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Crop management effects on soil carbon sequestration on selected farmers' fields in northeastern Ohio

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Abstract

Soil organic carbon (SOC) pool is the largest among terrestrial pools. The restoration of SOC pool in arable lands represents a potential sink for atmospheric CO_2. Restorative management of SOC includes using organic manures, adopting legume-based crop rotations, and converting plow till to a conservation till system. A field study was conducted to analyze soil properties on two farms located in Geauga and Stark Counties in northeastern Ohio, USA. Soil bulk density decreased with increase in SOC pool for a wide range of management systems. In comparison with wooded control, agricultural fields had a lower SOC pool in the 0–30 cm depth. In Geauga County, the SOC pool decreased by 34% in alfalfa (*Medicago sativa* L.) grown in a complex rotation with manuring and 51% in unmanured continuous corn (*Zea mays* L.). In Stark County, the SOC pool decreased by 32% in a field systematically amended with poultry manure and 40% in the field receiving only chemical fertilizers. In comparison with continuous corn, the rate of SOC sequestration in Geauga County was 379 kg C ha^{-1} $year^{-1}$ in no-till corn (2 years) previously in hay (12 years), 760 kg C ha^{-1} $year^{-1}$ in a complex crop rotation receiving manure and chemical fertilizers, and 355 kg C ha^{-1} $year^{-1}$ without manuring. The rate of SOC sequestration was 392 kg C ha^{-1} $year^{-1}$ on manured field in Stark County.

Keywords: Carbon sequestration; CN pools; Soil fertility; Crop management; Crop rotation; Conservation tillage; Manure addition; Soil pH

1. Introduction

Restoration of soil organic carbon (SOC) in arable lands represents a potential sink for atmospheric CO_2 (Lal and Kimble, 1997). Strategies for SOC restoration by adoption of recommended management practices (RMPs) include conversion from conventional tillage to no-till, increasing cropping intensity by eliminating summer fallows, using highly diverse rotation, introducing forage legumes and grass mixtures in the rotation cycle, increasing crop production, and increasing carbon (C) input into the soil (Lal et al., 1998; Lal, 1999; Desjardins et al., 2001; Hao et al., 2002). In the US, cropland under no-till increased from 14.7% in 1995 to 19.6% in 2002 (Fawcett and Towery, 2003). There is a strong

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interaction among RMPs with regards to their effect on SOC concentration and soil quality (Jarecki and Lal, 2003). Adopting no-till in combination with other management practices can enhance SOC sequestration. In combination with minimum or no-till management, crop rotations can reduce soil erosion, enhance SOC concentration and sequester soil C (Lal, 2001). West and Post (2002) observed that changing plow till to no-till increased SOC pool at the rate of 57 g C m^{-2} $year^{-1}$ (or 570 kg ha^{-1} $year^{-1}$). Relatively lower rates (14 g C m^2 $year^{-1}$) of increase in SOC pool were associated with adoption of complex crop rotations. The efficiency of a no-till system for SOC sequestration is enhanced when used in combination with high intensity crop rotations and elimination of summer fallow (Potter et al., 1997; Campbell et al., 1998). Converting a monoculture to a crop rotation also leads to SOC sequestration, which increases residue inputs to the soil (Robinson et al., 1996; Drury et al., 1998; Halvorson et al., 2002). Increase in SOC may not occur in crop rotations, which include high frequency of low residue producing crops, such as soybean (*Glycine max* L.) (Omay et al., 1997; Dick et al., 1998; Studdert and Echeverria, 2000). Buried residues and roots decay faster than above ground or surface applied residues as is the case in a no-till system (Ghidey and Alberts, 1993). A strong interaction between C, water and N cycles impacts the SOC pool and soil erosion risks (Reicosky, 1994).

The data on SOC sequestration rate under on-farm conditions are scanty, but needed for assessing the C credits and evaluating the impact of management system on soil quality. Therefore, the objectives of this study were to compare SOC and N pools, and other soil properties under different crop management systems under on-farm conditions on selected farms in northeastern Ohio, USA.

2. Materials and methods

2.1. Sites and soil description

Two farms, one each in Geauga and Stark Counties in northeastern Ohio, were selected for the study. The long-term mean precipitation is 1112 mm per annum in Geauga County and 915 mm in Stark County. The precipitation distributed evenly throughout the year, and is adequate for crop production in most soils. The average annual temperature is 9.0 °C in Geauga and 10.2 °C in Stark County (USDA, 1971, 1982). The farms are located near Burton in Geauga County (41.29N, 81.07W) hereafter called "Geauga Farm", and near Louisville in Stark County (40.57N, 81.15W) hereafter called "Stark Farm". In both Counties dairy farming is the principal enterprise. However, the soils which are more suited for grasses than for row crops have been used in agriculture since the beginning of the 19th century. Soils of the Geauga Farm are classified as a Canfield silt loam (fine-loamy, mixed, mesic Aquic Fragiudalfs) and those of the Stark Farm as a Ravenna Canfield silt loam (fine-loamy, mixed, mesic Aeric Fragiudalfs). These are deep, gently sloping (2–4%), moderately well drained soils formed on glacial till (Wisconsin age) on uplands. They contain fragipan that restricts rooting depth and the movement of water. Permeability is moderate above the fragipan and slow in the fragipan and substratum (USDA, 1971, 1982). The mean texture particle size distribution for the surface layer comprises 30% sand, 38% clay and 32% silt in the Geauga Farm; and 29% sand, 33% clay and 38% silt in the Stark Farm.

