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Tillage Effects on Soil Quality Indicators and Nematode Abundance in Loessial Soil under Long-Term No-Till Production

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Abstract: Soil quality indicators and nematode abundance were characterized in a loessial soil under long-term conservation tillage to evaluate the effects of no-till, double-disk, chisel, and moldboard plow treatments. Indicators included soil electrical conductivity (EC), soil texture, soil organic matter (SOM), and total particulate organic matter (tPOM). Nematode abundance was positively correlated with EC, silt content, and total POM and negatively correlated with clay content. Clay content was the main source of variation among soil quality indicators and was negatively correlated with nematode abundance and most indicators. The gain in SOM in the no-till system amounted to 10887 kg over the 24 years or 454 kg ha^{-1} $year^{-1}$, about half of this difference (45%) resulting from soil erosion in plowed soils. The balance of gain in SOM with no till (249 kg ha^{-1} $year^{-1}$) was due to SOM sequestration with no till. No-till

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management reduced soil erosion, increased SOM, and enhanced soil physical characteristics.

Keywords: Loess, nematode abundance, no-till, soil quality, tillage

INTRODUCTION

Identification of soil quality indicators and assessment approaches is complicated by multiple physical, chemical, and biological factors and their temporal and spatial variation. Practical assessment of soil quality, however, requires consideration of these multiple factors and their variation in time and space (Larson and Pierce 1991). Producers, researchers, and policy makers are interested in an integrative soil quality index to monitor changes over time. Obviously, there are numerous soil properties that change in response to changes in management practice and land use, some of which are highly sensitive, whereas others are more subtle (Bezdicek, Papendick, and Lal 1996). On the other hand, nematode faunae in agroecosystems and their relationship to soil processes suggest that they are potential bioindicators (Yeates and Bongers 1999). For example, laboratory experiments and field studies have demonstrated that nematodes that feed on bacteria and fungi play important roles in influencing turnover of the soil microbial biomass and thus the availability of plant nutrients (Bardgett et al. 1999). However, the literature searched indicates that the effects of changes in agricultural practices on nematode community structure can produce contradictory results.

Soil quality indicators included in this study (2005) are electrical conductivity (EC), soil reaction (pH), soil organic matter (SOM), particulate organic matter (POM), total nitrogen (N), total carbon (C), ammonium (NH_4^+), nitrate (NO_3^-), water-filled pore space (WFPS), water-stable aggregates (WSA), soil texture (% clay, sand, and silt), mechanical resistance, soil water infiltration, soil respiration, and nematode abundance.

This study was conducted within a long-term conservation tillage project at the Rogers Memorial Farm near Lincoln, Nebraska, under sorghum–soybean cropping rotation. In 2005, corn replaced sorghum after 20 years, to start a new crop rotation. The soil series originally mapped at the site was the Sharpsburg silty clay loam in the county soil survey (Brown et al. 1980), classified as fine, smectitic, mesic Typic Argiudoll. The objectives were (1) to characterize the effects of no tillage, double disk, chisel, and moldboard plow on soil quality indicators and (2) to examine the indicators' relationship with nematode abundance. Because soil tillage is usually a combination of disturbances, we expected to find both higher nematode abundance in no-till plots and positive relationships between nematode abundance and soil quality indicators, particularly soil EC, soil texture, SOM, POM, and aggregate stability.

MATERIALS AND METHODS

Characteristics of the Experimental Site

This research was conducted at the University of Nebraska–Lincoln, Rogers Memorial Farm, 9 km east of Lincoln, located at the west upland (0–3% slope) 40° 84′ 65″ N and 96° 47′ 19″ W, in approximate area of 3,780 m^2 (54 m × 70 m). The soil morphology was typical of the Sharpsburg soil series, a fine, smectitic, mesic Typic Argiudolls. Current taxonomy was verified in the official soil description at this NRCS web site, www.http://ortho.ftw.nrcs.usda.gov/osd/, in November 2005. However, using the soil profile description and the current soil taxonomy keys (Soil Survey Staff 1999), we classified the soil in the no-till and moldboard plow plots as a fine, smectitic, mesic Typic Hapludolls and in the double-disk and chisel plots as a fine, smectitic, mesic Mollic Hapludalfs because of erosion of the A horizon. Erosion and loss of a portion of the A horizon in the cultivated areas of eastern Nebraska has produced many acres of Mollisols that would now classify as Alfisols (Olson et al. 2005). Lime has been spread on the plot surface without incorporation in fall 1997, 1999, and 2001 at a rate of 4.95 tons per hectare to correct pH (personal communication, Paul Jasa, July 2006). Annual precipitation and temperature in the area are 719.32 mm and 10.88 °C, based on data from Havelock Nebraska station (A254699) since 5 May 1983. (High Plain Regional Climate Center 2005).

Description of the Rogers Farm Tillage Experiment

The experimental site was established in 1981 in small plots 9 m wide (12 rows spaced 76 cm apart) by 23 m long. Six treatments were arranged in a randomized complete block design with three replicates, with grain sorghum and soybean grown in the rotation until 2004. In 2005, corn was planted into the soybean residue, using the same moldboard plow, chisel plow, and tandem disk every year. Typical operation depths and speeds were used every year, and no insecticides were used in any year. Anhydrous ammonia was applied preplant at 157.2 kg ha^{-1} (140 lbs/A) on 4 April. Crop cultivation was once on 15 June, except on the no-till treatment (Table 1).

This study (soil quality indicators 2005) includes four of the six tillage treatments (1) no-till (NT), where the soil is left undisturbed after harvest, with pre- and postemergent herbicide application in spring and two soil disturbance operations for planting and knife application of NH_3; (2) double disk (DD), which included five soil disturbing operations, two diskings after preplant herbicide application in spring,

Table 1. Operations for the tillage planting systems and annual schedule, Rogers Memorial Farm, 2005 (personal communication, Paul Jasa and Stu Hoff, November, 2005)

Operations	Tillage depth[a]	No till	Double disk	Chisel	Plow	Date
Fall moldboard plow	20.3				X	10 Nov.
Fall chisel plow	30.5			X		10 Nov.
Knife apply NH_3	15.2	X	X	X	X	4 April
Apply herbicide 1		X	X	X	X	11 April
Disk 1	15.2		X		X	31 March
Disk 2	15.2		X	X	X	17 April
Plant	5.08	X	X	X	X	28 April
Apply herbicide 2		X	X	X	X	28 May
Apply herbicide 3		X	X	X	X	7 June
Crop cultivate	7.6		X	X	X	15 June
Harvest		X	X	X	X	30 Sep.

