 22% of all cropland area in 2002 according to the 2002 National crop residue management survey conducted by the Conservation Technology Information Center (unpublished data), which almost doubled that in 1992. Deep ripping is an effective and popular tool that can be used to overcome soil compaction in the Midwest. Although, deep ripping is not a conservation tillage system, it still results in less soil disturbance than moldboard plowing. However, there have been few studies that quantify these main tillage alternatives with different tillage intensities on soil C and N changes over time compared with moldboard plowing in the Midwest soils where a corn (*Zea mays* L.)–soybean (*Glycine max* (L.) Merr.) rotation is the primary cropping system.

Conversion of cropland particularly marginal land to pasture has the greatest potential for increasing C sequestration in the soil (Lal et al., 1998). Corn–soybean–alfalfa (*Medicago sativa* L.) rotation is an effective and primary crop rotation system that has been used in the Midwest to improve soil quality and productivity. Smooth bromegrass (*Bromus inermis* Leyss.), and switchgrass (*Panicum virgatum* L.) are the two main perennial grass species that have been widely used for grazing in the Midwest. There is very little information on whether these perennial grass cropping systems are superior to a corn–soybean–alfalfa rotation in improving soil C and N storage under the Midwest production environment.

The effects of soil and crop management practices on SOC and TN dynamics, in part, depend on soil properties and environmental factors, such as soil texture, clay mineralogy, topography, and climate (Janssen, 1984; Bohn et al., 1985; Campbell et al., 1999). Therefore, an understanding of possible differential effects of management practices on SOC and TN dynamics of different soil types and under different production areas is essential in developing best management practices and prediction tools for SOC and TN management. The objectives of this study were to (1) examine short-term SOC and TN responses to various tillage alternatives in the CNW soil association under a corn–soybean rotation; (2) evaluate whether tillage (no-tillage and chisel plowing) effects on SOC and TN differ on different soil associations under a corn–soybean rotation; and (3) assess the effects of perennial smooth bromegrass and switchgrass cropping systems on SOC and TN contents relative to a corn–soybean–alfalfa rotation under no-tillage management.

2. Materials and methods

This study consisting of three different experiments was designed to evaluate the short-term effects of tillage and cropping systems on SOC and TN contents in various soil associations across Iowa. Location and basic soil information of each experiment are presented in Table 1.

2.1. Experimental design

The 2-tillage experiment was established in 1994 on CNW, GPS, KFC, M, and OMT soil associations under a corn–soybean rotation. No-tillage and chisel plowing treatments with three replicates were applied to both corn and soybean seasons by using a randomized complete block design. No-tillage was defined as no preplant tillage. No-tillage crops were planted using a planter with a single coulter to cut through crop residue and loosen soil. The only soil disturbance associated with no-tillage was due to planting and fertilizer applications. Chisel plowing was preformed with a commercially available model with straight shanks and twisted sweeps. The shanks were mounted on 4 tool bars in a staggering order to ensure an effective spacing of 30 cm between shanks. The depth of tillage with chisel plowing was 22–25 cm. Both corn and soybean were planted in 76-cm rows each season. Anhydrous ammonium was injected in the fall at an actual N rate of 135 kg ha^{-1} 1 for corn. Soybean did not receive any N fertilizer applications. No P or K fertilizer was applied to either corn or soybean because the soil testing results showed that both P and K were sufficient at each location. The plot size was 127 m × 38 m for all the treatments.

The 5-tillage experiment was established on CNW soil association under a corn–soybean rotation in 1998, and consisted of no-tillage, strip-tillage, chisel plowing, deep ripping, and moldboard plowing treatments. A randomized complete block design

Table 1
Soil association, series, and classification for each experiment

Experiment	Location	Soil association[a]	Soil series[b]	Classification
2-tillage	Kanawha	CNW	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
			Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
	Sutherland	GPS	Galva	Fine-silty, mixed, superactive, mesic Typic Hapludolls
			Primghar	Fine-silty, mixed, superactive, mesic Aquic Hapludolls
			Marcus	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
	Nashua	KFC	Floyd	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
			Kenyon	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
	Armstrong	M	Marshall	Fine-silty, mixed, superactive, mesic Typic Hapludolls
	Crawfordsville	OMT	Mahaska	Fine, smectitic, superactive, mesic Aquic Argiudolls
			Nira	Fine-silty, mixed, superactive, mesic Typic Hapludolls
5-tillage	Ames	CNW	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
Cropping system	Castana	MIH	Monona	Fine-silty, mixed, superactive, mesic Typic Hapludolls
			Ida	Fine-silty, mixed, superactive, calcareous, mesic Typic Udorthents
			Hamburg	Coarse-silty, mixed, superactive, calcareous, mesic Typic Udorthents

[a] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; MIH, Monona-Ida-Hamburg; OMT, Otley-Mahaska-Taintor.

