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Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn–soybean rotation

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Abstract

A wide range of tillage systems have been used by producers in the Corn-Belt in the United States during the past decade due to their economic and environmental benefits. However, changes in soil organic carbon (SOC) and nitrogen (SON) and crop responses to these tillage systems are not well documented in a corn–soybean rotation. Two experiments were conducted to evaluate the effects of different tillage systems on SOC and SON, residue C and N inputs, and corn and soybean yields across Iowa. The first experiment consisted of no-tillage (NT) and chisel plow (CP) treatments, established in 1994 in Clarion–Nicollet–Webster (CNW), Galva–Primghar–Sac (GPS), Kenyon–Floyd–Clyde (KFC), Marshall (M), and Otley–Mahaska–Taintor (OMT) soil associations. The second experiment consisted of NT, strip-tillage (ST), CP, deep rip (DR), and moldboard plow (MP) treatments, established in 1998 in the CNW soil association. Both corn and soybean yields of NT were statistically comparable to those of CP treatment for each soil association in a corn–soybean rotation during the 7 years of tillage practices. The NT, ST, CP, and DR treatments produced similar corn and soybean yields as MP treatment in a corn–soybean rotation during the 3 years of tillage implementation of the second experiment. Significant increases in SOC of 17.3, 19.5, 6.1, and 19.3% with NT over CP treatment were observed at the top 15-cm soil depth in CNW, KFC, M, and OMT soil associations, respectively, except for the GPS soil association in a corn–soybean rotation at the end of 7 years. The NT and ST resulted in significant increases in SOC of 14.7 and 11.4%, respectively, compared with MP treatment after 3 years. Changes in SON due to tillage were similar to those observed with SOC in both experiments. The increases in SOC and SON in NT treatment were not attributed to the vertical stratification of organic C and N in the soil profile or annual C and N inputs from crop residue, but most likely due to the decrease in soil organic matter mineralization in wet and cold soil conditions. It was concluded that NT and ST are superior to CP and MP in increasing SOC and SON in the top 15 cm in the short-term. The adoption of NT or CP can be an effective strategy in increasing SOC and SON in the Corn-Belt soils without significant adverse impact on corn and soybean yields in a corn–soybean rotation.

Keywords: Carbon input; Corn; Soil organic carbon; Soil organic nitrogen; Soybean; Tillage; Yield

Abbreviations: CNW, Clarion–Nicollet–Webster; GPS, Galva–Primghar–Sac; KFC, Kenyon–Floyd–Clyde; M, Marshall; OMT, Otley–Mahaska–Taintor; SOC, soil organic C; SON, soil organic N

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1. Introduction

Soil organic C (SOC) and N (SON) are important in sustaining soil quality, promoting crop production, and protecting the environment (Bauer and Black, 1994; Doran and Parkin, 1994; Robinson et al., 1994) due to their effects on water retention, soil aeration, nutrient cycling, and plant root growth (Sainju and Kalisz, 1990; Sainju and Good, 1993). Carbon and N losses from soil to the atmosphere as gases due to natural and management-induced causes can contribute to global warming (Reicosky, 1997a,b). However, soil can also function as a net sink for sequestering atmospheric CO_2 through appropriate soil and crop management, and thus attenuating the increase in atmospheric CO_2 (Paustian et al., 1992; Lal et al., 1995).

It has been well documented that soil can be managed to increase SOC and SON 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). In contrast, intensive tillage can reduce the storage of these two components, because it incorporates crop residue into the soil, disrupts soil aggregates, and increases soil aeration (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993). However, short-term (≤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 (NT) 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 six years or less when weather conditions were favorable.

Conservation tillage systems such as NT and strip-tillage (ST) have been increasingly used for crop production in the Corn-Belt during the past decade due to their significant environmental advantages over moldboard plow (MP). For example, NT systems in the Midwest were used in over 22% of all cropland area in 2002 (Conservation Technology Information Center, 2003), which almost doubled that in 1992. Deep rip (DR) is another tillage system used widely under the assumption of correcting soil compaction and increasing crop yields in the Corn-Belt. Although DR is not a conservation tillage system, it still results in less soil disturbance and mixing and greater crop residue coverage on the soil surface than moldboard plow. There have been few studies that quantify the effects of these major tillage alternatives on soil C and N changes and residue C and N inputs compared with MP in the Corn-Belt soils where a corn–soybean rotation is the primary cropping system.

Effects of soil and crop management practices on SOC and SON changes, 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, understanding the effects of management practices on SOC and SON of major soils in a specific agro-ecological and production area is essential in developing best management practices and prediction tools for SOC and SON management. Tillage practices and crop residue management can play a significant role in replenishing SOC and SON, but plant materials contain a wide range of C and N compounds that have different decomposition rates affected by many soil factors (Ajwa and Tabatabai, 1994). Thus, changes in soil moisture, temperature, oxygen content, pH, nutrient availability, and other soil factors can alter the decomposition rates of plant biomass and the mineralization rate of soil organic matter (Broadbent et al., 1964; Kowalenko et al., 1978; Clark and Gilmour, 1983). The question is whether short-term (≤10 years) implementation of conservation tillage practices and crop residue have advantages over conventional tillage in increasing SOC and SON sequestration in a corn–soybean rotation. Therefore, the primary objective of this study was to examine the short-term effects of major tillage alternatives on SOC and SON changes with depth, aboveground residue biomass C and N inputs, and corn and soybean yields compared with conventional tillage in a corn–soybean rotation.

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

Experiment	Location	Soil association[a]	Soil series	Classification
Two-tillage treatments	Kanawha	CNW	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
	Sutherland	GPS	Sac	Fine-silty, mixed, superactive, mesic Typic Hapludolls
			Primghar	Fine-silty, mixed, superactive, mesic Aquic Hapludolls
	Nashua	KFC	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
Five-tillage treatments	Ames	CNW	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
			Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
			Webster	Fine-loamy, mixed, superactive, mesic Typic Hapludolls

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

2. Materials and methods

2.1. Site description and experimental design

This study was designed to document the effects of different tillage systems on SOC and SON contents at different depths in the soil profile, aboveground biomass C and N inputs, and grain yield on six Iowa State University research farms. The experiments represented five major soil associations (Table 1).

The first experiment consisted of two-tillage treatments of no-tillage and chisel plow with three replicates, established in 1994 in Clarion–Nicollet–Webster (CNW), Galva–Primghar–Sac (GPS), Kenyon–Floyd–Clyde (KFC), Marshall (M), and Otley–Mahaska–Taintor (OMT) soil associations in a corn–soybean rotation, using a randomized complete block design (Table 1). Tillage practices were applied to both corn and soybean. The no-tillage was defined as no pre-plant tillage. The no-tillage crop was planted by using a planter with a single coulter to cut through crop residue and loosen the soil. The only soil disturbance associated with no-tillage was due to planting and fertilizer applications. The chisel plow treatment was conducted with a commercially available model with straight shanks and twisted sweeps. The shanks were mounted on four tool bars in a staggering order to ensure an effective spacing of 30 cm between shanks. The depth of tillage with chisel plow was 22–25 cm. Both corn and soybean were planted in 76-cm rows each season. Anhydrous ammonia was injected in the fall using a mole knife with two cover disks at 76 cm spacing between knives applying an actual N rate of 135 kg ha^{-1} for corn. Soybean did not receive any N fertilizer. No P or K fertilizer was applied to either corn or soybean based on soil test results. The plot size was 127 m × 38 m for both treatments. Chisel plow tillage and corn–soybean rotation were used prior to the experiment establishment on this site.