[a]Soil depth disturbance by tillage in centimeters.

three soil disturbing operations for planting and knife-applied NH_3, and a crop cultivation in June; (3) single chisel (CH), including one operation after harvest (fall chisel plow) plus disk operations performed in treatment 2 for a total of five soil disturbing operations, and (4) plow operation (PL), which included fall moldboard plow, plus the operation performed in treatment 2, for a total of six tillage soil operations. All harvesting was by a combine harvester, and the grain was weighed with a weigh wagon. For statistical comparisons for this 2005 soil quality study, the no-till system was the control treatment.

Soil Sampling Protocol for the 2005 Soil Quality Project

Soil samples were collected in the spring, summer, and fall, previous to and during tillage management and corn cropping operations in 2005. In April, soil was sampled to a depth of 7.5 cm using a composite of six 7.4-cm-diameter field cores, randomly taken within each plot. In June, three soil cores were taken from in-row (25% area), six from interrow (50% area), and three from the wheel track interrow by each plot with an Oakfield probe (1.74 cm diameter) at three depth increments (0–7.5, 7.5–15, and 15–30 cm). In September, a composite of six 1.74-cm-diameter field cores were sampled from plant rows to a depth of 15 cm. The minimum soil volume for the soil laboratory analysis was 108 cm^3. The sampled row area represents about 25% of the surface area for 76-cm row spacing. For nematode sampling, soil cores were taken 7.5 cm from a plant in a circular pattern, because this was considered to be the plant-affected area (rhizosphere) for soil nematodes. A total of 36 samples were taken from three replications of four treatments and three depths within each plot. Some soil properties were evaluated in the field using "field soil quality kit" tools developed by Doran (1999). Soil infiltration determinations were duplicated in each row location (six per plot) by inserting two 7.5-cm-diameter cylinders in track, interrow, and row areas. After adding two 2.54-cm increments of distilled water, the samples were allowed to drain freely for 24 h and then sampled for field water-holding capacity. These rings, and intact soils, were dug up in the field and transported to the USDA/ARS/LAB, where they were covered with plastic after carbon dioxide (CO_2) detection paddles were inserted in the soil. After 4 h, the paddle color was compared with the Solvita color chart to infer the amount of CO_2 that was produced. This respiration test was corroborated by measuring CO_2 production by gas chromatography after 1, 2 and 4 h at 60 °C. An in-field test for soil CO_2 flux was conducted using a model LI-6400, LI-COR CO_2 analyzer (LI Manual 1999). Plastic rings 9.5 cm in diameter were inserted at each location 1 day before measuring the CO_2 flux, when the portable photosynthesis system was attached to the rings.

Total porosity, as a fraction of total volume, was calculated by Eq. (1), where D_b is soil bulk density and soil particle density D_p is assumed to be 2.65 g/cm^3:

$$P = 1 - \left(\frac{D_b}{D_p}\right) \tag{1}$$

Water-filled pore space (WFPS), which is synonymous with relative saturation, was calculated from the relation between volumetric water (Wv) and total porosity, by Eq. (2):

$$\%\mathrm{WFPS} = \left(\frac{Wv}{p}\right) \times 100 \tag{2}$$

The volumetric water content is given in Eq. (3):

$$Wv = WC \times D_b \tag{3}$$

This is obtained from soil water content, Eq. (4):

$$WC = \frac{wet - dry(g)}{dry\ soil\ weight(g)} \tag{4}$$

and multiplied by soil bulk density, Eq. (5):

$$Db = \frac{Drysoil(g)}{volume\ of\ solid + void} \tag{5}$$

To measure soil aggregate stability, five shovels of soil to a 7.5-cm depth were gently dug from each row, interrow, and wheel track location; transported to the laboratory; and dried at room temperature for 2 days. All the air-dried soil samples were passed through a 2- and 1-mm sieve using the minimum necessary force. Three grams of soil retained by the 1-mm sieve were placed in a 12.7-cm-diameter, 0.5-mm-mesh sieve and submerged overnight in 500 ml of diluted water. The mesh was placed 2 cm below the top of the water and raised and lowered 20 times in 40 s. Finally after the wet sieving, the sieve and contents were dried and the weight retained determined (personal communication, Bob Grossmam, July 2005). The current method is in the USDA-NRCS Soil Survey laboratory manual (2004).

Penetration resistance was measured using a hand soil cone penetrometer 12.83 mm in diameter, ASAE EP542 (2003). A significant restriction of root growth for many important annual crops is encountered at a threshold of about 2 MPa with conventional tillage. This threshold may increase to between 3 and 5 MPa with no-tillage because of the presence of earthworm tunnels and old root channels, which roots can follow to move through a generally dense soil (Arshad, Lowery, and Grossman 1996).

Laboratory Evaluation

Soil samples were passed through a 2-mm sieve, dried at room temperature, and ground to less than 2 mm before chemical and physical analyses. Large pieces ($> \sim 2$ cm) of plant residue were removed by hand. To test soil electrical conductivity (EC) and soil acidity, 10 g of fresh soil were passed through a 2-mm sieve; pH and EC were determined in a 1:1 soil–water slurry (Dahnke and Whitney 1988; Eckert 1988). Total soil N and organic C were determined by dry combustion using the procedure of Schepers, Francis, and Thompson (1989). Soil nitrate and ammonia were determined by the copperized cadmium method (Miller and Keeney 1982). Soil particulate organic matter (0.053–2.0 mm) (POM) and soil organic matter (SOM) were estimated by weight loss on ignition, which also includes a soil particle size analysis using the sieving technique (Kettler, Doran, and Gilbert 2001). Carbon dioxide concentration was determined by gas chromatography (Tracor MT-220) using a thermal conductivity detector at 110 °C, a column oven temperature of 60 °C, and helium as the carrier gas.