[b] According to FAO soil classification, Canisteo and Marcus belong to Gleysols; Ida and Hamburg belong to Regosols; Mahaska belongs to Greyzems; Monona, Galva, Nicollet, Primghar, Floyd, and Kenyon belong to Chernozems; and Marshall and Nira belong to Phaeozems.

was used with three replicates. Tillage practices were applied to both corn and soybean. The no-tillage and chisel plowing treatments were the same as those applied to the 2-tillage experiment. The strip-tillage plots were tilled 20 cm wide × 20 cm deep on 76-cm centers with an anhydrous knife centered between two cover disks. The tilled zone was created in rows of the previous corn or soybean crop and was 10 cm high. The deep ripping treatment was performed using a commercially available deep ripper with 4 straight shanks on 97-cm center of 3-m tool bar (3 points). The effective tillage depth with the straight shanks was 40–46 cm. The moldboard plowing treatment utilized a commercially available model with 4 full bottoms, each 46 cm wide, and 25 cm deep. Moldboard plowing resulted in a complete inversion of the soil surface and nearly 100% incorporation of crop residue. All treatments except no-tillage and strip-tillage received one spring field cultivation to a 10-cm depth prior to planting. The field cultivator with shovels was mounted on 4 tool bars in a staggering order to ensure an effective spacing between shovels of 30 cm. The row width for both corn and soybean was 76 cm each year. The tillage system and crop rotation used prior to the experiment establishment was chisel plowing and corn–soybean, respectively. Anhydrous ammonium was injected in the fall at an actual N rate of 135 kg ha^{-1} for corn after soybean. There was no N application after corn harvest or during the soybean season. Phosphorus and K fertilizers were applied as needed. The plot size was 230 m × 64 m.

The cropping system experiment was established in 1991 using a randomized complete block design with four replicates on MIH soil association. Three treatments including smooth bromegrass, switchgrass, and corn–soybean–alfalfa were established side by side on the same soil association. The smooth bromegrass treatment was grazed continuously from mid-June to mid-August, while switchgrass was grazed on a rotational basis every 3 weeks from May to September. Corn–soybean–alfalfa rotation consisted of one corn season followed by one soybean season and by three consecutive seasons of alfalfa for each 5-year period. All the treatments were under no-tillage management. Both perennial grass treatments received an average N rate of 90 kg ha^{-1} yr^{-1}. Corn received 90 kg N ha^{-1}, but soybean and alfalfa received no N fertilizer in any of the seasons. Phosphorus and K fertilizers were applied as needed. Prior to corn planting, alfalfa was sprayed with 2,4-D and Roundup in late April or early May. The plot size was 200 m × 80 m.

2.2. Soil and crop residue sampling and analysis

Initial soil samples were collected at the 0–15 cm soil depth for SOC determination prior to the establishment of these three experiments. Soil samples were taken again for SOC and TN contents analyses in fall 2000 after harvest at the soil depth intervals of 0–15 cm and 15–30 cm. Ten to twelve cores of soil were randomly collected within each plot with hand probes of 1.9 cm i.d. after removing the visible crop residue from the soil surface. Soil samples were placed in soil-sampling bags and stored in a cooler. Soil samples were maintained in a field moisture condition and passed through a 2-mm sieve and subsequently air-dried. Four soil bulk density samples were taken in 2000 at the same soil depth intervals for each plot using a core method with a copper cylinder of 5 cm in height and 5 cm in diameter similar to that used by Culley (1993). Bulk density was used to convert SOC and TN concentrations (g kg^{-1}) to mass per soil area (Mg ha^{-1}) within a certain soil depth. Three aboveground soybean residue samples were collected in 2000 and three aboveground corn residue samples were taken in both 2001 and 2003 using a 1-m^2 frame from each plot in the 2-tillage and 5-tillage experiments after harvest but before any tillage operations. Residue samples were oven dried at 64 °C, cleaned from soil, weighed, ground, and analyzed for total C and N concentrations.

The concentrations of total C and total N of soil and crop residue were determined by dry combustion with a LECO CHN analyzer. Soil inorganic C was estimated using a modified pressure-calcimeter method (Sherrod et al., 2002) for the soil samples with pH greater than 7.1. Soil organic C was assumed to be equal to the soil total C if soil pH is not greater than 7.1, otherwise, SOC was estimated as the difference between soil total C and inorganic C. Initial SOC content at 0–15 cm soil depth for each experiment is presented in Table 2.

Table 2
Initial SOC content at the 0–15 cm soil depth for each experiment[a]

Experiment	Sampling year	Soil association[b]	SOC (Mg ha^{-1})
2-tillage	1994	CNW	44.6
	1994	GPS	35.7
	1994	KFC	38.0
	1994	M	30.3
	1994	OMT	38.9
5-tillage	1998	CNW	43.5
Cropping system			
Smooth bromegrass	1991	MIH	23.7
Switchgrass	1991	MIH	28.7
Corn–Soybean–Alfalfa	1991	MIH	21.6

[a] SOC, soil organic C.