The second experiment consisted of five-tillage systems, which were established in 1998 on the Agronomy Research Farm in Boone County, West of Ames, Iowa. The tillage treatments consisted of no-tillage, strip-tillage, chisel plow, deep rip, and moldboard plow in the CNW soil association in a corn–soybean rotation with soybean planted in 1998 (Table 1). The layout of the experiment was a randomized complete block design with three replicates. Tillage practices were applied to both corn and soybean. The no-tillage and chisel plow treatments were the same as those applied to the two-tillage treatments experiment. The strip-tillage treatment plots were tilled 20 cm deep with an anhydrous knife centered between two cover disks 20 cm apart. The tilled zone was 20 cm wide and 10 cm high created in close proximity of the previous corn or soybean rows. The deep rip treatment was performed using a commercially available model with four straight shanks on 3 m long tool bar (three points). The spacing between straight shanks was 76 cm and the effective tillage depth with the straight shanks was 40–46 cm. The moldboard plow treatment utilized a commercially available model with four full bottoms 46 cm wide and 25 cm deep. Moldboard plow 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 operation 10 cm in depth prior to planting. Both corn and soybean were planted in a 76-cm row width each season. Anhydrous ammonia was injected using a mole knife with two cover disks in 76 cm spacing 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 according to the soil test results. The plot size was 230 m long and 64 m wide. Chisel plow and corn–soybean rotation were used in this field prior to the experiment establishment.

2.2. Soil and crop residue sampling and analysis

Soil sampling was conducted at the 0–15-cm soil depth for SOC and SON prior to treatment establishment in each experiment. Soil samples were taken from each location in 1994 for the two-tillage treatments experiment and in 1998 for the five-tillage treatments experiment. Thirty soil cores per sample were randomly collected from four replications with a 1.9 cm diameter soil probe after removing visible crop residue from the soil surface. Each sample was placed in a soil-sampling bag, and then stored indoor in a cooler at 4 °C. All samples were passed through a 2-mm sieve while still moist, and subsequently air-dried. Soil samples were collected after crop harvest in fall of 2000 at depth intervals of 0–5, 5–10, 10–15, 15–30, and 30–60 cm from each plot for SOC and SON analyses in both experiments. Ten to twelve soil cores per sample were randomly collected with a 1.9-cm diameter soil probe. Soil samples storage and processing procedures were the same as those used for the initial soil samples. Similar number of soil bulk density samples was taken in fall of 2000 from each plot using a core method with a copper cylinder 5 cm in height and 5 cm in diameter similar to that used by Culley (1993). The soil depth intervals for bulk density were the same as those for the soil samples for SOC and SON analyses. Bulk density was used to convert SOC and SON concentrations (g kg^{-1}) to mass per soil area (Mg ha^{-1}) within certain soil depth.

Three aboveground soybean residue samples were collected in 2000, and three aboveground corn residue samples were taken in 2001, from each plot in both the two-tillage treatments and five-tillage treatments experiments using a 1-m^2 frame after harvest and before any tillage operations. Residue samples were cleaned from any excess soil, oven-dried at 64 °C, weighed, and ground using a plant grinder with 2-mm sieve (Wiley Mill, Model 2 Pulverized Carbon Steel by Arthur H. Thomas CO., Philadelphia, PA, U.S.A.).

Soil organic C, N, and crop residue C and N concentrations were determined by dry combustion using a LECO CHN-2000 analyzer (St. Joseph, MI, U.S.A.). Soil pH was measured using a 1:1 (soil:water) suspension. Generally, soil samples with pH value greater than 7.1 were treated with 1 M HCl to eliminate any inorganic carbonates prior to SOC determination with dry combustion using the LECO CHN-2000 analyzer. Very few soil samples at the lower depths had a pH value >7.1. Therefore, SOC was assumed to be equal to the soil total C if soil pH is not greater than 7.1. Soil organic C and N concentrations were converted to mass per area (Mg ha^{-1}) for all depths intervals using a 15-cm soil depth equivalent.

Initial SOC and SON contents at the 0–15-cm soil depth at the establishment of each experiment (Table 2) were used as baseline values for determining temporal changes of SOC and SON due to tillage practices at the top 15 cm. Selected soil properties at the 0–15-cm soil depth at the time of sampling in fall 2000 are listed in Table 3.

Table 2
Initial SOC, SON, and BD at the top 0–15-cm soil depth for each experiment[a]

Experiment	Soil association	Sampling year	SOC (Mg ha^{-1})	SON (Mg ha^{-1})	BD (Mg m^{-3})
Two-tillage treatments	CNW	1994	44.6	3.3	1.22
	GPS	1994	35.7	2.9	1.21
	KFC	1994	38.0	4.4	1.31
	M	1994	30.3	2.5	1.11
	OMT	1994	38.9	3.1	1.18
Five-tillage treatments	CNW	1998	43.5	3.4	1.42

[a] SOC, soil organic C; SON, soil organic N; BD, bulk density; CNW, Clarion–Nicollet–Webster; GPS, Galva–Primghar–Sac; KFC, Kenyon–Floyd–Clyde; M, Marshall; OMT, Otley–Mahaska–Taintor.

Table 3
Selected soil properties (0–15 cm deep) at the time of soil sampling in fall of 2000 for each experiment

Experiment	Soil association[a]	Soil series	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	pH	Drainage class[b]
Two-tillage treatments	CNW	Canisteo	217	453	330	6.2	Poorly drained
	GPS	Sac	26	626	348	6.5	Well drained
		Primghar	26	626	348	6.5	Somewhat poorly drained
	KFC	Kenyon	342	415	243	5.7	Moderately well drained
	M	Marshall	18	691	291	6.0	Well drained
	OMT	Mahaska	15	638	347	6.2	Somewhat poorly drained
		Nira	15	638	347	6.5	Moderately well drained
Five-tillage treatments	CNW	Canisteo	100	600	300	7.9	Poorly drained
		Clarion	378	367	255	6.0	Well drained
		Webster	100	600	300	7.0	Poorly drained

[a] CNW, Clarion–Nicollet–Webster; GPS, Galva–Primghar–Sac; KFC, Kenyon–Floyd–Clyde; M, Marshall; OMT, Otley–Mahaska–Taintor.
[b] Information on drainage class was taken from county soil surveys of Iowa.