Soil Nematodes Procedure

Thirty-six samples of 100 cm^3 of soil were obtained on each sampling date (April, June, and September). Each sample was taken from within-row locations using a 1.74-cm-diameter soil core to depth of 7.5 cm in April and 15 cm in June and September. Soil was refrigerated and stored in plastic bags until extraction. Nematodes were extracted from soil by a modified sugar centrifugation procedure (Southey 1986) within 2 weeks. Nematodes were counted using a dissecting microscope and killed using gentle heat. They were fixed in a 4:1 formalin–glycerin solution and slowly evaporated to low glycerin concentration. Nematodes were moved 10 to a slide on aluminum Cobb mounts (Neher and Cambell 1994) to be counted and identified.

Statistical Analyses

To analyze the intraspecific variation among soil quality indicators and to obtain their correlation with nematode abundance, a principal component analysis (PCA) was performed. Briefly, this technique consists of a series of linear transformation of the original observation into new vectors PCA. The PCA was performed using the R package (R Development Core Team 2005). Thirty-six data points were used for both PCA and multicorrelation among nematode abundance and soil quality indicators. These data were from the in-row location only for each sampling date in April, June, and September. The SAS statistical package for analysis of variance (ANOVA-proc glimix, SAS Institute 2005), was used to determine the differences among four tillage practices and their effects on soil quality indicators and nematode abundance. The experimental tillage plots were treated as a split-plot design, dividing the principal tillage plots into three locations (in-row, interrow, traffic interrow), three soil depths (0–7.5, 7.5–15, 15–30 cm), and three sampling times (April, June, and September).

RESULTS AND DISCUSSION

Soil Physical and Chemical Characteristics

Most of the physical properties evaluated in this study were strongly affected by increased tillage. As illustrated in Table 2, the thickness in the A horizon of the more disturbed plots averaged about 10 cm less than that in the no-till soil after 24 years of tillage at the Rogers Memorial Farm. The increased clay content in the soil surface of traffic rows and more disturbed soil treatments ($Pr > F = 0.0001$) reduces soil water infiltration and encourages runoff (Table 3, Figure 1). Clay content was the most variable soil quality indicator and was significantly correlated to nematode abundance ($r = -0.51$), silt content ($r = -0.84$), and soil EC

Table 2. Soil profile description by treatments, west tillage experiment at Rogers Memorial Farm, April 2005

		Tillage plot by treatments			
Horizons	Variables	NT[a]	DD[b]	CH[b]	PL[a]
Ap	Soil depth	0–18 cm	0–12 cm	0–12 cm	0–12 cm
	Clay (%)	38	31	31	40
	OC (%)	1.95	1.96	1.98	1.92
AB	Soil depth	18–28 cm			12–28 cm
	Clay (%)	40			42
	OC (%)	1.88			1.57
Bt	Soil depth		12–21 cm	12–20 cm	
	Clay (%)		39	38	
	OC (%)		1.6	0.99	
Bw_1	Soil depth	28–56 cm	21–61 cm	20–64 cm	28–68 cm
	Clay (%)	37	33	28	45
	OC (%)	1.11	0.70	0.71	1.57
BC	Soil depth	101–161 cm	115–160 cm	118–155 cm	68–100
	Clay (%)	29	21	19	40
	OC (%)	0.20	0.19	0.24	0.32
C	Soil depth				100–165 cm
	Clay (%)				36
	OC (%)				0.22
Bw_2	Soil depth	56–101 cm	61–115 cm	64–118 cm	
	Clay (%)	31	33	19	
	OC (%)	0.34	0.32	0.31	

[a]In the no-till (NT) and moldboard plow (PL) plots, the soil was classified as Fine smectitic, mesic Typic Hapludolls.

[b]In the double-disk (DD) and chisel (CH) plots, the soil was classified as Fine smectitic, mesic Mollic Hapludalfs.

($r = -0.52$) (Table 4). The clay content was 3 to 4.3% greater in the chisel and plow plots than the no-tilled plots at the 0- to 7.5-cm soil depth ($Pr > F = <.0001$) and was on average 2% greater in traffic areas of chisel and plow compared to no-till ($Pr > F = 0.0014$) (Figure 1), where a channel had formed to conduct runoff water. However, clay content was not significantly different between treatments at the 15- and 30-cm soil depths. That suggests that clay exposure caused by tillage and runoff is an indicator of soil degradation. Based on decreases in the depth of the A horizon and SOM content and increases in clay content, about 45% of the surface soil had eroded in the plow treatment. Conversely, silt content was affected by depth ($Pr > F = <0.0001$) with greatest values in the soil surface and decreasing with depth; however, it was not affected by treatment and location. Silt content was significantly correlated to nematode abundance and soil EC (Table 4).

Table 3. Mean and probabilities of differences (ANOVA) of surface soil (0–7.5 cm) characteristics, sampled in June 2005 at Rogers Memorial Farm

		Overall treatment by location means				Pr > F	
Variable	Location	NT	DD	CH	PL	Treatments	Locations
Clay (%)	Row	34.5	34.0	37.4	38.8	0.0050	<.0001
	Inter-r	35.3	35.3	37.2	39.9	0.0077	
	track	34.9	36.4	39.5	40.0	0.0034	
D_b (g cm^{-3})	Row	1.24	1.29	1.31	1.42	0.2650	<.0001
	Inter-r	1.36	1.30	1.26	1.29	0.7278	
	Track	1.52	1.29	1.58	1.60	0.8040	
WFPS (%)	Row	0.29	0.36	0.31	0.34	0.6102	<.0001
	Inter-r	0.38	0.33	0.34	0.35	0.8158	
	Track	0.56	0.58	0.71	0.67	0.1004	
SOM by LOI (kg ha^{-1})	Row	46,368	41,417	41,822	40,990	0.0126	NS
	Inter-r	45,455	40,685	39,170	37,038	0.0120	
	Track	51,482	47,048	48,717	46,205	0.0106	
Total POM (kg ha^{-1})	Row	11,929	8,499	7,335	4,662	<.0001	0.0091
	Inter-r	9119	7,169	6,293	3,929	0.0010	
	Track	10,006	7,610	6,546	4,818	0.0090	
EC (dS m^{-1})	Row	0.27	0.23	0.24	0.22	0.5550	<.0001
	Inter-r	0.32	0.31	0.27	0.27	0.4713	
	Track	0.38	0.45	0.31	0.35	0.0109	
pH (1:1)	Row	6.88	7.3	7.2	7.0	0.1718	0.0091
	Inter-r	6.3	7.0	7.3	7.1	0.0035	
	Track	6.4	6.8	7.1	7.0	0.0324	