[b] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; MIH, Monona-Ida-Hamburg; OMT, Otley-Mahaska-Taintor.

2.3. Estimation of annual crop residue biomass and C and N inputs

Annual C and N inputs from aboveground crop residue refer to the amount of C and N in crop residue produced under each tillage system that is left on the soil surface after harvest and before any tillage operation is performed. Aboveground corn and soybean residue biomass was estimated by using annual grain yield since the experiment establishment and multiplying it by its harvest index. Annual C and N inputs from the estimated crop residue during the entire study period were calculated for the 2-tillage and 5-tillage experiments by including both corn and soybean residues under a corn–soybean rotation. The C and N inputs of a corn or soybean season were calculated as the quotients of grain yield and harvest index and then multiplying by the total C and N concentrations in crop residue (corn or soybean), respectively. Grain yields of corn and soybean were measured each year for these experiments, and were adjusted to moisture content of 15.5% for corn and 13% for soybean. The harvest index (grain yield ÷ aboveground biomass yield without grain) used in this estimation was 0.59 for corn and 0.57 for soybean (Licht, 2003). Total C and N concentrations in corn and soybean residues were determined by using the soybean residue samples collected in 2000 and corn residue samples collected in 2001 and 2003 from these experiments. The weather conditions and crop yields in 2000, 2001, and 2003 were very typical to the average conditions of each location of the experiments.

2.4. Statistical analysis

Statistical analyses of variance for the data were conducted using the SAS statistical package (SAS Institute, 2002). The ANOVA procedure was used for all measurements within each experiment. Data were analyzed for each individual location and across locations as well if there were multiple locations within an experiment. Mean separations were achieved by using a protected least significant difference (LSD) test. The probability level less than 0.05 was designated as significant. If there was a statistically significant interaction, then the interaction was presented, but the main effects of the treatment factors that were involved in this interaction were not reported. Otherwise, only the main effects of treatments were presented.

3. Results and discussion

3.1. Tillage effects on soil C and N contents

3.1.1. 2-tillage experiment

When data of the five soil associations were analyzed separately in this experiment, the difference in either SOC or TN content in 2000 between no-tillage and chisel plowing was not significant in any of the soil associations (Table 3). However, all the soil associations showed an increasing trend in both SOC and TN contents with no-tillage compared with chisel plowing at the 0–15 cm soil depth. Statistical

Table 3
Tillage effects on SOC and TN contents, soil C:N ratio, and BD after 3 and 7 year implementation of the tillage experiments under a corn–soybean rotation[a]

Experiment	Soil association[b]	Tillage treatment	0–15 cm				15–30 cm			
			SOC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N ratio	BD (g cm^{-3})	SOC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N ratio	BD (g cm^{-3})
2-tillage	CNW	No-tillage	54.3 a[c]	3.9 a	13.9 a	1.24 a	39.0 a	2.1 a	18.6 a	1.30 a
		Chisel plowing	46.4 a	3.3 a	14.1 a	1.22 a	33.3 a	2.3 a	14.5 a	1.27 a
	GPS	No-tillage	40.5 a	3.2 a	12.7 a	1.21 a	39.6 a	3.0 a	13.2 a	1.35 a
		Chisel plowing	38.7 a	3.2 a	12.1 a	1.21 a	41.4 a	3.0 a	13.8 a	1.31 a
	KFC	No-tillage	42.3 a	4.8 a	8.8 a	1.35 a	27.0 b	3.3 a	8.2 a	1.48 a
		Chisel plowing	35.4 a	4.4 a	8.0 a	1.31 a	31.2 a	4.2 a	7.4 a	1.45 a
	M	No-tillage	32.9 a	2.7 a	12.2 a	1.13 a	35.9 a	2.9 a	12.4 a	1.09 a
		Chisel plowing	30.9 a	2.6 a	11.9 a	1.11 a	36.3 a	2.9 a	12.5 a	1.13 a
	OMT	No-tillage	47.6 a	3.8 a	12.5 a	1.28 a	35.0 a	2.6 a	13.5 a	1.36 a
		Chisel plowing	39.9 a	3.0 a	13.3 a	1.18 a	35.1 a	2.4 a	14.6 a	1.32 a
	Average	No-tillage	43.5 a	3.6 a	12.1 a	1.24 a	35.4 a	2.9 a	12.2 a	1.32 a
		Chisel plowing	38.3 b	3.3 b	11.6 a	1.20 a	35.4 a	3.0 a	11.8 a	1.29 a
5-tillage	CNW	No-tillage	39.6 a	3.6 a	11.0 a	1.39 a	44.7 a	4.1 a	10.9 a	1.60 a
		Strip-tillage	49.2 a	4.5 a	10.9 a	1.34 a	48.5 a	4.2 a	11.5 a	1.44 a
		Chisel plowing	47.7 a	4.4 a	10.8 a	1.42 a	41.7 a	3.8 a	11.0 a	1.54 a
		Deep ripping	38.4 a	3.0 a	12.8 a	1.39 a	37.7 a	3.0 a	12.6 a	1.48 a
		Moldboard plowing	42.9 a	3.3 a	13.0 a	1.35 a	46.4 a	3.2 a	14.5 a	1.53 a

[a] SOC, soil organic C; TN, total N; BD, bulk density.