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

Estimation of annual crop residue biomass and C and N inputs were conducted for both experiments. Aboveground corn and soybean residue biomass was estimated by using annual grain yield and multiplying it by its harvest index. Grain yields of corn and soybean were measured each year for both experiments, and were adjusted to a 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).

Annual C and N inputs from aboveground crop residue refer to the respective amount of C and N in crop residue that is left on the soil surface after harvest and before any tillage implementation each year. The C and N inputs of a corn or soybean season were calculated by multiplying crop residue biomass by the organic C and N concentrations in crop residue of corn or soybean, respectively. Soybean residue C and N concentrations of 2000 and corn residue C and N concentrations of 2001 were used in determining residue inputs of C and N. The weather conditions and crop yields in 2000 and 2001 were typical of the average conditions of each location of both experiments.

2.4. Statistical analysis

Statistical analysis of the data was conducted by using a SAS statistical package (SAS Institute, 2002) for analysis of variance. For SOC and SON contents and bulk density in each experiment, the mixed procedure with repeated measures was used because soil depth interval was a non-randomized factor. For crop residue biomass, organic C and N concentrations of crop residue, and annual C and N inputs from crop residue, the mixed procedure was used for each experiment. Data within each experiment were analyzed separately for each location. Mean separations were achieved by using the least significant difference. The probability level of less than 0.05 was designated as significant. If there was a statistically significant interaction between tillage treatments and soil depths, then the main effect of tillage treatments that were involved in this interaction was not presented.

3. Results

3.1. Two-tillage treatments experiment

3.1.1. Corn and soybean yields

Corn yields of NT and CP treatments were not statistically different averaged over 7 years of tillage practices in a corn–soybean rotation in any of the five soil associations (Table 4). Numerically, NT reduced corn yield by 6.9, 11.0, and 5.7% in the CNW, GPS, and KFC soil associations, respectively, compared with CP treatment. However, NT increased corn yield by 6.3% in the M soil association, and produced almost identical corn yield in the OMT soil association relative to CP treatment. It seemed that NT system is more suitable in the M soil association for corn production than the CNW, GPS, and KFC soil associations. This greater suitability may be due to a better drainage condition with the M soil association (Table 3). Seven-year averages of soybean yields were almost identical for both tillage systems regardless of soil association (Table 4).

3.1.2. Annual crop residue C and N inputs

Similar to grain yields, NT produced a similar amount of crop residue biomass as CP treatment averaged over 7 years of tillage practices in the five soil associations (Table 5). Tillage systems did not have any affect on C concentration in either corn or soybean residue regardless of soil association (Table 5). On the other hand, N concentration in corn residue was 17 and 13% greater with NT treatment than CP treatment in the CNW and OMT soil associations, respectively (Table 5). In contrast, NT corn residue N concentration in KFC and M soil

Table 4
Tillage effects on corn and soybean yields averaged over the 3 or 7-year-period in a corn–soybean rotation[a]

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

[a] There are three corn seasons and four soybean seasons in the two-tillage treatments experiment (1994–2000), and one corn season and two soybean seasons in the five-tillage treatments 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 of the two-tillage treatments experiment or within the five-tillage treatments experiment followed by the same letter are not significantly different at $P < 0.05$.

Table 5
Tillage effects on annual corn and soybean crop residue biomass and organic C and N concentrations at the end of 3 or 7 years in a corn–soybean rotation[a]

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

[a] There are three corn seasons and four soybean seasons in the two-tillage treatments experiment (1994–2000), and one corn season and two soybean seasons in the five-tillage treatments experiment (1998–2000). Annual crop residue biomass under columns of corn, soybean, and average are referred to the aboveground residue yield averaged over all corn seasons, all soybean seasons, and 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 of the two-tillage treatments experiment or within the five-tillage treatments experiment followed by the same letter are not significantly different at $P < 0.05$.

associations was 16 and 24%, respectively, lower than that of CP treatment. Meanwhile, organic N concentration of soybean residue of the two-tillage treatments was not significantly different across all soil associations.

Average annual C inputs from both corn and soybean residue during the 7 years tillage practices of NT did not differ significantly from those of CP in any of the five soil associations (Figs. 1–5). Similarly, average residue N input with NT and CP treatments was the same for the CNW, KFC, and M soil associations, but NT reduced residue annual N input by 24 and 12% for the GPS and OMT soil associations, respectively (Figs. 1–5). In addition, soil bulk density values of both NT and CP treatments were not significantly different for each soil association (Table 6).

3.1.3. Soil organic C and N contents

Tillage effects on SOC content in the fall of 2000 varied significantly with soil depth at the end of 7 years of tillage practices in a corn–soybean rotation for most soil associations (Figs. 1–5). In the CNW soil association, NT resulted in significantly greater SOC content (15–21%) than CP treatment at the 0–5 and 5–10-cm soil depths (Fig. 1). The CNW soil association is characterized as having a nearly level to gently sloping, poorly drained, and dark clay loam surface and subsoil substratum (Table 3).

No significant difference in SOC between NT and CP treatments was observed for the GPS soil association regardless of depth interval (Fig. 2). The non-significant tillage effects on SOC in this soil association can be attributed to the characteristics of Primghar soil series, as level to gently sloping and somewhat poorly drained

