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Impact of Nitrogen Fertilization and Cropping System on Carbon Sequestration in Midwestern Mollisols

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Abstract

Growing interest in the potential for agricultural soils to provide a sink for atmospheric C has prompted studies of effects of management on soil organic carbon (SOC) sequestration. We analyzed the impact on SOC of four N fertilization rates (0–270 kg N ha^{-1}) and four cropping systems: continuous corn (CC) (*Zea mays* L.); corn–soybean [*Glycine max* (L.) Merr.] (CS); corn–corn–oat–alfalfa (oat, *Avena sativa* L.; alfalfa, *Medicago sativa* L.) (CCOA), and corn–oat–alfalfa–alfalfa (COAA). Soils were sampled in 2002, Years 23 and 48 of the experiments located in northeast and north-central Iowa, respectively. The experiments were conducted using a replicated split-plot design under conventional tillage. A native prairie was sampled to provide a reference (for one site only). Cropping systems that contained alfalfa had the highest SOC stocks, whereas the CS system generally had the lowest SOC stocks. Concentrations of SOC increased significantly between 1990 and 2002 in only two of the nine systems for which historical data were available, the fertilized CC and COAA systems at one site. Soil quality indices such as particulate organic carbon (POC) were influenced by cropping system, with CS < CC < CCOA. In the native prairie, SOC, POC, and resistant C concentrations were 2.8, 2.6, and 3.9 times, respectively, the highest values in cropped soil, indicating that cultivated soils had not recovered to precultivation conditions. Although corn yields increased with N additions, N fertilization increased SOC stocks only in the CC system at one site. Considering the C cost for N fertilizer production, N fertilization generally had a net negative effect on C sequestration.

Keywords

ρb, CC, continuous corn CCOA, corn–corn–oat–alfalfa CE, Carlo-Erba COAA, corn–oat–alfalfa–alfalfa CS, corn–soybean MAP, mean annual precipitation PMC, potential mineralization of carbon POC, particulate organic carbon SIC, soil inorganic carbon SOC, soil organic carbon SOM, soil organic matter TN, total nitrogen WB, Walkley-Black

Disciplines

Agronomy and Crop Sciences | Natural Resources Management and Policy | Soil Science

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ABSTRACT

Growing interest in the potential for agricultural soils to provide a sink for atmospheric C has prompted studies of effects of management on soil organic carbon (SOC) sequestration. We analyzed the impact on SOC of four N fertilization rates (0–270 kg N ha^{-1}) and four cropping systems: continuous corn (CC) (*Zea mays* L.); corn–soybean [*Glycine max* (L.) Merr.] (CS); corn–corn–oat–alfalfa (oat, *Avena sativa* L.; alfalfa, *Medicago sativa* L.) (CCOA), and corn–oat–alfalfa–alfalfa (COAA). Soils were sampled in 2002, Years 23 and 48 of the experiments located in northeast and north-central Iowa, respectively. The experiments were conducted using a replicated split-plot design under conventional tillage. A native prairie was sampled to provide a reference (for one site only). Cropping systems that contained alfalfa had the highest SOC stocks, whereas the CS system generally had the lowest SOC stocks. Concentrations of SOC increased significantly between 1990 and 2002 in only two of the nine systems for which historical data were available, the fertilized CC and COAA systems at one site. Soil quality indices such as particulate organic carbon (POC) were influenced by cropping system, with CS < CC < CCOA. In the native prairie, SOC, POC, and resistant C concentrations were 2.8, 2.6, and 3.9 times, respectively, the highest values in cropped soil, indicating that cultivated soils had not recovered to precultivation conditions. Although corn yields increased with N additions, N fertilization increased SOC stocks only in the CC system at one site. Considering the C cost for N fertilizer production, N fertilization generally had a net negative effect on C sequestration.

There is a critical need for best management practices that enhance SOC sequestration. At the local and regional levels, increased SOC contributes positively to soil tilth, fertility, and water-holding capacity, and thereby increases crop production, promotes sustainability, and enhances land value for producers (Lal et al., 1997). At the global level, increased sequestration of C in agricultural soils has the potential to mitigate the increase in atmospheric greenhouse gases (Sampson and Scholes, 2000; Young, 2003). Widespread adoption of recommended management practices could sequester 45 to 98 Tg of SOC in croplands in the USA (Lal, 2003).

Within the current conceptual framework, management practices that optimize cropping systems and N fertilization are believed to offer the greatest potential for increasing SOC storage in agricultural soils (Lal et al., 1999; Lal, 2002). For example, analysis of long-term experiments indicated that increasing crop rotation complexity increased SOC sequestration by 20 g C m^{-2} yr^{-1}, on average (West and Post, 2002). In long-term experiments in Canada, SOC sequestration rates were 50 to 75 g C m^{-2} yr^{-1} in well-fertilized soils with optimum cropping systems (Dumanski et al., 1998). In contrast, long-term experiments in the northern Great Plains (ND) have shown that fertilizer N increased crop residue returns, but generally did not increase SOC sequestration (Halvorson et al., 2002). Timing and intensity of tillage also must be taken into account in the design of best management practices for maximizing SOC sequestration (Studdert and Echeverría, 2000).