[b] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; OMT, Otley-Mahaska-Taintor.

[c] Values in column within each soil association or averaged across the soil associations of each tillage experiment followed by the same letter are not significantly different at 0.05 probability level.

insignificance in SOC and TN contents in response to tillage systems at the 0–15 cm soil depth interval was most likely due to the short-term implementation of no-tillage, and the quantity of SOC impacted by tillage are small relative to the pool of SOC already present in the soil (Ellert et al., 2001).

There was clear stratification of SOC and TN contents within 0–30 cm of the soil profile in the CNW, KFC, and OMT soil associations in 2000 regardless of tillage treatment (Table 3). However, no such stratification was observed in the GPS and M soil associations. The magnitude of SOC and TN stratification was similar in the two tillage treatments. Soil bulk density values were quite similar for no-tillage and chisel plowing in each soil association (Table 3), therefore, the effect both tillage systems had on SOC and TN was due to changes in concentrations of SOC and TN rather than bulk density. At the end of 7 years of tillage practices, no significant difference in SOC to TN (C:N) ratio was observed between no-tillage and chisel plowing regardless of soil depth and soil association (Table 3). This can be attributed to the biological linkage between SOC and TN.

Averaged over the five soil associations, no-tillage resulted in SOC content 13.6% (5.2 Mg ha^{-1}) greater than chisel plowing at the 0–15 cm soil depth at the end of 7 years of tillage practices (Table 3). However, no significant difference was observed between the two treatments at the 15–30 cm soil depth interval. Similar to SOC, TN responses to tillage systems also varied with soil depth (Table 3). No-tillage increased TN content by 9.1% (0.3 Mg ha^{-1}) over chisel plowing averaged across the five soil associations at the 0–15 cm soil depth, but TN content at the 15–30 cm soil depth was similar under the two tillage systems. Franzluebbers et al. (1999) reported that SOC and TN contents decreased with increase in the intensity and frequency of tillage operations.

Similar SOC and TN values of the 15–30 cm soil depth for both tillage treatments averaged across the five soil associations indicated that the elevated SOC and TN at the 0–15 cm soil depth of no-tillage compared with chisel plowing were not due to the stratification of SOC and TN in the soil profile, rather due to the actual increases in SOC and TN contents at the 0–15 cm soil depth. In addition, improvement in SOC and TN contents at the 0–15 cm soil depth with no-tillage averaged across the five soil associations was not due to soil bulk density, because bulk density values of no-tillage and chisel plowing were quite similar (Table 3). Therefore, the elevated SOC and TN contents on a volumetric basis under no-tillage in this experiment were resultant from the actual increases in soil C and N concentrations.

Chisel plow produces more soil disturbance and mixing than no-tillage. However, greater SOC and TN contents in 0–15 cm with no-tillage (Table 3) may have resulted from slow crop residue decomposition due to the placement of crop residue on the soil surface and the decreased contact of crop residue with soil microorganisms (Havlin et al., 1990; Salinas-Garcia et al., 1997; Schomberg and Steiner, 1999), or can be attributed to the reduced mineralization rate of soil organic matter due to decreased soil aeration and less exposure of SOC fractions within soil aggregates with no-tillage (Doran, 1980; Eghball et al., 1994). In contrast, incorporation of crop residue into the soil under chisel plow may have resulted in more rapid decomposition of crop residue, and thus lowered SOC and TN contents (Blevins et al., 1983; Doran, 1987). Meanwhile, no-tillage usually results in cooler and wetter soil conditions, which may also decrease the mineralization rate of soil organic matter. In addition, no-tillage can reduce soil erosion loss, thus conserving more SOC.

When SOC content at the 0–15 cm soil depth at harvest in 2000 were compared with the initial SOC value prior to experiment initiation in 1994, no-tillage increased SOC 1.4 and 1.2 Mg ha^{-1} yr^{-1} in the CNW and OMT soil association, respectively, and 0.7, 0.6, and 0.4 Mg ha^{-1} yr^{-1} in GPS, KFC, and M soil associations, respectively, during the 7-year period of the experiment (Tables 2 and 3). Changes in SOC among different soil associations were expected due to the differences in soil physical, chemical, and biological properties. In contrast, chisel plowing generally did not alter SOC during the 7-year period. Greater SOC and TN contents under no-tillage at the 0–15 cm soil depth in this experiment suggest that switching from chisel plowing to no-tillage improves soil C sequestration during the first 7 years. Reicosky et al. (1995) reported a similar trend that SOC increased 840 kg ha^{-1} yr^{-1} at the 0–15 cm soil depth averaged over several no-tillage experiments.