Soil compaction generally affects root growth and the permeability to water and air. Mechanical resistance ranged between 2 and 4.3 MPa and was twofold greater in the wheel traffic area of no-till compared to row areas ($Pr > F = 0.066$). Mechanical resistance increased with depth ($Pr > F = 0.0001$) when clayey Bt horizon was present in the sampling zone of more disturbed plots and traffic locations. The greatest compaction was observed in the DD plots from 7.5 to 15 cm. These results are in agreement with the pan layer observed by Jasa et al. (1999). These results were probably influenced by the dry field conditions (14% moisture). A similar trend occurred for soil bulk density, which was also significantly different among row locations ($Pr > F = 0.0001$) and soil depths ($Pr > F = 00.0179$). Although soil bulk density was not significantly different among treatments, it was affected by both plot location and soil depth ($Pr > F = <.0001, 0.0179$) with greatest values occurring at the 15- to 30-cm soil depth. The effect of location and soil depth on soil bulk density was also reflected in soil volumetric water content and percentage of water-filled pore, because these indicators are functions of

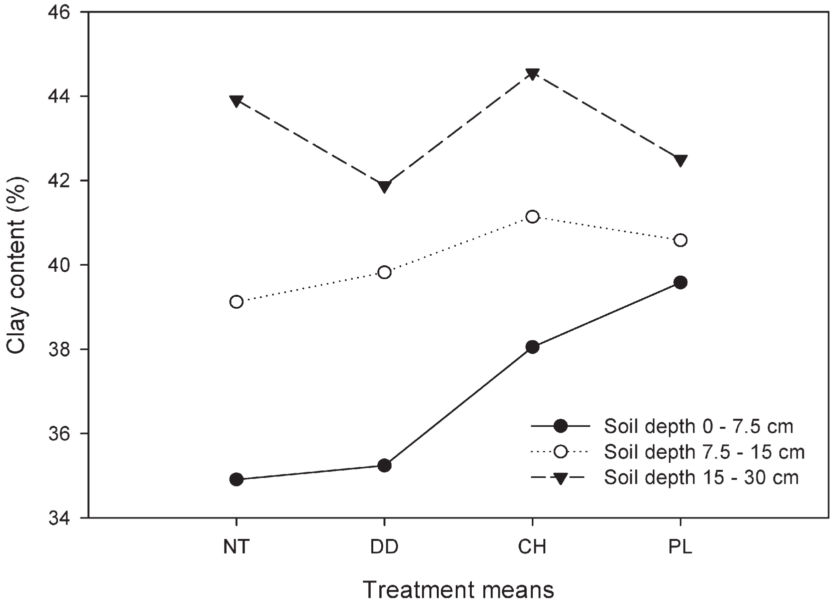

Figure 1. Means of clay content by three soil depths and for no-till (NT), double-disk (DD), chisel (CH), and plow (PL) treatments. Soil depths were only significantly different in the surface 0–7.5 cm (Pr > F = 0.0162). Rogers Memorial Farm, June 2005.

soil bulk density. Differences in soil mechanical resistance and bulk density were similar to those for soil water infiltration (Figure 2), which was faster in all row locations and in the no-till treatment than in traffic areas and plowed plots, except for the between-row area. The water infiltration rate average across depth and location ranged from 28 (plow) to 45 min (chisel) for the first 2.54 cm of water added. However, for the second 2.54 cm of water (5.08 cm total), infiltration ranged from 67 min per 5.08 cm of water (no till) to 230 min (plow) (Figure 2). Infiltration rate for the second 2.54 cm of water was 80% slower than the first 2.54 cm of water that was added to dry soil (14% field moisture; Pr > F = 0.0021). The average infiltration rates were also 7 and 10 times faster during the first and second increment of water in the row location than wheel track location (Pr > F = 0.0143). Because the infiltration time for the first 2.54 cm of water was greater than 28 to 45 min, these soils may allow water runoff and erosion, because the probability of a 2.54-cm rainfall for a 30-min duration can be expected every year in Lincoln, Nebraska (Herschfield 1961; Mendoza 2006). On the other hand, with no till, the infiltration time for 5.08 cm of water is 67 min, which indicates a potential for runoff and erosion every 5 years for a 1-h duration rainfall and every 2–3 years for a rainfall duration of 2 h. The double-disk, chisel, and plow

Table 4. Multiple correlations between nematode abundance and soil quality indicators at the 0- to 15-cm soil depth within row location only, sampling in April, June, and September 2005 at the Rogers Memorial Farm

	Nema	Sand	Silt	Clay	Total POM	SOM	POM (%)	EC	pH	WFPS
Nema	1									
Sand	0.006[a]	1								
	NS[b]									
Silt	0.46	−0.44	1							
	0.004	0.007								
Clay	−0.51	−0.114	−0.84	1						
	0.001	NS	<.0001							
Total POM	0.35	0.46	−0.03	−0.23	1					
	0.033	0.005	NS	NS						
SOM	0.043	−0.002	0.11	−0.120	0.06	1				
	NS	NS	NS	NS	NS					
(%) POM	0.066	0.53	−0.174	−0.13	0.62	0.468	1			
	NS	0.0009	NS	NS	<.0001	0.004				
EC	0.49	−0.17	0.56	−0.51	0.30	0.043	−0.12	1		
	0.002	NS	0.0004	0.0013	NS	NS	NS			
pH	−0.07	−0.30	0.28	−0.13	−0.37	0.11	−0.12	0.10	1	
	NS	NS	NS	NS	0.026	NS	NS	NS		
WFPS	−0.21	−0.21	0.19	−0.08	−0.43	0.262	−0.36	0.18	0.32	1
	NS	NS	NS	NS	0.0097	NS	0.03	NS	NS	

[a]First row is correlation coefficient (r), second row is probability (P).
[b]NS = not significant at p = 0.05 level.