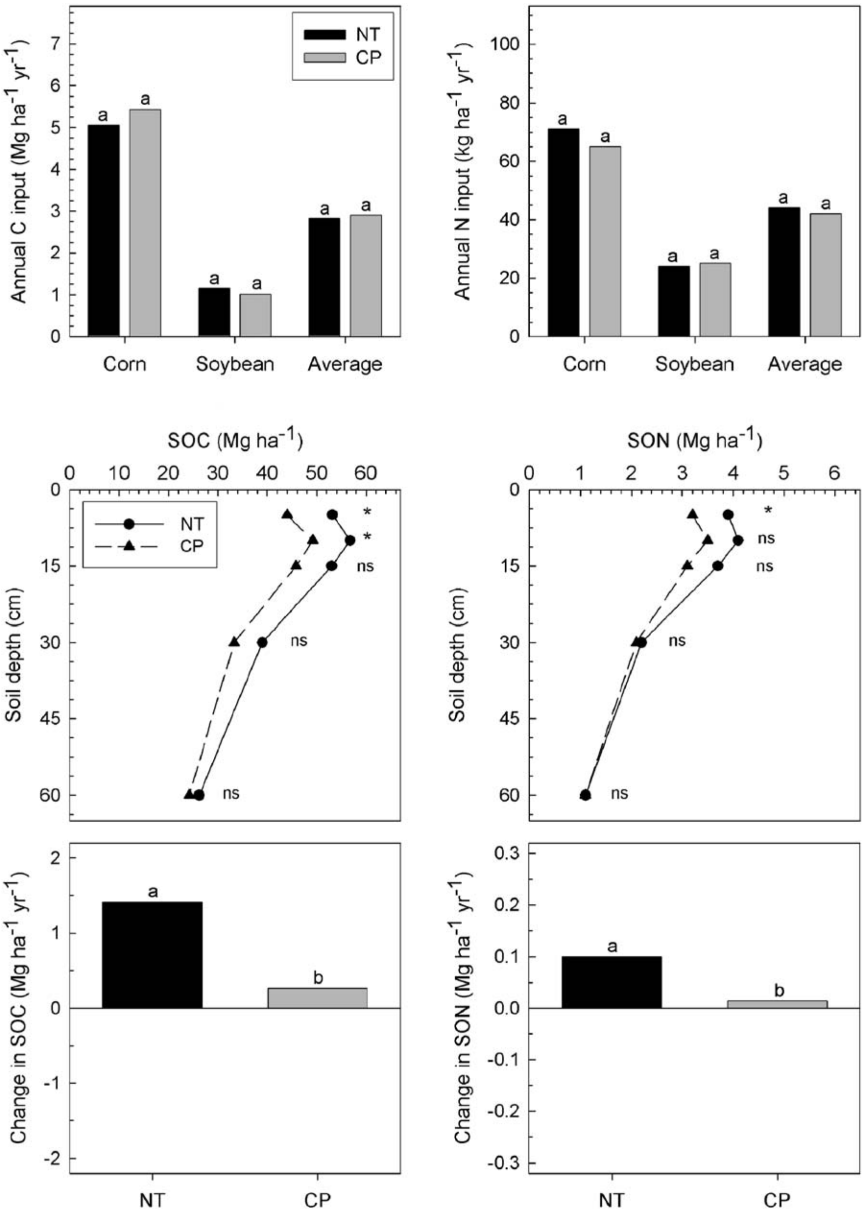

Fig. 1. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the CNW soil association over the 7-year-period with a corn–soybean rotation. CNW, Clarion–Nicollet–Webster; SOC, soil organic C; SON, soil organic N; NT, no-tillage; CP, chisel plow. There are three corn seasons and four soybean seasons over the 7-year-period (1994–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

that are dominant in this soil association at this site. Thus, short-term changes in SOC due to tillage were negligible due to minimum soil erosion and poor drainage for potential soluble C leaching.

Soil organic C contents at the 5–10 and 10–15-cm soil depths were 25% greater with NT treatment than with CP treatment in the KFC soil association (Fig. 3), which is moderately well drained and formed on

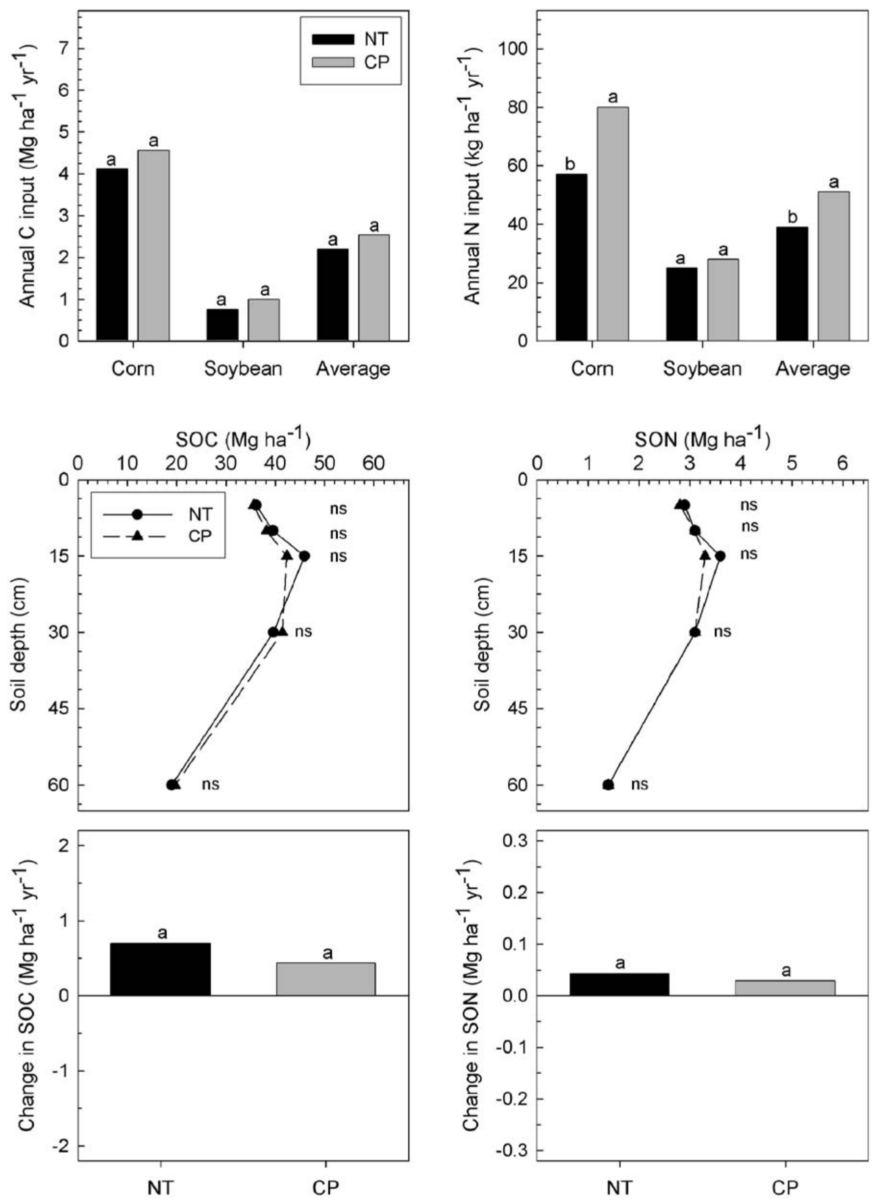

Fig. 2. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the GPS soil association over the 7-year-period with a corn–soybean rotation. GPS, Galva–Primghar–Sac; SOC, soil organic C; SON, soil organic N; NT, no-tillage; CP, chisel plow. There are three corn seasons and four soybean seasons over the 7-year-period (1994–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

loamy sediments (Table 3). However, SOC of NT treatment at 0–5-cm soil depth of M and OMT soil associations was 47 and 32%, respectively, greater than that of CP treatment (Figs. 4 and 5). The dominant soils series within these two soil associations are Marshall and Mahaska, silty clay loam well- to moderately-well drained and somewhat poorly drained soil series, respectively (Table 3).