3.1.2. 5-tillage experiment

No significant differences in SOC or TN were observed among the five tillage treatments regardless of soil depth at the end of 3 years of tillage practices although the degrees of soil disturbance caused by these tillage systems were different (Table 3). However, strip-tillage and chisel plowing resulted in numerically greater SOC and TN contents than moldboard plowing at the 0–15 cm soil depth. The results of this experiment suggest that both SOC and TN contents may have a delayed response to conservation tillage systems, particularly to no-tillage. Similar results were reported by West and Post (2002) who observed that the response of soil C sequestration rate to no-tillage practices can be expected to have a delayed response, reach peak sequestration rates in 5–10 years, and then decline to near zero in 15–20 years, based on the analyses of a large global data set. No-tillage results in this experiment also agree with a review by Lal et al. (1998), based on the results from Franzluebbers and Arshad (1996) that there may be little to no increase in SOC in the first 2–5 years after a change from conventional tillage to no-tillage.

Compared with the initial SOC content prior to the establishment of this experiment in 1998 (Table 2), SOC content declined by 1.7 and 1.3 Mg ha^{-1} yr^{-1} with deep ripping and no-tillage treatments, respectively, but increased by 1.9 and 1.4 Mg ha^{-1} yr^{-1} with strip-tillage and chisel plowing systems, respectively. Because chisel plowing was the tillage system used on this field before the establishment of this experiment, our results suggest that changing chisel plowing to no-tillage cause no significant improvement in soil C sequestration during such a short period of time (3 years) after the tillage was changed. Similarly, the results show that continuous adoption of chisel plowing or switching chisel plowing to other tillage systems in addition to no-tillage caused no significant increase in SOC within the first 3 years.

3.2. Cropping system effects on soil C and N contents

Smooth bromegrass and switchgrass cropping systems resulted in substantially greater SOC content

Table 4
Cropping system effects on SOC and TN contents, soil C:N ratio, and BD after 10-year implementation of the cropping system experiment under no-tillage management[a]

Cropping system	0–15 cm				15–30 cm			
	SOC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N ratio	BD (g cm^{-3})	SOC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N ratio	BD (g cm^{-3})
Smooth bromegrass	47.1 a[b]	4.7 a	10.0 b	1.08 b	33.2 a	2.0 a	16.6 b	1.12 c
Switchgrass	40.7 a	2.4 b	17.0 a	1.25 a	26.3 a	0.8 b	32.9 a	1.17 b
Corn–soybean–alfalfa	26.7 b	2.1 b	12.7 b	1.27 a	17.0 b	0.8 b	21.3 b	1.29 a

[a] SOC, soil organic C; TN, total N; BD, bulk density.

[b] Values in column followed by the same letter are not significantly different at 0.05 probability level.

than a corn–soybean–alfalfa rotation at both soil depth intervals at the end of 10 years of cropping system establishment (Table 4). Soil organic C of smooth bromegrass system was 76% (20.4 Mg C ha^{-1}) and 95% (16.2 Mg C ha^{-1}) greater than that in a corn–soybean–alfalfa rotation at the 0–15, and 15–30 cm soil depths, respectively. Switchgrass increased SOC 52% (14.0 Mg C ha^{-1}) in the 0–15 cm soil layer, and 55% (9.3 Mg C ha^{-1}) in the 15–30 cm soil depth, compared with that with a corn–soybean–alfalfa rotation of the same depths, respectively. Similarly, smooth bromegrass system increased TN content 124% (2.6 Mg N ha^{-1}) in 0–15 cm, and 150% (1.2 Mg N ha^{-1}) in 15–30 cm, compared with that of a corn–soybean–alfalfa rotation. However, soil TN content did not differ between switchgrass and corn–soybean–alfalfa treatments regardless of soil depth. Interestingly, smooth bromegrass resulted in greater soil TN than switchgrass at both soil depths. Soil C:N ratio with smooth bromegrass and corn–soybean–alfalfa systems was lower than that of switchgrass at each soil depth.

Generally, perennial grass cropping systems maintain a more stable soil environment due to less soil disturbance than row cropping systems. This stable soil environment can contribute to the increased soil C sequestration in the perennial grass systems. The other factor that contributes to the greater SOC in the perennial grass systems is the extensive root system of the perennial grasses. Campbell et al. (1991) suggested that roots may be more important than aboveground crop residue in sustaining soil organic matter. We did not measure below ground biomass production in this experiment, but we agree that grass roots would be an important component in sustaining SOC.

The trend that smooth bromegrass seemed to have greater effects on SOC and TN than switchgrass may be due to the fact smooth bromegrass is a cool-season grass, while switchgrass is a warm-season grass. As a result, smooth bromegrass photosynthesizes from early spring through late fall; whereas switchgrass photosynthesizes only during the warmer months and then becomes dormant. Therefore, smooth bromegrass could allocate more C and N to the root system and subsequently returned more C and N to the soil over time. In addition, the difference in C:N ratio between the two perennial grass systems may be attributed to the fact that switchgrass is a C_4 plant, which is more efficient in fixing CO_2 than smooth bromegrass, which is a C_3 plant.