Changes in SOC due to management practices are difficult to quantify because changes occur slowly, are relatively small compared with the total SOC pool size, and vary both spatially and temporally (Paustian et al., 1997; Russell et al., 2004). Soil C fractions, such as POC and potentially mineralizable carbon (PMC), are expected to be more responsive to management than total SOC (Powlson and Jenkinson, 1981; Cambardella and Elliott, 1992). Thus, these fractions may serve as harbingers of future changes in total SOC that are presently undetectable. Whereas PMC provides an index of labile SOC, POC is a measure of SOC that turns over on intermediate time scales (Cambardella and Elliott, 1992). Resistant SOC generally has longer turnover times, and thus provides information about the long-term potential for SOC sequestration (Paul et al., 2001). Because these soil C fractions are characterized by their turnover times, their pool sizes provide insight into the effects of management practices that could not be gleaned from studies of total SOC alone.

Model simulations indicate that reduced tillage and greater inputs of organic matter can return soils to precultivation levels of SOC (Paustian et al., 1998). Modeled potential C sequestration, however, may not be readily attainable (Ingram and Fernandes, 2001) due to various limiting factors (e.g., climate, time, and less-than-optimum management). Realistic estimates of SOC sequestration potential are best derived from careful analysis of long-term, replicated experiments in sites without confounding histories. Currently, there is a need for more data for some of the most productive and intensively managed soils of the world, Mollisols in the midwestern Corn Belt. Well-managed long-term experimental sites are rare, but thanks to the diligence of our predecessors we had access to two sites with experi-

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Abbreviations: ρ_b, bulk density; CC, continuous corn; CCOA, corn–corn–oat–alfalfa; CE, Carlo-Erba; COAA, corn–oat–alfalfa–alfalfa; CS, corn–soybean; MAP, mean annual precipitation; PMC, potential mineralization of carbon; POC, particulate organic carbon; SIC, soil inorganic carbon; SOC, soil organic carbon; SOM, soil organic matter; TN, total nitrogen; WB, Walkley-Black.

ments designed for testing long-term effects of N fertilization and cropping systems under conventional management. The objectives of this study were to quantify the long-term effects of N fertilization and cropping system on SOC stocks and fractions, to determine the rate of change in SOC during the last 12 yr, and to advance understanding of the mechanisms by which these management systems influence soil C sequestration.

MATERIALS AND METHODS

Site Descriptions

Soil samples for this study were collected from selected plots of two long-term experiments regarding cropping system and N fertilization and one native prairie site. The experimental sites, Nashua and Kanawha, named after nearby towns, were located in fields of the Iowa State University Northeast and Northern Research and Demonstration Farms, respectively. The experiments were established in 1954 at Kanawha and in 1979 at Nashua. Information about cropping systems, soil management, N fertilization treatments, and crop yields has been published before (Mallarino and Pecinovsky, 1999; Mallarino and Rueber, 1999). Methods relevant to this SOC sequestration study are briefly summarized here. Treatments included four N fertilization rates, 0 to 270 kg N ha^{-1} applied only to corn at both sites, three cropping systems at Nashua, and four cropping systems at Kanawha. The systems sampled were CC for grain, CS, CCOA, and COAA (Kanawha only). In previous studies at these sites, the alfalfa phase in the rotation was referred to as "meadow" (Robinson et al., 1996). At both sites, all phases of each rotation are present in every year, but we sampled only plots of the first corn phase of the rotations. A split-plot randomized block design was used at both sites, with cropping system in main plots and N treatments in subplots. The Nashua site had three blocks for a total of 36 plots, and the Kanawha site had two blocks, 32 plots total. Subplot size was 4.6 by 15.2 m at Nashua and 6.1 by 12.2 m at Kanawha. The predominant soil at Nashua was Kenyon (fine-loamy, mixed, superactive, mesic Typic Hapludolls), with a smaller area of Readlyn (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Average particle size composition for the 15-cm surface layer (Robinson et al., 1996) was 319, 456, and 224 g kg^{-1} for sand, silt, and clay, respectively. The soil at Kanawha was Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls). Average particle size composition for the 15-cm layer (Robinson et al., 1996) was 219, 449, and 332 g kg^{-1} for sand, silt, and clay, respectively.