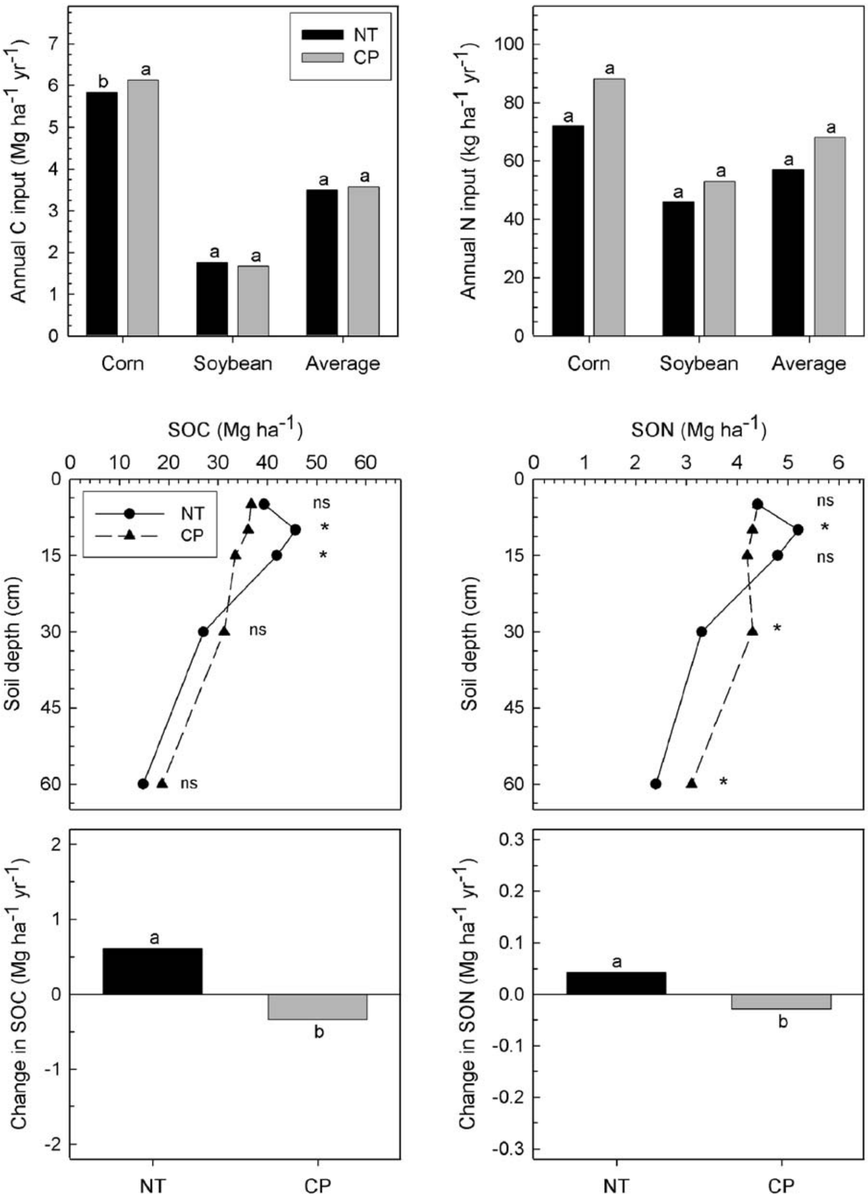

Fig. 3. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the KFC soil association over the 7-year-period with a corn–soybean rotation. KFC, Kenyon–Floyd–Clyde; SOC, soil organic C; SON, soil organic N; NT, no-tillage; CP, chisel plow. There are three corn seasons and four soybean seasons over the 7-year-period (1994–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

Similar to SOC, SON changes due to tillage effect also varied with soil depth in most soil associations (Figs. 1–5). In the CNW soil association, SON content was 22% greater with NT treatment than CP treatment at the 0–5-cm soil depth (Fig. 1). However, SON did not differ significantly between NT and CP treatments in the GPS association regardless of soil depth (Fig. 2). Soil organic N of NT treatment was about 21% greater

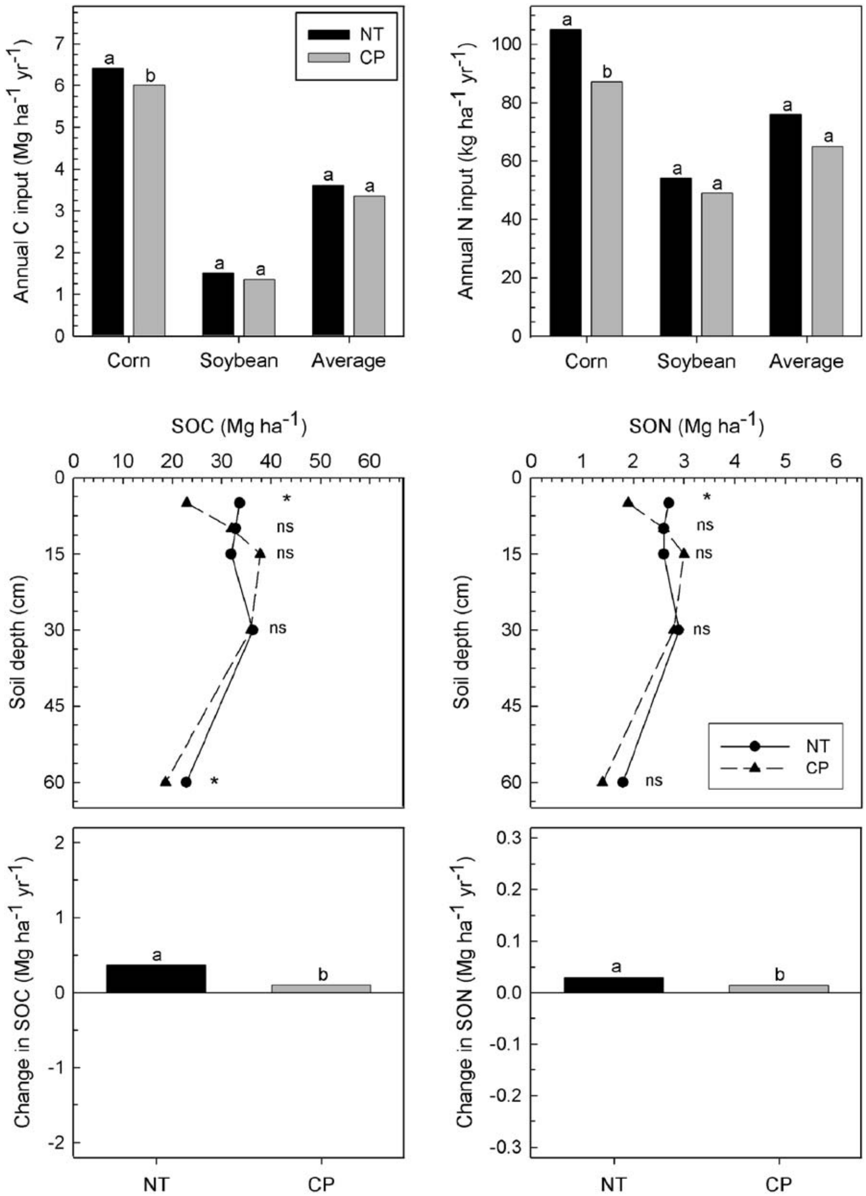

Fig. 4. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the M soil association over the 7-year-period with a corn–soybean rotation. M, Marshall; SOC, soil organic C; SON, soil organic N; NT, no-tillage; CP, chisel plow. There are three corn seasons and four soybean seasons over the 7-year-period (1994–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

in 5–10 cm, but 23% lower at the 15–30 and 30–60-cm soil depths, than that of CP treatment in the KFC soil association (Fig. 3). The SON content of M and OMT soil associations in NT increased by 42 and 38% at the 0–5-cm soil depth compared with CP treatment, respectively (Figs. 4 and 5). A similar trend in SOC and SON changes within the same tillage system in all the soil associations can be explained that organic C and N pools are biologically linked and are affected equally by tillage practices.