Smooth bromegrass and switchgrass systems increased SOC 2.3 and 1.2 Mg ha^{-1} yr^{-1} at the 0–15 cm soil depth compared with the initial SOC content at the beginning of experiment in 1991 (Tables 2 and 5), respectively. However, corn–soybean–alfalfa resulted in an increase in SOC of only 0.5 Mg ha^{-1} yr^{-1} during the 10-year period. This finding suggests that perennial grass cropping systems are more effective in sequestering soil C than row cropping systems, and smooth bromegrass seems to be more efficient than switchgrass in soil C sequestration in the Midwest. Similarly, Sharpley et al. (1983) reported a 42% lower SOC concentration in eight cultivated soils (26.0 g kg^{-1}) than their virgin analogues (15.1 g kg^{-1}) in different Major Land Resource Area's across the U.S.

3.3. Tillage effects on crop residue C and N inputs

A major factor contributing to changes in SOC and TN is the amount of C and N returned to the soil

Table 5
Tillage effects on annual C and N input from crop residue over the 3 and 7 year periods of the tillage experiments under a corn–soybean rotation[a]

Experiment	Soil association[b]	Treatment	Annual C input			Annual N input		
			Corn (Mg ha^{-1} yr^{-1})	Soybean (Mg ha^{-1} yr^{-1})	Average (Mg ha^{-1} yr^{-1})	Corn (kg ha^{-1} yr^{-1})	Soybean (kg ha^{-1} yr^{-1})	Average (kg ha^{-1} yr^{-1})
2-tillage	CNW	No-tillage	5.06 a[c]	1.15 a	2.82 a	70.6 a	24.1 a	44.0 a
		Chisel plowing	5.44 a	1.01 a	2.91 a	64.6 a	25.3 a	42.1 a
	GPS	No-tillage	4.11 a	0.76 a	2.20 a	57.4 b	25.3 a	39.0 b
		Chisel plowing	4.56 a	1.00 a	2.53 a	80.3 a	28.2 a	50.6 a
	KFC	No-tillage	5.83 b	1.76 a	3.50 a	71.5 a	46.3 a	57.1 a
		Chisel plowing	6.13 a	1.67 a	3.58 a	88.3 a	52.7 a	68.0 a
	M	No-tillage	6.41 a	1.51 a	3.61 a	104.5 a	53.9 a	75.6 a
		Chisel plowing	6.00 b	1.36 a	3.35 a	87.3 b	48.5 a	65.1 a
	OMT	No-tillage	5.96 a	1.73 a	3.54 a	55.3 b	50.8 a	52.7 b
		Chisel plowing	6.05 a	1.82 a	3.63 a	73.8 a	50.4 a	60.4 a
	Average	No-tillage	5.47 a	1.38 a	3.13 a	71.9 b	40.1 a	53.7 a
		Chisel plowing	5.64 a	1.37 a	3.20 a	78.9 a	41.0 a	57.2 a
5-tillage	CNW	No-tillage	6.08 bc	1.52 a	3.04 ab	60.6 a	42.3 a	48.4 a
		Strip-tillage	5.72 c	1.22 a	2.72 b	68.0 a	38.9 a	48.6 a
		Chisel plowing	6.29 abc	1.36 a	3.00 ab	74.2 a	39.9 a	51.3 a
		Deep ripping	6.58 ab	1.42 a	3.14 a	77.5 a	47.7 a	57.6 a
		Moldboard plowing	6.72 a	1.72 a	3.39 a	81.7 a	41.8 a	55.1 a

[a] There are three corn seasons and four soybean seasons in the 2-tillage experiment (1994–2000), and one corn season and two soybean seasons in the 5-tillage experiment (1998–2000). Annual C and N input under columns of corn, soybean, and average is referred to the input averaged over all corn seasons, all soybean seasons, and the weighted average input of all corn and soybean seasons, respectively.

[b] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; OMT, Otley-Mahaska-Taintor.

[c] Values in column within each soil association or averaged across the soil associations of the 2-tillage experiment or within the 5-tillage experiment followed by the same letter are not significantly different at 0.05 probability level.

through crop residue and roots each year. As C input from crop residue increases, SOC sequestration is expected to increase provided the added C is not lost as CO_2 to the atmosphere (Reicosky, 1997a, b).

3.3.1. 2-tillage experiment

Average annual C and N inputs from both corn and soybean crop residues during the 7 years of tillage practices were never greater for no-tillage than with chisel plowing in any soil association or averaged across the five soil associations (Table 5). This observation reflects that greater SOC and TN contents associated with no-tillage in this experiment (Table 3) were not due to the differences in annual C and N inputs from crop residue, but most likely due to the decreased mineralization rate of soil organic matter with no-tillage. In addition, lower annual N input with no-tillage than with chisel plowing in the GPS and OMT soil associations was related to the corn crop performance rather than soybean.