The land use and management system chosen for the Geauga Farm included: a wooded control (wooded), continuous corn (CC), continuous corn with no-till management (CCNT), alfalfa in crop rotation with cattle manure (ARM) and grass meadow in an unmanured crop rotation (GRUM) (Table 1). All fields and wooded area in the Geauga Farm were located within a 2.5 km radius and have the same loamy texture. Land use and management systems chosen for the Stark Farm included: a wooded control (wooded), corn in poultry manured corn/soybean rotation (manured) and soybean with chemical fertilizer (mineral) in corn/soybean rotation (Table 1). Both fields in the Stark Farm are adjacent to each other and bordered with a wooded area. In both farms, all fields were managed with a minimum till system with the exception of CCNT in the Geauga Farm where a no-till system was practiced. Minimum till system refers to minimum cultivation required to grow a crop successfully, and in the Geauga Farm and Stark Farm, the soil cultivation was restricted to chisel and disc. The no-till corn was planted directly into the seedbed, which was not tilled since the previous corn crop.

Table 1
Characteristic of fields and wooded areas sampled in Geauga Farm and in Stark Farm

Land use or crop	Description
Geauga Farm	
Wooded control (wooded)	Forty to fifty years old non-grazed wooded area mainly with sugar maple (*Acer sacharrum* L.) white oak (*Quercus alba* L.) and American beech (*Fagus grandifolia* L.)
Corn (CC)	Three-years continuous corn (*Zea mays* L.) fertilized per ha: 95 kg N, 55 kg P and 20 kg K ha^{-1}, minimum till, herbicides applied at planting and at the end of June, yield 6.9–7.2 Mg ha^{-1}, prior to corn wheat (*Triticum asetivum* L.) and soybean (*Glycine max* L.)
Corn NT (CCNT)	Fourteen years no-till field: second year continuous corn fertilized per ha: 95 kg N, 55 kg P and 20 kg K ha^{-1}, herbicides applied at planting and at the end of June. Previously 12 years in hay (grasses with low addition of legumes)
Grass rotation unmanured (GRUM)	Orchard grass (*Dactylis glomerata* L.) with alfalfa addition in minimum till rotation: corn, corn, wheat, grass, grass fertilized 200 kg K ha^{-1}. Previously fertilized NPK and limed (7 Mg ha^{-1}) under the wheat, unmanured
Alfalfa rotation with manure (ARM)	Alfalfa (*Medicago sativa* L.) in minimum till rotation: corn, corn, wheat alfalfa, alfalfa yield 4.5–4.9 dry matter Mg ha^{-1}. Limed (7 Mg ha^{-1}) under the wheat. Cattle manure 2 years prior to sampling 4.6 Mg ha^{-1} dry weight
Stark Farm	
Wooded control (wooded)	Sixty years old undisturbed non-grazed wooded area mainly with white oak (*Quercus alba* L.), sugar maple (*Acer sacharrum* L.) and American beech (*Fagus grandifolia* L.)
Corn (manured)	In corn–soybean rotation with minimum till, corn yield 6.5–7 Mg ha^{-1}, soybean yield 2.3–2.7 Mg ha^{-1}, PK fertilized, from 13 years amended every 2–3 years by poultry manure 7–11 Mg ha^{-1} dry weight, last time 2 years before sampling
Soybean (mineral)	In corn–soybean rotation with minimum till, soybean yield 2.3–2.7 Mg ha^{-1}, corn yield 6.5–7 Mg ha^{-1}, NPK fertilized, unmanured

Both practices comprise the conservation tillage, which is defined as ‘‘any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce water erosion; or where wind erosion is primary concern, maintain at least 1000 kg ha^{-1} of flat, small grain residue equivalent on the surface during the critical wind erosion period (CTIC, 2002).

2.2. Soil sampling, preparation and bulk density measurements

Soil samples were collected in June 2002 from each field and wooded area. Samples were taken at each of the five points across the sites. Sampling points were separated from each other by a distance of 50 m. A composite sample from each point included two cores (4.3 cm diameter) for 0–5, 5–10, 10–20, 20–30 and 30–50 cm depths. Soil bulk density (b) was corrected for gravel (>2 mm), assuming the average gravel particle density of 2.65 Mg m^{-3} (Blake and Hartge, 1986). The remaining soil was combined to obtain a composite sample for further analysis. Soil samples for chemical analyses were air-dried, ground and sieved through a 2 mm sieve. Soil samples for C and N analyses were additionally ground using a ball mill and sieved through a 0.125 mm sieve.