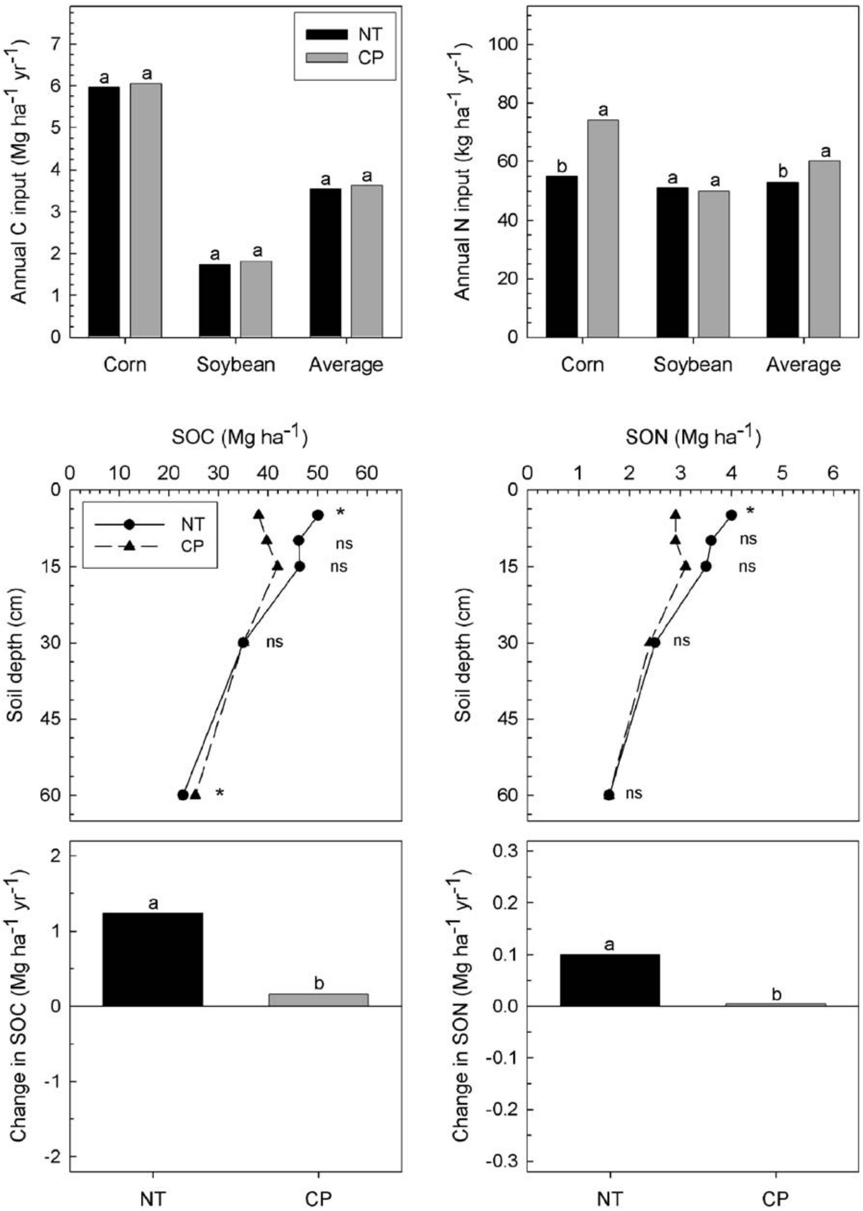

Fig. 5. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the OMT soil association over the 7-year-period with a corn–soybean rotation. OMT, Otley–Mahaska–Taintor; SOC, soil organic C; SON, soil organic N; NT, no-tillage; CP, chisel plow. There are three corn seasons and four soybean seasons over the 7-year-period (1994–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

3.1.4. Temporal changes in soil organic C and N contents

In NT treatment, SOC at the 0–15-cm soil depth had been increased from 1.24 to 1.41 Mg ha^{-1} year^{-1} in the CNW and OMT soil associations, and from only 0.37 to 0.70 Mg ha^{-1} year^{-1} in the GPS, KFC, and M associations, over 7 years from 1994 to 2000 (Figs. 1–5). Chisel plow treatment consistently resulted in

Table 6
Tillage effects on BD at different soil depths (cm) at the end of 3 or 7 years of tillage system implementation[a]

Experiment	Soil association	Tillage system	BD 0-5 ($Mg\ m^{-3}$)	5–10 ($Mg\ m^{-3}$)	10–15 ($Mg\ m^{-3}$)	15–30 ($Mg\ m^{-3}$)	30–60 ($Mg\ m^{-3}$)
Two-tillage treatments	CNW	No-tillage	1.19 a[b]	1.23 a	1.31 a	1.30 a	1.31 a
		Chisel plow	1.03 b	1.29 a	1.33 a	1.27 a	1.30 a
	GPS	No-tillage	1.14 a	1.22 a	1.26 a	1.35 a	1.31 a
		Chisel plow	1.11 a	1.23 a	1.29 a	1.31 a	1.30 a
	KFC	No-tillage	1.22 a	1.44 a	1.40 a	1.48 a	1.44 a
		Chisel plow	1.24 a	1.28 a	1.40 a	1.45 a	1.43 a
	M	No-tillage	1.10 a	1.17 a	1.10 a	1.09 a	1.10 a
		Chisel plow	0.99 a	1.19 a	1.14 a	1.13 a	1.14 a
	OMT	No-tillage	1.22 a	1.31 a	1.31 a	1.36 a	1.34 a
		Chisel plow	1.01 a	1.25 a	1.26 a	1.32 a	1.29 a
Five-tillage treatments	CNW	No-tillage	1.28 a	1.46 a	1.45 a	1.60 a	1.53 a
		Strip-tillage	1.26 a	1.38 a	1.38 a	1.44 a	1.41 a
		Chisel plow	1.19 a	1.53 a	1.54 a	1.54 a	1.54 a
		Deep rip	1.30 a	1.44 a	1.43 a	1.48 a	1.46 a
		Moldboard plow	1.31 a	1.38 a	1.37 a	1.53 a	1.45 a

[a] BD, bulk density; CNW, Clarion–Nicollet–Webster; GPS, Galva–Primghar–Sac; KFC, Kenyon–Floyd–Clyde; M, Marshall; OMT, Otley–Mahaska–Taintor.