The amount of annual C and N inputs from crop residue was dependent on the amount of crop residue returned to the soil and C and N concentrations in crop residue. It was obvious in this experiment that there were almost no significant differences between no-tillage and chisel plowing in residue yield of corn and soybean, C concentration in corn residue, or C and N concentrations in soybean residue for each soil association or averaged across the five soil associations (Table 6). Similarly, corn or soybean yields of no-tillage and chisel plowing systems were not statistically different averaged over seven yr of tillage practices in a corn–soybean rotation in any of the five soil associations (Table 7); the results of this experiment are in agreement with previous findings from various long-term tillage studies across Iowa (Al-Kaisi and Yin, 2004; Yin and Al-Kaisi, 2004). These results further show that annual C and N inputs from crop residue were generally not affected significantly by the type of tillage system. However,

Table 6
Tillage effects on annual crop residue biomass and total C and N concentrations in biomass over the 3 and 7 year periods of the tillage experiments under a corn–soybean rotation[a]

Experiment	Soil association[b]	Treatment	Crop residue biomass			Concentration in corn residue		Concentration in soybean residue	
			Corn (Mg ha^{-1} yr^{-1})	Soybean (Mg ha^{-1} yr^{-1})	Average (Mg ha^{-1} yr^{-1})	C (g kg^{-1})	N (g kg^{-1})	C (g kg^{-1})	N (g kg^{-1})
2-tillage	CNW	No-tillage	11.61 a[c]	3.80 a	7.14 a	436.0 a	6.1 a	302.0 a	6.4 a
		Chisel plowing	12.41 a	3.90 a	7.54 a	438.0 a	5.2 b	259.1 a	6.5 a
	GPS	No-tillage	9.32 a	3.10 a	5.77 a	441.0 a	6.2 a	246.2 a	8.2 a
		Chisel plowing	10.33 a	2.98 a	6.13 a	441.3 a	7.8 a	335.8 a	9.5 a
	KFC	No-tillage	13.10 b	5.60 a	8.81 a	445.0 a	5.4 b	314.1 a	8.3 a
		Chisel plowing	13.84 a	5.53 a	9.09 a	442.7 a	6.4 a	302.2 a	9.5 a
	M	No-tillage	14.50 a	4.93 a	9.03 a	442.0 a	7.2 a	306.2 a	10.9 a
		Chisel plowing	13.64 a	4.90 a	8.65 a	440.3 a	6.4 b	276.5 a	9.9 a
	OMT	No-tillage	13.25 a	4.76 a	8.40 a	450.0 a	4.2 b	362.9 a	10.7 a
		Chisel plowing	13.49 a	4.99 a	8.64 a	448.7 a	5.5 a	365.8 a	10.1 a
	Average	No-tillage	12.36 a	4.44 a	7.83 a	442.8 a	5.8 b	306.3 a	8.9 a
		Chisel plowing	12.74 a	4.46 a	8.01 a	442.2 a	6.3 a	307.9 a	9.1 a
5-tillage	CNW	No-tillage	13.67 a	4.16 a	7.33 ab	451.3 a	4.5 a	404.3 a	11.7 a
		Strip-tillage	12.55 a	3.70 a	6.65 b	448.0 a	5.3 a	397.8 a	11.7 a
		Chisel plowing	14.12 a	3.99 a	7.36 ab	451.7 a	5.3 a	386.9 a	11.2 a
		Moldboard plowing	14.64 a	4.39 a	7.81 a	447.0 a	5.4 a	394.1 a	9.4 a
		Deep ripping	14.66 a	4.31 a	7.76 a	451.0 a	5.3 a	353.2 a	11.8 a

[a] There are three corn seasons and four soybean seasons in the 2-tillage experiment (1994–2000), and one corn season and two soybean seasons in the 5-tillage experiment (1998–2000). Annual crop residue biomass under columns of corn, soybean, and average is referred to the aboveground residue yield averaged over all corn seasons, all soybean seasons, and the weighted average residue yield of all corn and soybean seasons, respectively.

[b] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; OMT, Otley-Mahaska-Taintor.

[c] Values in column within each soil association or averaged across the soil associations of the 2-tillage experiment or within the 5-tillage experiment followed by the same letter are not significantly different at 0.05 probability level.

some significant differences were observed in N concentration of corn residue in most soil associations. The differences in annual N input averaged over corn and soybean between the two tillage systems in the GPS and OMT soil associations could be attributed to the differences in N concentration in corn residue.