2.3. Soil chemical analyses

The C and N analyses were performed on an NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). The HCl test to indicate the carbonate presence was negative, thus total C concentration was assumed to be SOC. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined in NH_4OAc extract, exchangeable acidity by $BaCl_2$-TEA extraction (Thomas, 1982), and pH in 1:1 soil–water suspension (Mc Lean, 1982).

2.4. Calculations of soil organic carbon pool

The SOC and total N concentrations were converted to mass per unit area for a fixed depth corresponding to 0–5, 5–10, 10–20, 20–30 and 30–50 cm depth by multiplying with ρ_b and depth (Lal et al., 1998). The SOC and N pools for 0–20, 0–30 and 0–50 cm depths were computed using the equivalent soil depth method described by Ellert and Bettany (1995) where additional thickness of subsurface layer required to attain the equivalent soil mass was computed as follow:

$$T_{\mathrm{add}} = \frac{(M_{\mathrm{soil,equiv}} - M_{\mathrm{soil,surf}}) \times 0.0001\,\mathrm{ha\,m^{-2}}}{\rho_{\mathrm{b\,subsurface}}}$$

where T_{add} = additional thickness of subsurface layer (m); $M_{\mathrm{soil,\ equiv}}$ = equivalent soil mass = mass of heaviest layer (Mg ha^{-1}); $M_{\mathrm{soil,\ surf}}$ = sum of soil mass in surface layer(s) (Mg ha^{-1}); $\rho_{\mathrm{b\ subsurface}}$ = bulk density of subsurface layer (Mg m^{-3}).

2.5. Stratification

Stratification ratios were calculated from soil properties at 0–5 cm depth divided by those at 10–20 cm depth. Stratification is defined as a soil property at the soil surface divided by the same soil property at

Table 2
Soil bulk density, SOC and N concentration, C/N ratio and SOC and N pools for each fixed soil layer under different land use and crop management in Geauga Farm

Depth (cm)	Land use or crop	Soil bulk density (Mg m^{-3})	SOC (g kg^{-1})	N (g kg^{-1})	C:N	SOC pool (Mg ha^{-1})	N pool (Mg ha^{-1})
0–5	Wooded	1.02 c	42.2 a	3.14 a	13.5 a	21.4 a	1.59 a
	CC	1.29 ab	16.2 b	1.31 b	12.3 bc	10.4 c	0.84 c
	CCNT	1.25 b	18.4 b	1.55 b	11.8 c	11.4 bc	0.96 bc
	ARM	1.25 b	21.2 b	1.74 b	12.3 bc	13.3 b	1.09 b
	GRUM	1.31 a	17.5 b	1.36 b	12.8 b	11.4 bc	0.89 c
	LSD ($P < 0.05$)	0.05	5.4	0.43	0.7	2.7	0.22
5–10	Wooded	1.07 c	30.8 a	2.20 a	14.2 a	16.3 a	1.16 a
	CC	1.39 a	13.6 c	1.12 c	12.1 bc	9.4 c	0.78 b
	CCNT	1.31 b	15.4 c	1.18 c	13.0 b	10.1 c	0.77 b
	ARM	1.30 b	19.6 b	1.62 b	12.1 bc	12.6 b	1.05 a
	GRUM	1.31 b	14.6 c	1.25 c	11.7 c	9.6 c	0.82 b
	LSD ($P < 0.05$)	0.07	4.0	0.35	0.9	1.7	0.16
10–20	Wooded	1.22 c	24.5 a	1.84 a	13.3 a	29.9 a	2.25 a
	CC	1.42 a	12.9 d	1.06 d	12.2 bc	18.1 c	1.49 c
	CCNT	1.33 b	14.2 cd	1.11 cd	12.9 ab	18.7 c	1.46 c
	ARM	1.36 ab	18.3 b	1.49 b	12.4 bc	25.0 ab	2.04 ab
	GRUM	1.33 b	16.4 bc	1.36 bc	12.0 c	21.8 bc	1.82 bc
	LSD ($P < 0.05$)	0.08	3.3	0.25	0.8	5.2	0.38
20–30	Wooded	1.27 c	14.0 a	1.06 a	12.6 a	17.5 a	1.36 a
	CC	1.44 ab	3.8 b	0.40 b	9.7 c	5.5 b	0.56 b
	CCNT	1.42 b	5.7 b	0.50 b	11.7 ab	8.1 b	0.69 b
	ARM	1.44 ab	5.0 b	0.48 b	10.8 bc	7.3 b	0.67 b
	GRUM	1.51 a	5.0 b	0.48 b	10.8 bc	7.5 b	0.69 b
	LSD ($P < 0.05$)	0.07	3.4	0.23	1.5	4.0	0.27
30–50	Wooded	1.38 c	4.8 a	0.44	10.9 a	13.2 a	1.21
	CC	1.59 a	2.5 b	0.34	7.3 b	8.0 b	1.08
	CCNT	1.52 ab	2.1 b	0.30	7.2 b	6.4 b	0.92
	ARM	1.48 b	3.1 b	0.36	8.6 b	9.1 ab	1.05
	GRUM	1.54 ab	2.5 b	0.31	8.1 b	7.8 b	0.95
	LSD ($P < 0.05$)	0.08	1.2	ns[a]	2.0	3.2	ns

Abbreviations: wooded, wooded control; CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured. Different letter(s) on the same column and for the same depth are significantly different at $P < 0.05$ according to LSD separation test.