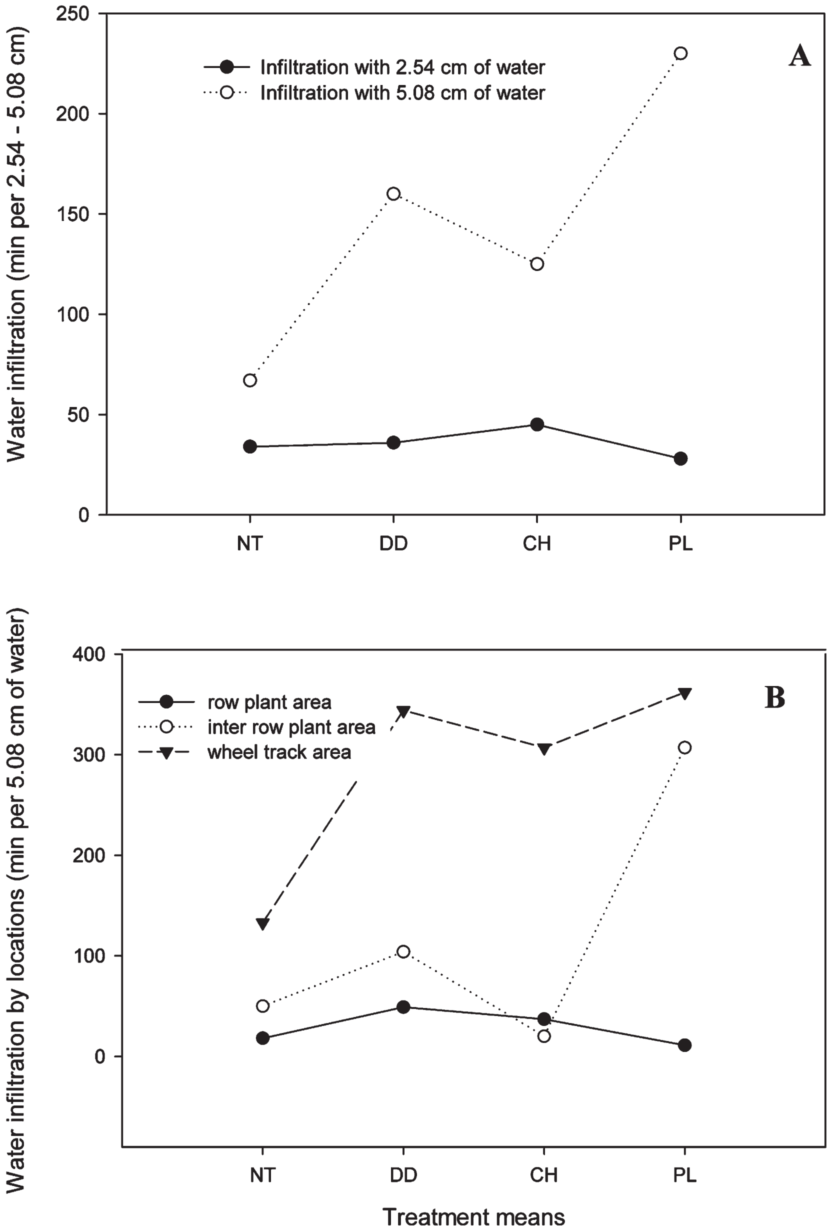

Figure 2. Means of soil water infiltration in minutes per (A) 2.54 cm of water added and (B) 5.08 cm of water added by row location for no-till (NT), double-disk (DD), chisel (CH), and plow (PL) management practices. Infiltration was significantly different for row location and amount of water added ($Pr > F = 0.0143$ and 0.0014). Rogers Memorial Farm, June 2005.

systems have an even greater potential for erosion and runoff because their infiltration rates are much slower than no till.

Soil EC values between 0 and 1.0 dS m^{-1} and soil pH values between 6 and 7.5 are generally acceptable for plant growth and microbial activity (Doran and Jones 1996; Smith and Doran 1996). In this study, EC values were not significantly different among treatments (Table 3). However, EC values in no till and double disk were 18% greater compared to plow and chisel plots in the upper 7.5 cm of soil. Electrical conductivity was significantly affected by locations ($Pr > F = 0.0043$), with highest values in the wheel traffic area (Table 3). In general, the EC values decreased with depth for all treatment except the chisel treatment, where EC increased with soil depth. This is probably related to soil depth and disturbance characteristic of the tillage operations. Electrical conductivity was significant positively correlated to silt content and nematode abundance (Table 4). Conversely, pH was significantly affected by treatment and was greater in plowed plots (Table 3, Figure 3). This increase in pH in plowed treatments is probably also related to the exposure of carbonates on the soil surface in plow plots, as the A horizon is eroded and also to the better mixing of added lime due to tillage. The higher pH in the soil surface ($Pr > F = 0.0001$) and row areas