[b] Values in column within each soil association of the two-tillage treatments experiment or within the five-tillage treatments experiment followed by the same letter are not significantly different at $P < 0.05$.

much lower increase in SOC than NT treatment over the 7-year-period for each soil association. Temporal SON changes due to tillage were similar to those observed in SOC (Figs. 1–5).

3.2. Five-tillage treatments experiment

3.2.1. Corn and soybean yields

Although there was no statistical significant difference in corn or soybean yield among the five-tillage treatments averaged over the 3-year-period of tillage practices (Table 4), NT, ST, and CP treatments produced numerically lower corn and soybean yields than MP treatment in the CNW soil association. However, DR treatment had almost the same yields as MP treatment. The fact that Canisteo and Webster soil series within the CNW soil association are dominant at this site with poorly drained conditions may contribute to the slightly poor corn and soybean performance with NT and ST treatments at this site.

3.2.2. Annual residue C and N inputs

In general, ST produced significantly less residue biomass of corn and soybean than MP treatment (Table 5), while others produced similar biomass to MP treatment over the 3-year-period of tillage practices. However, organic C and N concentrations of both corn and soybean residue did not differ significantly among the five-tillage treatments (Table 5).

Average annual organic C input from above-ground crop residue over the 3-year-period of the experiment in a corn–soybean rotation was significantly affected by the tillage system used in this soil association (CNW) (Fig. 6) and total amount of residue associated with these five-tillage systems rather than organic C and N concentrations. Therefore, the amount of organic C returned to soil with ST was 0.67 $Mg\ ha^{-1}\ year^{-1}$ less than that of MP treatment. However, other tillage systems had similar annual organic C input to MP treatment. In contrast, annual organic N input from crop residue did not differ among the five-tillage systems (Fig. 6). Overall, these results confirm that the increase in SOC and SON contents are not linked directly to annual C and N inputs from crop residue during such a short period (3 years) in the five-tillage treatments experiment.

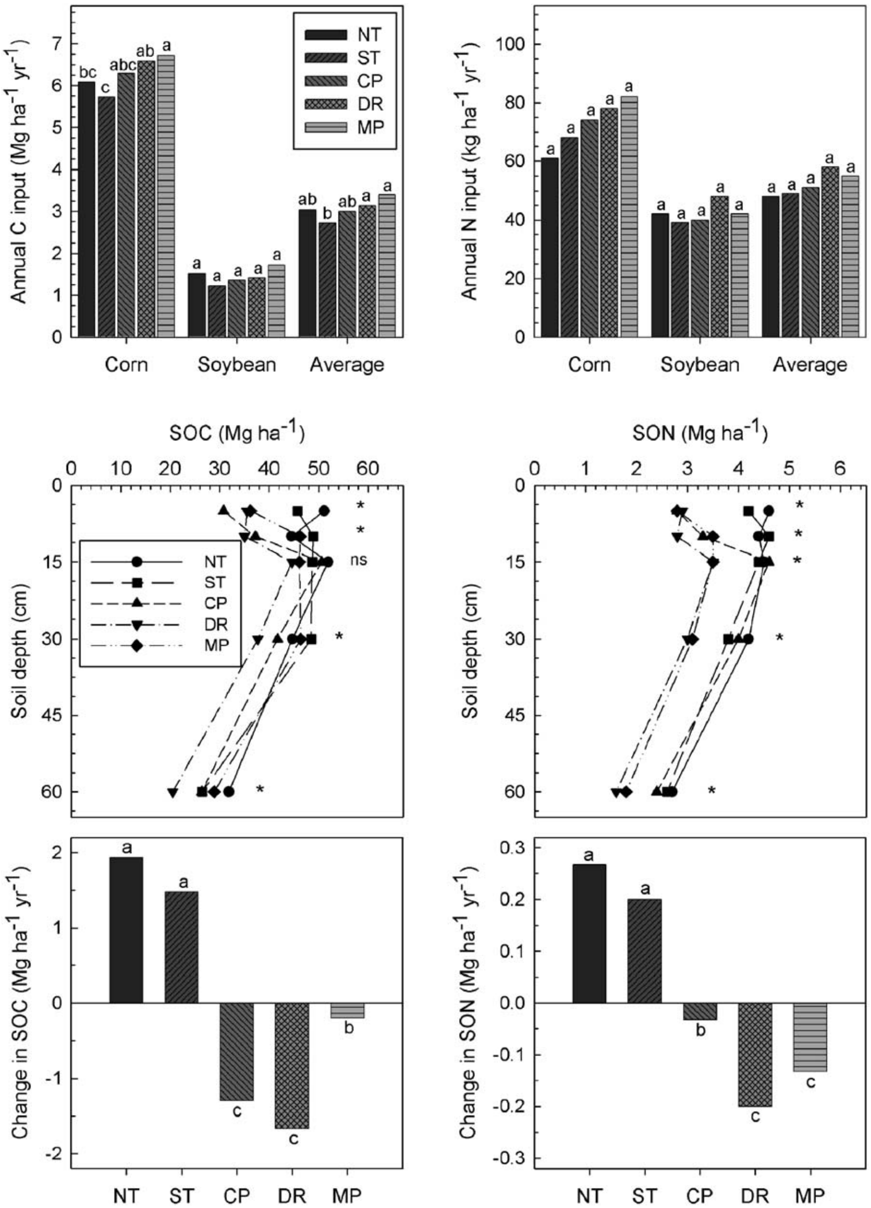

Fig. 6. Tillage effects on annual C and N inputs from crop residue, SOC and SON contents, and temporal changes in SOC and SON in the CNW soil association over the 3-year-period with a corn–soybean rotation. CNW, Clarion–Nicollet–Webster; SOC, soil organic C; SON, soil organic N; NT, no-tillage; ST, strip-tillage; CP, chisel plow; DR, deep rip; MP moldboard plow. There are one corn season and two soybean seasons over the 3-year-period (1998–2000). Annual C and N inputs of corn, soybean, and average are referred to the annual input averaged over all corn seasons, all soybean seasons, and all corn and soybean seasons, respectively. Bars within each small chart followed by the same letter are not significantly different at $P < 0.05$.

3.2.3. Soil organic C and N contents

No-tillage and ST treatments increased SOC content by 41 and 26% at the top 0–5-cm soil depth compared with MP treatment over the 3-year-period for the CNW soil association (Fig. 6). However, no significant difference in SOC content was observed between CP and MP treatments regardless of soil depth interval. Deep rip treatment resulted in significantly lower SOC than MP treatment at the 5–10, 15–30, and 30–60-cm soil depths.

Soil organic N content with both NT and ST treatments was greater than that with MP treatment at each soil depth interval (Fig. 6). Chisel plow treatment resulted in greater SON content than MP treatment at the 10–15, 15–30, and 30–60-cm soil depths. However, differences between DR and MP treatments were significant only at the 5–10-cm soil depth, where SON content with DR treatment was lower.