[a] Non-significant.

a lower depth, such as the bottom of the tillage layer (Franzluebbers, 2002).

2.6. Statistical analyses

Experiments performed on the farms did not allow for randomization, and replicated sampling points from the fields were used as ‘‘pseudoreplications’’ (Reganold, 1994; Bergstrom et al., 1998). The analysis of variance (ANOVA) was computed for each farm separately and means were compared by the least significant differences (LSD) test at $P < 0.05$ (SAS Institute Inc., 1994).

3. Results and discussion

3.1. Soil bulk density

In the Geauga Farm, the ρ_b was lower in wooded than in the crop fields, and ranged from 1.25 to 1.31 Mg m^{-3} in 0–5 cm layer and 1.48 to 1.59 Mg m^{-3} in 31–50 cm layer (Table 2). Significantly higher ρ_b in CC was observed in 5–10 cm depth compared to other fields, and 10–20 cm depth compared to CCNT and GRUM (Table 2). There were no consistent differences in ρ_b among fields in deeper layers (Table 2).

In the Stark Farm, the lowest ρ_b was observed in wooded than in manured, and the highest in mineral field for 0–5 cm depth. There were no significant differences in ρ_b among different fields for 10–50 cm depth (Table 3).

3.2. Soil organic carbon concentration

In the Geauga Farm, the SOC concentration was higher in wooded than in the crop fields for all depths (Table 2). There were no differences in SOC concentration among fields for 0–5 cm depth. The SOC was higher in ARM than in the other fields for 5–10 cm depth, higher in ARM than CCNT and CC for 5–20 cm depth, and no differences among the fields for 20–50 cm depth (Table 2). Soil bulk density was inversely related to SOC concentration (Fig. 1).

A lack of significance in SOC concentration among CC and CCNT fields may be due to similar tillage management. The CC was under minimum tillage (disc and chisel) and received less soil disturbance than regular tillage. Therefore, conversion to no-till did not induce significant changes in soil properties. Tillage-induced differences in SOC concentration are generally limited to the surface layer up to 7 cm depth (Havlin et al., 1990; Potter et al., 1997). Further conversion from conventional tillage to no-till may not always increase total SOC sequestration (Franzluebbers and Arshad, 1996; Salinas-Garcia et al., 1997). Rasmussen and Collins (1991) indicated the importance of thermic factor limiting changes in SOC due to tillage management i.e. lower annual temperatures are not conducive to drastic changes in SOC concentration. Dick (1983) reported similar results to those in this study that no-till may delay decline in SOC compared to plow till. No-till enhances SOC concentration in the surface soil under most conditions (Potter and Chichester, 1993; Potter et al., 1997; Lal and Kimble, 1997; West and Post, 2002).

There were also differences in SOC concentration among management systems at the Stark Farm. High SOC concentration was observed in wooded and manured than in the mineral field in the 0–10 cm and in the 20–30 cm depths (Table 3). The comparison in SOC concentration between manured and mineral treatment support the hypothesis that organic amend-

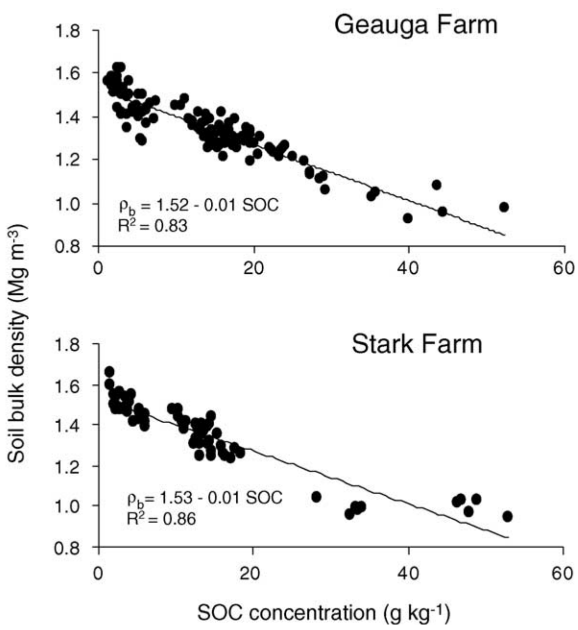

Fig. 1. Relationship between soil bulk density and soil organic carbon concentration.