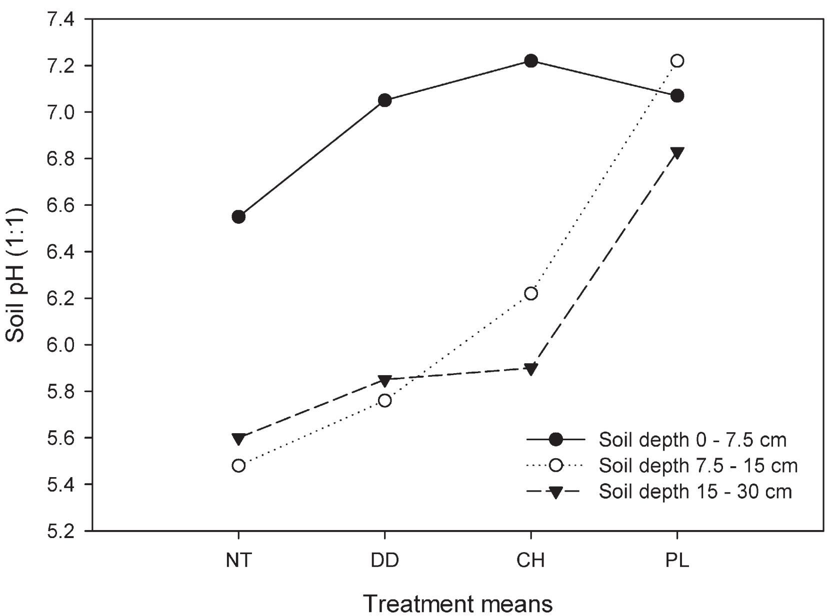

Figure 3. Means of soil pH (1:1) during June sampling, by three soil depths. For no-till (NT), double-disk (DD), chisel (CH), and plow (PL) treatment. Soil depths were significantly different ($Pr > F =$ 0.0058, <.0001, and <.0001 for 0–7.5, 7.5–15, and 15–30 cm). Rogers Memorial Farm, June 2005.

(Pr > F = 0.0017) is also probably due to liming practices in the past (personal communication, Paul Jasa, July 2006). This pattern was similar during April and September (Mendoza 2006). In our study, there was little or no relationship between EC and pH (Table 4) as compared with the findings of Smith and Doran (1996), who found a strong negative relationship due to active nitrification of applied N fertilizer.

No-tillage management, often characterized by an accumulation of crop residues on the surface, results in greater C, N, and water content of the surface 5 to 10 cm of soil compared to conventional tilled (plowed) soils (Fleige and Baeumer 1974; Blevins, Thomas, and Cornelius 1977; Doran 1980). In this study, the SOM concentration was both high in the wheel traffic location (Pr > F = 0.0001) and under no-tilled plots. The greatest concentration SOM was in the 0- to 7.5-cm depth and was highest with no-till management (Pr > F = 0.0001) (Tables 3 and 5).

We found that total particulate organic matter (tPOM) was a very sensitive indicator of soil quality in surface soil due to tillage management. For example, the tPOM (Tables 3 and 5; Figure 4) was greater in the surface 0- to 7.5-cm soil depth (Pr > F = <.0001) and was greater in the plant row location (Pr > F = 0.0006). No-tilled treatment plots (Pr > F = 0.022) had significantly greater POM, which in the surface 7.5-cm soil depth averaged 10,352, 7,759.5, 6,724.9, and 4,470.3 kg ha^{-1} in no-till, double-disk, chisel, and moldboard plow plots. The tPOM was significantly correlated to sand content, nematode abundance, WFPS, and soil pH (Table 3). Those correlation coefficient (r) values were 0.46, 0.35, −0.43, and −0.37.

No significant treatment differences in soil NO_3^--N and NH_4^+-N concentrations were found among treatments, but concentrations were greater in wheel traffic areas (Pr > F = 0.0003 and Pr > F = 0.0162 for

Table 5. Soil organic matter (SOM) and total particulate organic matter (tPOM) for three soil depths, Rogers Memorial Farm, June 2005

Soil depth (cm)	Till treatments effects				
	NT	DD	CH	PL	Pr > F
	Soil organic matter in kg ha^{-1}-depth				
0–7.5	47190.0	42458.75	42219.25	40317.73	0.0003
7.5–15	41402.5	42656.75	42343.0	41409.0	0.7178
15–30	42143.5	38067.1	39674.1	38122.2	0.0167
0–30	130736.0	123182.6	124236.3	119848.9	0.0659
	Total particulate organic matter in kg ha^{-1}-depth				
0–7.5	10043.25	7611.75	6615.25	4334.5	<.0001
7.5–15	2577.75	3005.0	3131.5	4347.5	0.0031
15–30	2133.13	1836.4	1873.3	2693.9	1.542
0–30	14754.1	12453.1	11620.0	11375.9	0.0227