3.2.4. Temporal changes in soil organic C and N contents

Soil organic C since the establishment of these treatments in 1998–2000, at the 0–15-cm soil depth increased by 1.93 and 1.47 Mg ha^{-1} $year^{-1}$ with NT and ST treatments, respectively (Fig. 6). The results suggest that changing tillage system from the initial tillage system, CP, to NT or ST system resulted in an increase in SOC content during the 3-year-period. Similar trends were observed in SON changes.

4. Discussion

4.1. Two-tillage treatments experiment

Our results showed more consistent yield in soybean than corn with NT and the greater dependence of NT corn performance on the drainage condition of the soil association compared with NT soybean. These results are in agreement with previous findings from various long-term tillage studies across Iowa (Al-Kaisi and Yin, 2004; Yin and Al-Kaisi, 2004).

The annual organic C and N inputs averaged over corn and soybean residue for NT treatment during the 7 year of tillage practices were not greater than those of CP treatment for any of the five soil associations. Therefore, the increases in SOC and SON contents at the top 0–15-cm depth with NT in this experiment (in the short-term) were not due to the differences in annual organic C and N inputs from crop residue, rather due to tillage effect. On the other hand, SOC and SON at the 15–30-cm soil depth for both NT and CP treatments were similar. The similarity in SOC and SON values at the 15–30-cm soil depth in both tillage systems is highly related to the depth of tillage effect with CP, where the effective tillage disturbance was in the top 15 cm only. In addition, soil bulk density values of both NT and CP treatments were not significantly different for each soil association (Table 6). Therefore, tillage effect on SOC and SON contents was most likely due to the changes in SOC and SON concentrations. Overall, greater SOC and SON contents at the 0–15-cm soil depth with NT treatment were most likely due to the decrease in soil disturbance and thus reduced mineralization rate of soil organic matter.

It is well known that CP causes more soil disturbance and mixing, and thus greater incorporation and decomposition of crop residue into the soil than NT treatment. Therefore, greater SOC and SON contents at the 0–15-cm soil depth under NT treatment (Figs. 1–5) may have resulted from slower crop residue decomposition due to the placement of crop residue on the soil surface and the decreased contact with soil microorganisms (Havlin et al., 1990; Salinas-Garcia et al., 1997; Schomberg and Steiner, 1999). Also, NT may cause reduction in organic matter mineralization due to wetter and cooler soil conditions, decreased soil aeration, and less exposure of organic C fractions within soil aggregates (Doran, 1980; Eghball et al., 1994). In addition, NT reduces soil erosion loss, thus reducing organic C losses. In contrast, crop residue incorporation into the soil with CP may have resulted in a rapid decomposition of crop residue, causing lower SOC and SON contents (Blevins et al., 1983; Doran, 1987).

Overall, NT treatment increased SOC and SON contents in most soil associations, but CP treatment generally did not alter these two parameters during the 7-year-period (Figs. 1–5). These results suggest that switching from CP tillage, which was the primary tillage system to NT system over the 7-year-period contributed to the increase of SOC and SON in the top 15 cm. Kladivko et al. (1986) reported a SOC increase of 0.93 Mg ha^{-1} $year^{-1}$ at the 0–7.5-cm soil depth with NT system over conventional tillage in a corn–soybean rotation at the end of 7 year of implementation in Indiana. Soil organic C increase of 0.85 Mg ha^{-1} $year^{-1}$ at the 0–30-cm soil depth was reported due to the shift from conventional tillage to NT in a corn–soybean rotation over 18 years in Ohio (Dick et al., 1997). Our results of temporal organic C changes are similar to those reported by Dick et al. (1997) and Kladivko et al. (1986) if the results are compared by using the same soil depth equivalent. Soil organic C and N changes over 7 years are most likely a function of tillage system effect rather than biomass C input, since neither NT yield nor dry matter production were statistically different from those of CP treatment.

4.2. Five-tillage treatments experiment

The average annual C and N input results (Fig. 6) do not agree with the report by Sherrod et al. (2003) that annual stover biomass explained 80% of the variation in SOC averaged over all cropping systems, potential evapotranspiration sites, and slope positions. This disagreement may be due to the fact that our experiments lasted only for 3 years, as compared with their experiment of 12 years.

The annual SOC increase during the 3-year-period in the five-tillage treatments experiment (Fig. 6) is similar to the SOC increase of 0.93 Mg ha^{-1} $year^{-1}$ at the 0–7.5-cm soil depth reported in Indiana due to shifting from conventional tillage to NT with a corn–soybean rotation during the first 7 years of implementation (Kladivko et al., 1986). Our results suggest that increases in SOC and SON in this soil association (CNW) were a function of tillage system effect rather than organic C and N inputs from residue biomass, since NT and ST residue biomass was lower than that of MP treatment.

Overall, our short-term tillage results of both experiments confirm the potential of adopting less intensive tillage alternatives such as NT and ST over CP, or more intensive tillage systems in increasing SOC and SON stocks even from a short-term perspective. Increasing C storage in the soil will reduce atmospheric CO_2, thereby partially attenuating the current increase in atmospheric CO_2. Therefore, it is obvious that the adoption of less intensive tillage systems will be beneficial in mitigating global warming.

5. Conclusions

Both corn and soybean yields of NT were statistically comparable to those of CP treatment for the CNW, GPS, KFC, M, and OMT soil associations in a corn–soybean rotation during the 7 years of tillage practices. No-tillage, ST, CP, and DR treatments resulted in similar corn and soybean yields as MP treatment in the CNW soil association in a corn–soybean rotation during the 3 years of tillage implementation. Significant increases in SOC with NT treatment over CP treatment were observed at the top 15-cm soil depth in all the soil associations except the GPS soil association. No-tillage treatment increased SOC by 17.3, 19.5, 6.1, and 19.3% averaged over the 0–15-cm soil depth in the CNW, KFC, M and OMT soil associations, respectively, compared with CP treatment in a corn–soybean rotation at the end of 7 years. It appeared that NT and ST treatments resulted in significantly similar increases in SOC of 14.7 and 11.4%, respectively, compared with MP treatment after a short period (3 years) of tillage implementation. It was also observed that changes in SON due to tillage were similar to those in SOC in both experiments. It appeared that the increase in SOC and SON with NT treatment compared with CP or MP treatments was not related to vertical SOC and SON stratification in the soil profile or annual C and N inputs from crop residue. Rather, it was due to tillage system effect. Therefore, the positive changes in SOC at the top 0–15-cm soil depth with NT treatment may be attributed most likely to the decrease in soil organic matter mineralization rate. It is highly possible using less intensive tillage alternatives such as NT and ST over CP, or more intensive tillage systems can be an effective strategy in improving SOC and SON stocks in a corn–soybean rotation in the Corn-Belt soils without significant adverse impact on corn and soybean yields. Furthermore, it may be feasible to implement C credit programs that base payments on measurable increases in SOC content at the top 0–15-cm soil depth over a certain short period (3–7 years) in the Corn-Belt soils.

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