Table 3
Soil bulk density, SOC and N concentration, C/N ratio and SOC and N pools for each fixed soil layer under different land use and crop management in Stark Farm

Depth (cm)	Land use or crop	Soil bulk density (Mg m^{-3})	SOC (g kg^{-1})	N (g kg^{-1})	C:N	SOC pool (Mg ha^{-1})	N pool (Mg ha^{-1})
0–5	Wooded	1.00 c	48.6 a	2.88 a	16.9 a	24.3 a	1.43 a
	Manured	1.26 b	17.0 b	1.38 b	12.7 b	10.8 b	0.85 b
	Mineral	1.32 a	14.3 c	1.12 c	12.9 b	9.4 c	0.73 c
	LSD ($P < 0.05$)	0.05	2.5	1.0	0.9	0.9	0.08
5–10	Wooded	0.99 b	32.4 a	1.84 a	17.8 a	16.0 a	0.90 a
	Manured	1.37 a	14.8 b	1.18 b	12.4 b	10.1 b	0.82 a
	Mineral	1.39 a	12.5 c	0.98 c	12.6 b	8.7 c	0.69 b
	LSD ($P < 0.05$)	0.06	2.2	0.19	1.1	1.1	0.09
10–20	Wooded	1.31	12.7	0.82	15.6 a	16.6	1.07 b
	Manured	1.37	12.3	0.94	13.2 b	16.8	1.27 a
	Mineral	1.39	11.6	0.92	13.0 b	16.1	1.24 a
	LSD ($P < 0.05$)	ns[a]	ns	ns	1.6	ns	0.17
20–30	Wooded	1.44	5.6 a	0.39	14.6 a	8.1 a	0.56
	Manured	1.49	4.8 a	0.41	11.7 b	7.2 a	0.61
	Mineral	1.48	3.8 b	0.38	10.0 b	5.6 b	0.56
	LSD ($P < 0.05$)	ns	0.9	ns	2.1	1.2	ns
30–50	Wooded	1.55	2.2	0.27	8.1	6.8	0.85
	Manured	1.50	2.8	0.32	8.5	8.2	0.97
	Mineral	1.50	2.9	0.34	8.2	8.5	1.01
	LSD ($P < 0.05$)	ns	ns	ns	ns	ns	ns

Abbreviations: wooded, wooded control; manured, corn in manured corn/soybean rotation; mineral soybean with chemical fertilizer in corn/soybean rotation. Different letter(s) on the same column and for the same depth are significantly different at $P < 0.05$ according to LSD separation test.

[a] Non-significant.

ment applied to the soil increases SOC concentration, which in turn induces changes in ρ_b (Haynes et al., 1991; Barzegar et al., 2002) and other soil properties.

3.3. Soil nitrogen concentration and C:N ratio

Total N concentration followed a pattern similar to that of SOC, but the C:N ratio narrowed in subsoil layers (Tables 2 and 3). Jenkinson (1988) also observed a decrease in C:N ratio and attributed it to the presence of fixed NH_4^+ by clays, which either remains constant or increases whereas SOC decreases with depth. The wooded treatment in all layers in Geauga Farm and <30 cm layer in Stark Farm showed wider C:N ratio than that in the cropped fields. The wider C:N ratio is indicative of a high concentration of partially decomposed plant material due to slower decomposition rate in strongly acid soil conditions (Tables 2, 3 and 6) (Jenkinson, 1988). Wider C:N ratio in the subsoil layers in wooded than in cropland fields may be due to high level of SOC attributed to deep root system of native perennials. Page et al. (2003) reported that removal of deep-rooted native vegetation (*Acacia harpophylla* Benth.) and introducing shallow-rooted crops changed the soil environment, lowered SOC, and contributed to subsoil NH_4 concentration.

3.4. Soil organic carbon and nitrogen pools

There were significant differences in SOC and N pools among management systems. In the Geauga Farm, SOC pool was the highest in wooded control than in the ARM field (Table 2). There were no statistical differences in SOC pool among CC and CCNT field for the same soil depth (Table 2). In the Stark Farm, the SOC pool was the highest in the wooded control in the top 30 cm depth (with exception of the 5–20 cm layer), and it was higher in manured than in mineral treatment. In both farms, the N pool followed trends similar to those of the SOC pool (Tables 2 and 3).

3.5. Carbon and nitrogen pools on an equivalent soil mass basis

In the Geauga Farm, the mass of the soil in CC was designated as an ‘‘equivalent mass’’ of the reference site (Table 4). The SOC pool computed for 0–20 cm depth was in the order: wooded > ARM > GRUM = CCNT = CC (Table 4). A similar gradation of SOC pool was observed in 0–30 cm layer, but there were no statistical differences in SOC pool among ARM and GRUM treatments (Table 4). Trends in soil N pool were similar to those of the SOC pool. Significant increases in SOC and N pools in ARM compared to CC indicate that increase in cropping intensity can increase SOC pool (Franzluebbers et al., 1994).

In the Stark Farm, the mass of the soil in mineral field was designated as an ‘‘equivalent mass’’ of the reference site. The SOC and N pools computed for the 0–20 cm and 0–30 cm layers followed the order: wooded > manured > mineral (Table 4). The significant increase in SOC pool in manured field in the Stark Farm and in ARM field in the Geauga Farm indicate the importance of crop rotation, tillage and fertility management on SOC pool and its distribution (Rasmussen and Collins, 1991; Collins et al., 1992; Potter et al., 1997).