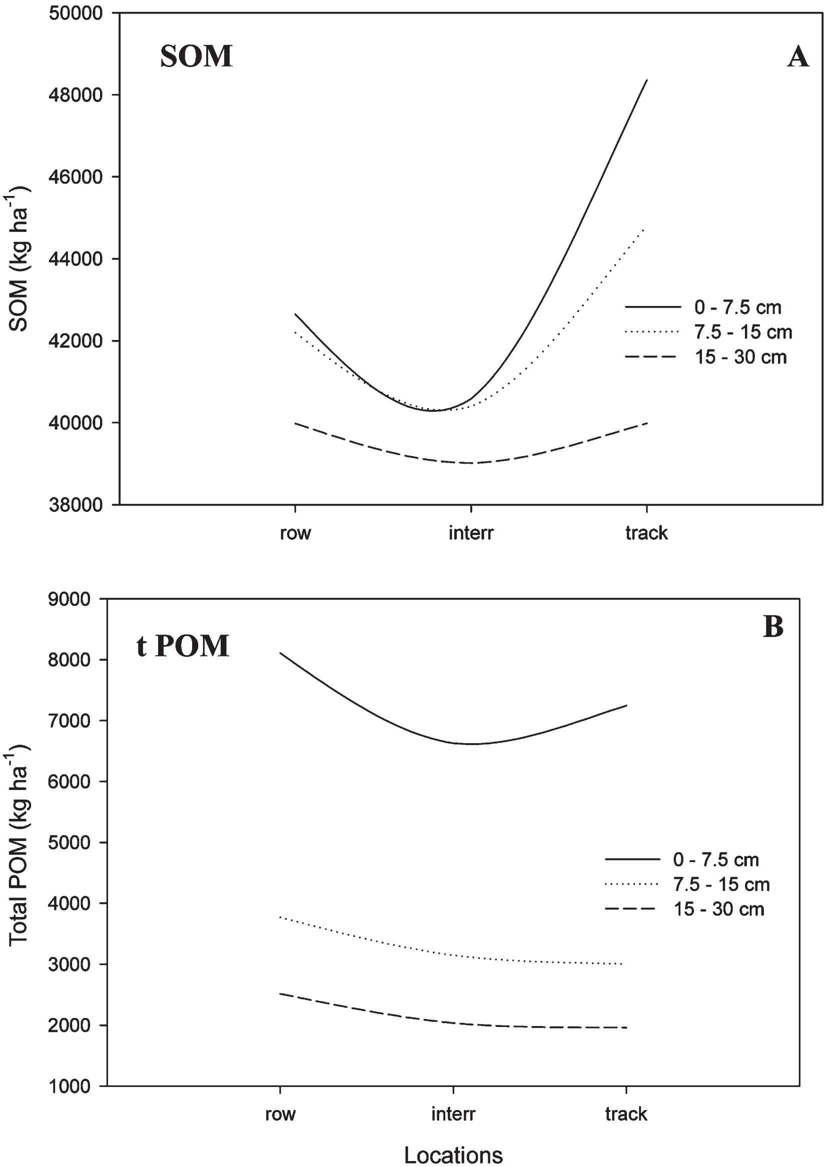

Figure 4. Means of (A) soil organic matter (SOM) and (B) total particulate organic matter (tPOM), by three soil depth, for in-row, interrow, and interrow track locations. SOM was significantly different at soil depths of 0–7.5 and 7.5–15 cm ($Pr > F = < 0.0001$ in both cases). The tPOM was significantly different only in the surface 0- to 7.5-cm soil depth ($Pr > F = 0.001$). Rogers Memorial Farm, June 2005.

nitrate and ammonium) and at the 7.5- and 15-cm sampling depths. Despite high nutrient (C, N, NH_4^+, NO_3^-) concentrations in the no-tilled plots, no significant differences in corn yield were observed. Yields for this year tended to be highest in the no-till plots, where it is presumed that greater early-season root growth enhanced the uptake of water and nutrients in that treatment (12137, 11846, 11701, and 11628 kg ha^{-1} in the no-till, double-disk, chisel, and moldboard plow treatments).

Biological Activity

Water and oxygen are the major factors influencing biological activity in soil. Linn and Doran (1984) found aerobic and anaerobic microbial activity was largely controlled by the effect of tillage on the proportion of WFPS. Relatively aerobic soil microbiological activity reaches a maximum at 60% of WFPS. At the time of collecting, the WFPS was not significantly different among treatments (Table 3); however, it reaches maximum values in wheel traffic areas ($Pr > F = 0.0001$) and between 7.5- and 15-cm soil depths ($Pr > F = 0.0001$) (Table 3). These data show that not only water was limiting (<60% of WFPS) in the soil surface for microbial activity, but also that aeration was limiting in the 15- to 30-cm soil depth and wheel track areas because WFPS was much higher than 60%. The WFPS was weakly correlated to pH, SOM, and silt content (0.32, 0.26, and 0.19) (Table 4). This would be expected because the correlations were not run separately for water-limiting ranges of WFPS (<60%) and aeration-limited ranges (>60%).

Soil respiration measured using both the solvita soil life test and the gas chromatography technique indicated significant differences among treatments ($Pr > F = <.0001$), where the no-till system was the greatest (1.1, 0.38, 0.34, and 0.25% of CO_2 respiration in no-till, double-disk, chisel, and moldboard plow treatments). It also was greater after 2 h ($Pr > F = 0.0001$).

Soil aggregation, as indicated by aggregate stability, not only physically protects SOM but also influences microbial community structure. It enhances oxygen diffusion, regulates water flow, determines nutrient adsorption and desorption, and reduces runoff and erosion. All of these processes have profound effects on SOM and nutrient cycling (Six et al. 2002). In our study, soil aggregate stability was greatest in the no-till treatment (26%) as compared with double-disk, chisel, and moldboard plow treatments (13, 15 and 11%). Soil aggregation was greatest in the row location and lowest in the track location (20, 16, and 13% in row, interrow, and track locations). These findings suggest that plant roots have an influence on aggregation in association with microorganisms and tPOM and SOM.

Nematodes were two times more abundant in September than in June or April ($Pr > ChiSq = <0.0001$; 515, 271, and 795 total individuals per 100 cm^3 of soil in April, June, and September). Nematode numbers in tillage treatments did not differ significantly ($Pr > ChiSq = <0.0984$) throughout the year. However, nematode numbers in no-till and double-disk treatments tended to be greater than these in chisel and plow for the sampling year (474, 466, 387, and 391 individual per 100 cm^3 of soil, respectively).

Association between Soil Quality Indicators and Nematode Abundance

Principal component analysis can be considered an extension of fitting straight lines and planes by least-square regression (Jongman, Ter braak, and Van Tongeren 1995). The horizontal axis is the first PCA axis, or first principal component. In our study, the ordinate diagram with arrows represents the soil quality indicators (Figure 5). The arrows indicate the increase of that variability along the plane of the first and second component. The direction of the arrows indicates the steepest ascent of the plane, where soil quality indicators and the length of the arrow equals the rate of change in that direction. In this scaling, the angle between arrows of each indicator provides an approximation of their pairwise correlation (Figure 5). Consequently, arrows that point in the same direction indicate positively correlated indicators, perpendicular arrows indicate lack of correlation, and arrows pointing in the opposite direction indicate negatively correlated soil quality indicators.

Based on 36 data point analysis across the year using a multicorrelation analysis (Table 4; Figure 5), nematode abundance was both significant and positively correlated to silt content, EC, and the tPOM ($r = 0.47$, 0.43, and 0.34) and significantly negatively correlated to clay content ($r = -0.5302$). Clay content was also significant negatively correlated to soil EC and negatively related to all other soil quality indicators tested during the experiment. This property was the main source of variation in this analysis (larger arrow), which suggests that clay is one of the more sensitive soil quality indicators for this soil. The percentage of WFPS was weakly correlated to pH, SOM, silt content, and EC, possibly because the data were not partitioned into water-limiting (<60% WFPS) and aeration-limiting (>60% WFPS) ranges for separate correlation. However, it was significantly negatively correlated to the total POM. These soil properties are strongly related to microbial activity and also in general positively associated with nematode abundance. On the other hand, silt content appears positively associated with nematode abundance and EC, pH, WFPS, and SOM.