3.3.2. 5-tillage experiment

Annual C input from crop residue averaged over the 3-year period of study in a corn–soybean rotation was significantly affected by tillage systems in the CNW soil association (Table 5). Strip-tillage received 0.67 Mg C ha^{-1} yr^{-1} less than moldboard plowing from crop residue. It seemed that the difference in annual C input between strip-tillage and moldboard plowing was related to the annual C input from both corn and soybean (Table 5). However, the decreased annual C input under strip-tillage relative to moldboard plowing did not transform to any reduction in SOC content (Table 3). Meanwhile, other tillage systems had similar annual C input as moldboard plowing. Annual N input from crop residue did not differ when no-tillage, strip-tillage, chisel plowing, and deep ripping were compared with moldboard plowing (Table 5). The results of annual C and N inputs confirm that the relationship between SOC and TN contents and annual C and N inputs from crop residue did not exist in such a short-term experiment.

Annual crop residue production using the weighted averages of corn and soybean residue was 15% lower under strip-tillage than moldboard plowing (Table 6). Similar trend was observed in annual corn and soybean crop residues (Table 6) and corn and soybean yields (Table 7) although the differences were statistically insignificant. On the other hand, C concentrations in both corn and soybean residues

Table 7
Tillage effects on corn and soybean yields averaged over the 3 and 7 year periods of the tillage experiments under a corn–soybean rotation[a]

Experiment	Soil association[b]	Treatment	Corn (Mg ha^{-1} yr^{-1})	Soybean (Mg ha^{-1} yr^{-1})
2-tillage	CNW	No-tillage	8.06 a[c]	2.49 a
		Chisel plowing	8.62 a	2.55 a
	GPS	No-tillage	6.47 a	2.03 a
		Chisel plowing	7.18 a	1.95 a
	KFC	No-tillage	9.09 a	3.67 a
		Chisel plowing	9.61 a	3.62 a
	M	No-tillage	10.07 a	3.23 a
		Chisel plowing	9.47 a	3.21 a
	OMT	No-tillage	9.19 a	3.12 a
		Chisel plowing	9.36 a	3.27 a
	Average	No-tillage	8.58 a	2.91 a
		Chisel plowing	8.85 a	2.92 a
5-tillage	CNW	No-tillage	9.49 a	2.79 a
		Strip-tillage	8.71 a	2.48 a
		Chisel plowing	9.80 a	2.67 a
		Deep ripping	10.17 a	2.89 a
		Moldboard plowing	10.16 a	2.94 a

[a] There are three corn seasons and four soybean seasons in the 2-tillage experiment (1994–2000), and one corn season and two soybean seasons in the 5-tillage experiment (1998–2000).

[b] CNW, Clarion-Nicollet-Webster; GPS, Galva-Primghar-Sac; KFC, Kenyon-Floyd-Clyde; M, Marshall; OMT, Otley-Mahaska-Taintor.

[c] Values in column within each soil association or averaged across the soil associations of the 2-tillage experiment or within the 5-tillage experiment followed by the same letter are not significant at 0.05 probability level.

were similar for strip-tillage and moldboard plowing (Table 6). Therefore, the difference in annual C input between strip-tillage and moldboard plowing (Table 5) could be attributed to the annual crop residue production rather than C concentration in crop residue.

4. Conclusions

Short-term tillage effects on SOC and TN contents occurred primarily in the 0–15 cm soil depth. Tillage effects on SOC and TN did not vary significantly with soil association. No-tillage resulted in greater SOC and TN contents at the 0–15 cm soil depth than chisel plowing at the end of 7 years of tillage practices averaged across the CNW, GPS, KFC, M, and OMT soil associations in a corn–soybean rotation. The increase in SOC and TN with no-tillage was not related to SOC and TN stratification in the soil profile or annual C and N inputs from crop residue, but most likely due to the decreased mineralization rate of soil organic matter. However, tillage effects on SOC and TN were negligible at the end of only 3 years of tillage practices for the CNW soil association in a corn–soybean rotation. Meanwhile, cropping systems of smooth bromegrass and switchgrass resulted in greater SOC and TN contents at the 0–15 cm, and 15–30 cm soil depths than a corn–soybean–alfalfa rotation after 10 years of management for the MIH soil association in no-tillage management. Smooth bromegrass and switchgrass systems increased SOC content 2.3 and 1.2 Mg ha^{-1} yr^{-1} at the 0–15 cm soil depth, respectively.

Our short-term results show that no-tillage was superior to chisel plowing with a corn–soybean rotation, and perennial smooth bromegrass and switchgrass systems were more effective than a corn–soybean–alfalfa rotation in sequestering soil SOC and TN with no-tillage management in Iowa. We conclude that from these short-term experiments reducing tillage intensity and adopting perennial grass cropping systems (particularly smooth bromegrass) could be effective strategies to improve soil C and N sequestration in Midwest soils.

Acknowledgments

We thank Dr. Antonio Mallarino, Department of Agronomy, Iowa State University and Dr. Mark Hanna, Department of Agricultural and Biosystem

Engineering, Iowa State University for their contributions to this study.

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