3.6. Stratification of soil properties

In the Geauga Farm, the stratification ratio of SOC concentration was greater in wooded control than in agricultural fields. However, there were no significant differences among land management treatments

Table 4
SOC and N pools, for 0–20 and 0–30 cm soil layer recalculated on the equivalent on soil mass under different land use and crop management in farms in northeastern Ohio

Depth (cm)	Land use or crop	SOC pool (Mg ha^{-1})	N pool (Mg ha^{-1})
Geauga Farm			
0–20	Wooded (23.9)[a]	74.3 a	5.52 a
	CC (20.0)	38.0 c	3.11 c
	CCNT (21.0)	41.0 c	3.27 c
	ARM (20.8)	51.5 b	4.23 b
	GRUM (20.8)	43.3 c	3.57 c
	LSD ($P < 0.05$)	6.9	0.58
0–30	Wooded (34.8)	88.2 a	6.64 a
	CC (30.0)	43.3 c	3.68 c
	CCNT (31.1)	48.6 c	3.94 c
	ARM (30.8)	58.5 b	4.89 b
	GRUM (30.3)	50.4 bc	4.22 bc
	LSD ($P<0.05$)	8.9	0.72
Stark Farm			
0–20	Wooded (23.1)	59.4 a	3.58 a
	Manured (20.4)	37.9 b	2.96 b
	Mineral (20.0)	34.2 c	2.67 c
	LSD ($P < 0.05$)	2.8	0.28
0–30	Wooded (33.2)	66.1 a	4.10 a
	Manured (30.4)	44.9 b	3.57 b
	Mineral (30.0)	39.8 c	3.22 c
	LSD ($P < 0.05$)	3.1	0.29

Abbreviations: wooded, wooded control; CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured; manured, corn in manured corn/soybean rotation; mineral soybean with chemical fertilizer in corn/soybean rotation. Different letter(s) on the same column and for the same depth are significantly different at $P < 0.05$ according to LSD separation test.

[a] Equivalent soil depth (cm).

Table 5
Stratification ratio (0–5 cm/10–20 cm) in the Geauga Farm and Stark Farm

Land use or crop	Stratification ratio				
	Soil bulk density	SOC concentration	N concentration	SOC pool	N pool
Geauga Farm					
Wooded	0.83 c	1.74 a	1.72 a	1.45 a	1.42 a
CC	0.91 b	1.26 b	1.26 bc	1.15 b	1.15 bc
CCNT	0.94 ab	1.31 b	1.43 ab	1.25 ab	1.36 ab
ARM	0.92 b	1.17 b	1.16 bc	1.03 b	1.03 c
GRUM	0.98 a	1.08 b	1.01 c	1.06 b	1.00 c
LSD ($P < 0.05$)	0.06	0.28	0.29	0.25	0.25
Stark Farm					
Wooded	0.76 b	3.84 a	3.52 a	2.93 a	2.69 a
Manured	0.92 a	1.41 b	1.48 b	1.29 b	1.36 b
Mineral	0.95 a	1.24 b	1.25 b	1.18 b	1.18 b
LSD ($P < 0.05$)	0.08	0.27	0.28	0.15	0.20

Abbreviations: wooded, wooded control; CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured; manured, corn in manured corn/soybean rotation; mineral, soybean with chemical fertilizer in corn/soybean rotation. Different letter(s) on the same column and for the same farm are significantly different at $P < 0.05$ according to LSD separation test.

(Table 5). The stratification ratio for N concentration in wooded control was similar to that of CCNT but higher than that in other fields (Table 5). The stratification ratio for SOC and N pools was similar for wooded control and CCNT, but ARM and GRUM field had lower stratification ratio for SOC pool than those in wooded control, and lower stratification ratio for N pool than those in wooded control and CCNT fields (Table 5). In Stark Farm, the stratification ratio of SOC and N concentrations and pools was more in wooded control compared to manured and mineral treatments (Table 5).

The concept of using stratification ratio as a soil quality indicator is based on the influence of surface SOC level on erosion control, water infiltration and nutrient conservation (Franzluebbers, 2002). High

Table 6
Effect of land use and crop management on soil reaction (pH)

Land use or crop	Depth (cm)				
	0–5	5–10	10–20	20–30	30–50
Geauga Farm					
Wooded	4.76 c	4.60 c	5.86 c	4.66 c	5.04 c
CC	6.82 a	6.72 a	6.30 b	5.78 b	5.26 c
CCNT	6.46 b	6.40 b	6.40 b	6.14 ab	5.25 c
ARM	6.82 a	6.98 a	6.83 a	6.36 a	6.40 a
GRUM	6.20 b	6.20 b	6.12 b	6.30 ab	5.98 b
LSD ($P < 0.05$)	0.30	0.31	0.32	0.55	0.39
Stark Farm					
Wooded	3.92 b	4.04 c	4.18 c	4.22 c	4.72 b
Manured	6.60 a	6.62 a	6.70 a	6.10 a	5.68 a
Mineral	6.21 a	5.98 b	5.74 b	5.36 b	4.94 b
LSD ($P < 0.05$)	0.45	0.29	0.25	0.30	0.43

Abbreviations: wooded, wooded control; CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured; manured, corn in manured corn/soybean rotation; mineral soybean with chemical fertilizer in corn/soybean rotation. Different letter(s) on the same column and for the same farm are significantly different at $P < 0.05$ according to LSD separation test.