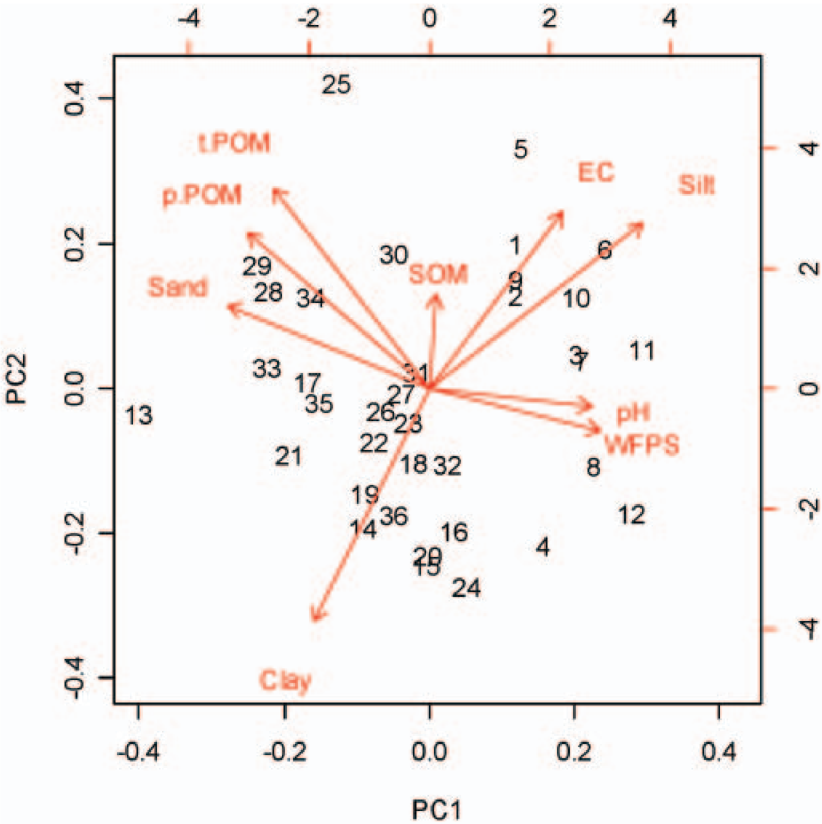

Figure 5. Principal component analysis (PCA) ordination diagram of the nematode abundance data in covariance biplot scaling with soil quality indicators represented by arrows. Indicators not represented in the diagram lie close to the origin (0,0). Analysis is based on 36 data points sampled in the 0- to 15-cm depth of soil in the within-row location only, during the April, June, and September sampling at the Rogers Memorial Farm, 2005.

High variability was the major factor resulting in poor correlation among variables, where principal component (PC)1 and PC2 together represent only 41 % of the variance. The PCA confirms the negative or positive association among soil quality indicators (Figure 5; Table 4).

CONCLUSIONS

This work has provided a more complete picture of the interaction among soil quality indicators, but also between crop-tillage management and nematode associations in this long-term study. The soil surface

(0–7.5 cm deep) was the zone affected most by tillage after 24 years. For example, soil erosion decreased the thickness of the A horizon for plots with increased tillage, apparently by up to 45% in the plow treatment. Consequently, the exposure of clay in the soil surface of double-disk, chisel and moldboard plow systems resulted in clay content being (1) the main source of variation among soil quality indicators and (2) the most important source of a negative correlation with total POM, soil EC, and nematode abundance. Hence, clay is one of the more sensitive soil quality indicators that is directly associated with the loss of A horizon induced by soil tillage and runoff. The negative relationship between clay content and the aforementioned soil quality indicators was likely due to its positive association with soil erosion and associated losses of soil organic matter.

Besides soil depth, location zone (row, interrow, wheel traffic row) was also significantly affected by tillage disturbance. The row location, which covered 25% of the plot area, represents the more active rhizosphere zone near the plant and is the major area of highest particulate organic matter, SOM, soil aggregate stability, and fastest water infiltration. This zone also showed a lower soil EC, clay content, moisture content, mechanical resistance, and bulk density. On the other hand, the non-trafficked interrow area, which represented 50% of the plot area, showed intermediate values in term of soil quality indicators. Yet, the wheel traffic interrow, which covered 25% of the plot area, was the area more negatively affected by compaction and clay accumulation.

Nematode abundance was significantly correlated to soil EC, silt content, total POM, and clay content ($r = 0.49$, 0.46, 0.35, and -0.51). On an annual basis, nematode populations tended to be greater in no-till and double-disk plots than in chisel and plowed plots ($P < 0.10$), but this trend was not significant at $P < 0.05$. However, nematode abundance by itself cannot be related to soil quality without understanding the dynamics in terms of composition, season, and ecological impact on the soil quality and crop production. On the other hand, positive associations were also observed between WFPS and soil pH, SOM, silt content, and EC ($r = 0.32$, 0.26, 0.19, and 0.18). These soil properties are not only related to microbial activity but are also generally positively associated with nematode abundance. Hence, the enhancement of microbial respiration and nematode number with no till likely resulted from more desirable food source and habitat space due to higher SOM, more optimal water and aeration regimes, and better physical properties.

The gain in SOM in the no-till system in the top 30 cm of soil amounted to 10,887 kg over the 24-year period or 454 $kg\,ha^{-1}\,yr^{-1}$. About half of this difference (45% or 204 $kg\,yr^{-1}$) likely resulted from SOM loss from plowed treatment due to soil erosion as estimated from changes in clay content and A horizon depth. The balance of the gain in

SOM per year (250 kg) with no till was due to SOM increase as a result of organic C buildup or sequestration in surface soil. Thus, the no-till system with higher SOM levels, faster water infiltration rates (which induce lower erosion potential), and highest potential yields becomes the most sustainable system from the standpoint of both environmental quality and farm productivity.

This study provided a more complete overview of the whole tillage system, as related to nematode counts and soil quality indicators. Therefore, using a small number of indicators such as soil EC, total POM, and both silt and clay content, the farmer can evaluate the soil and the quality improvement of their practices, and also predict some biological activities in the soil. This study also demonstrated clearly that to identify the effects of tillage management, soil analyses must be expressed on a volumetric basis (measure bulk density) and must use samples taken to permit proper separation of effects due to stratification with soil depth and also across row, interrow, and wheel track locations with row crops.

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