Table 7
Effect of land use and crop management on exchangeable bases, exchangeable acidity and cation exchange capacity (CEC) in 0–5 cm layer

Land use or till management	Bases ($cmol_c\ kg^{-1}$)					Acidity ($cmol_c\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)
	Ca^{2+}	Mg^{2+}	K^+	Na^+	Sum		
Geauga Farm							
Wooded	4.7 c	1.9 d	0.36	0.04 c	7.0 c	17.1 a	24.1 a
CC	9.5 a	4.6 a	0.50	0.05 b	14.7 a	7.0 bc	21.7 ab
CCNT	6.7 b	3.6 c	0.39	0.05 b	10.8 b	8.6 b	19.4 bc
ARM	9.4 a	4.1 b	0.40	0.07 a	14.0 a	6.4 c	20.4 b
GRUM	7.4 b	3.5 c	0.50	0.06 ab	11.5 b	6.2 c	17.7 c
LDS ($P < 0.05$)	1.49	0.4	ns[a]	0.017	1.9	2.1	2.4
Stark Farm							
Wooded	2.2 b	0.9 c	0.39 b	0.06 b	3.5 b	25.3 a	28.8 a
Manured	7.2 a	3.5 b	0.87 a	0.12 a	11.7 a	7.7 b	19.4 b
Mineral	8.4 a	4.5 a	0.64 ab	0.06 b	13.6 a	4.8 b	18.4 b
LDS ($P < 0.05$)	1.5	0.5	0.29	0.02	2.1	3.2	3.5

Abbreviations: wooded, wooded control; CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured; manured, corn in manured corn/soybean rotation; mineral soybean with chemical fertilizer in corn/soybean rotation. Different letter(s) on the same column and for the same farm are significantly different at $P<0.05$ according to LSD separation test.

[a] Non-significant.

stratification ratio of SOC and N pools reflects relatively undisturbed soil with high soil quality of surface layer. In arable lands, the stratification ratio is a function of tillage intensity and the amount of surface residue as the most important variable (Duiker and Lal, 1999). High stratification of SOC and N under no-till has also been reported by several researchers (Dick, 1983; Unger, 1991; Franzluebbers, 2002; Kay and VandenBygaart, 2002). In the present study however, corn grown on the field with 14 years of no-till management (CCNT) did not show significant differences in stratification ratio of several properties studied (Table 5). This support the findings of Balesdent and Balabane (1996) in that corn root derived C contributed 1.6 times more C to SOC than stoves-derived C.

3.7. Soil reaction, exchangeable bases, exchangeable acidity and cation exchange capacity

In the Geauga Farm, soil pH was neutral for CC and ARM, slightly acid for CCNT and GRUM, and very strongly acid for wooded control (Table 6). In the 30–50 cm layer, pH changed to slightly acid in ARM, moderately acid in GRUM, strongly acid in CC and CCNT, and remained very strongly acid in wooded control (Table 6). In the Stark Farm, soil pH was neutral in manured, slightly acid in mineral, and extremely acid in wooded control (Table 6). In the 30–50 cm layer, pH was moderately acid in manured and very strongly acid in mineral and wooded control treatments (Table 6). Similar trends of decline in pH in no-till were also reported by Dick (1983). In manured fields in both farms the pH was higher in all depths than in the other fields, and confirms that cattle and poultry manure can raise pH in the soils (Zhang, 1998; Whalen et al., 2000). In the Stark Farm, lower pH in mineral field may be due to use of N fertilization, and

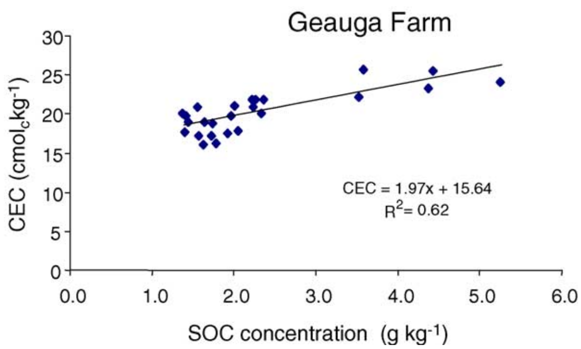

Fig. 2. Relationship between soil organic carbon and cation exchange capacity.

acidification caused by the attendant nitrification of surface applied N (Blevins et al., 1977; Dick, 1983).

In the Geauga Farm, sum of exchangeable bases in the surface 0–5 cm layer was higher for CC and ARM than for GRUM and CCNT, and was the lowest for wooded control (Table 7). The exchangeable acidity, was the highest in wooded control and the lowest in ARM and GRUM which were limed 2 years prior to sampling (Table 7). The highest CEC expressed as a sum of exchangeable bases and exchangeable acidity was in wooded control and CC and GRUM field had lower CEC than the other fields (CC, CCNT and ARM). These results show a relationship between SOC and CEC in Geauga Farm (Fig. 2). In the Stark Farm, there were no proved differences in the sum of exchangeable bases, exchangeable acidity and CEC among manured and mineral fields, but there was more Mg^{2+} in mineral than in manured field (Table 7). Similar to Geauga Farm, Stark Farm also had considerably lower amount of exchangeable bases, the highest exchangeable acidity, CEC and SOC concentration, and extremely acid pH in the wooded control (Table 7). Usually higher SOC concentration is associated with a higher cation exchange capacity (CEC) (Haynes and Naidu, 1998; Robert, 2001). Depending on soil pH, the SOC concentration may contribute 25–90% of total CEC (Stevenson, 1994; Loveland and Webb, 2003). Increase in CEC and SOC concentrations with application of organic manure and mineral fertilizer have also been observed in several long-term experiments (Schjønning et al., 1994). The comparison between manured and mineral treatments shows an increase in SOC but not in CEC, since the duration of manure management is 13 years and the manure is applied at low and irregular rates.

3.8. *The rate of sequestration of soil organic carbon*

The loss of SOC pool in 0–30 cm layer in cropland is estimated at 34% in ARM and 51% in CC in the Geauga Farm compared with 32% in manured and 40% in mineral in the Stark Farm (Table 4). The magnitude of SOC loss observed in these farms is similar to those reported by Davidson and Ackerman (1993) who found that conversion from natural to agricultural ecosystems resulted in 20–40% decline of SOC pool. The use of organic manures and adoption of complex rotations (comprising forages mixtures of legumes and grasses) enhanced SOC pools (Tables 4 and 8). In the Geauga Farm, the rate of SOC sequestration for CCNT used in previously hay field (no-till management for 14 years) vis-a-vis CC was 379 kg C ha^{-1} $year^{-1}$ (Table 8). This value is comparable to SOC gains reported by Puget et al. (2002) in 0–20 cm layer of silt-loam soil in east-central Ohio where 32 years of no-till management enhanced SOC pool at an average rate of 281 kg C ha^{-1} $year^{-1}$, and to SOC gains obtained in 0–30 cm layer of Wooster silt loam soil in central Ohio by Dick et al. (1998) where 30 years of no-till management enhanced SOC pool at an average rate of 566 kg C ha^{-1} $year^{-1}$. The highest rate of SOC sequestration was measured for complex diverse crop rotation combined with manuring and chemical fertilizer use. The rate of SOC sequestration in the ARM field was 760 kg C ha^{-1} $year^{-1}$ vis-a-vis CC field. Enhancing crop rotation complexity in the unmanured field with chemical fertilizer (GRUM) enhanced SOC pool at the rate of 355 kg C ha^{-1} $year^{-1}$ (Table 8). In the Stark Farm, under the same crop rotation but with different nutrient management, the rate of SOC sequestration in manured field was

Table 8
SOC gains in the Geauga Farm and Stark Farm fields with agricultural practices promoting SOC sequestration in 0–30 cm layer

Field	Factors promoting SOC sequestration	Duration (years)	SOC gain (kg ha^{-1} $year^{-1}$)
Geauga Farm (reference field = CC)			
CCNT	No-till, hay production	14	379
ARM	Rotation complexity with legume forages and manuring	20	760
GRUM	Rotation complexity with forage grasses	20	355
Stark Farm (reference field = mineral)			
Manured	Corn/soybean rotation amended with poultry manure	13	392

Abbreviations: CC, continuous corn; CCNT, continuous corn with no-till management; ARM, alfalfa in crop rotation with manure; GRUM, grass meadow in crop rotation unmanured; manured, corn in manured corn/soybean rotation; mineral soybean with chemical fertilizer in corn/soybean rotation. Calculations according to Lal et al. (1998).

392 kg C ha^{-1} year^{-1} vis-a-vis the mineral field (Table 8). Poultry manure appeared to be very effective in increasing SOC concentration (Nyakatawa et al., 2001).

4. Conclusions

The on farm data reported herein support the following conclusions:

(1) Increase in C input to the soils through manuring, judicious use of fertilizers and adoption of complex crop rotations is beneficial in enhancing agronomic productivity, which in turn enhances soil organic carbon pool.
(2) Manuring enhanced the soil organic carbon pool compared to chemical fertilizers because of additional input of carbon, improvement in soil quality, and increase in aggregation and structure.
(3) Adoption of no-till on-farm conditions in Ohio leads to similar rates of soil carbon sequestration as that on research plots.

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