At both sites, all cropping systems were tile drained and rain fed. Primary tillage in the fall following corn and alfalfa was chisel plowing at Nashua and moldboard plowing at Kanawha. At both sites, the soils were always disked once in the spring, hence spring disking was the only tillage used for soybean residues. Nitrogen fertilizer treatments were applied in spring before disking, using granulated urea at rates of 0, 90, 180, and 270 kg N ha^{-1}. At Kanawha, N rates had been increased in 1971, and again in 1984 to keep pace with contemporary practices. The N rates were 0, 34, 68, and 136 kg N ha^{-1} from 1954 until 1970. In 1971, the 34-kg N rate was changed to 202 kg N ha^{-1}. A final change of N rates was made in 1984, when the 68-kg rate was changed to 90 kg, the 136-kg rate to 180 kg, and the 202-kg rate was changed to 270 kg. Since 1984, the N rates evaluated have been 0, 90, 180, and 270 kg N ha^{-1}, the same as at Nashua. These N-rate treatments will be referred to as 0-N, 90-N, 180-N, and 270-N. An undisturbed prairie (Hayden Prairie), located 50 km north of Nashua, was also sampled to provide a reference point. The predominant soil series were similar to those at Nashua. The dominant plant species included *Poa pratensis* L., Kentucky bluegrass; *Andropogon gerardii* Vitman, big bluestem; *Heliopsis helianthoides* (L.) Sweet, smooth oxeye; *Rosa arkansana* Porter, prairie rose; *Calamagrostis canadensis* Michx. (Beauv.), Bluejoint reedgrass; and *Thalictrum dasycarpum* Fisch. & Avé-Lall, purple meadow rue (Christensen, 1996). The Kanawha site is 120 km west of Nashua. We had no reference for the Kanawha site, because native prairie on similar soils no longer exists near Kanawha. Mean annual precipitation (MAP) was 806 mm at Kanawha, ranging from 533 mm (1989) to 1221 mm (1993) during a 53-yr period (data from Clarion station) (1951–2003) (Iowa Environmental Mesonet, 2004). At Nashua, MAP was 847 mm, with a range of 421 mm (1989) to 1304 mm (1999) (Charles City station). Hayden Prairie MAP was 845 mm and ranged from 492 mm (1989) to 1161 mm (1999) (Osage station).

Sampling Protocol

For an intensive study at the Nashua site in 2001, soil samples (0–15 cm) were collected monthly (April–November) from plots of the 0- and 180-N treatments of the CC, CS, and CCOA systems. For an extensive study in 2002, soil profile samples (0–5, 5–15, 15–30, 30–50, 50–75, and 75–100 cm) were collected from all N treatments and cropping systems at both sites during a single postharvest sampling (in October) before fall tillage, and also from the native prairie (in late August). Soil cores were taken using a 3.2-cm-diam. probe in 2001, a 4.1-cm-diam. probe in 2002 for the agricultural plots, and a 6.0-cm core for the prairie. Six soil cores were taken from each plot, at points randomly selected within a design stratified by position: in the cornrow, the midpoint between cornrows, and halfway between those two positions. The six cores, collected at Nashua and Kanawha from each plot and soil depth, were bulked into a composite sample. The six cores that were taken from the prairie were analyzed separately (because replicates were not applicable). To avoid edge effects, no samples were collected within 1 m of the borders of the contiguous plots. All samples were air-dried, roots were removed, rock masses and volumes were determined, and soil was passed through a 2-mm sieve. Subsamples were dried at 105°C to determine conversion factors to a 105°C dry-weight basis.

For the intensive study, we measured SOC, total nitrogen (TN), PMC, POC, and resistant C (non-acid-hydrolyzable), for samples collected from April to November for one depth increment (0–15 cm). For the extensive study, we measured bulk density (ρ_b), SOC, TN, and soil inorganic carbon (SIC) for each depth increment, while PMC was measured only for the 5- to 15-cm depth.

Laboratory Evaluations

Total soil C and TN were determined by dry combustion using a Carlo-Erba NA1500 NSC elemental analyzer (Haake Buchler Instruments, Paterson, NJ) (CE method). Total SOC concentration was calculated as the difference between total C and SIC, which was measured by the modified pressure-calcimeter method (Sherrod et al., 2002). Storage of SOC was calculated as the product of ρ_b, soil thickness, and SOC concentration. Bulk density was determined for each depth increment by the soil core method, using the samples collected in October 2002 (Blake and Hartge, 1986). Measurements were corrected to exclude rocks. Sampling of unequal soil masses across treatments and across time can introduce bias into calculations of SOC stocks (Ellert et al., 2001). To minimize this bias, we used mean ρ_b across all plots within sites and depths in our calculations of SOC stocks, and sampled extensively to characterize each site when ρ_b would be least variable among treatments (postharvest, but before tillage). Plots at both sites were uniformly level, so differences in losses due to erosion were assumed to be equal. In the agricultural plots, the layer most sensitive to treatment effects, 0 to 15 cm, was situated well within the homogenized plow layer, such that samples at fixed depths within this layer were comparable among treatments and across time. Low ρ_b in the prairie resulted in a soil sample mass of only 6.57 kg, compared with an average of 10.12 kg per fixed volume (0- to 100-cm depth) in the Nashua agricultural plots. To compare soils on an equivalent-mass basis with the prairie soils, SOC stocks in the agricultural soils were summed to a depth of 67.7 cm.

Historical SOC data were not available from the beginning of either experiment; however, published data from a 1990 soil sampling for selected plots were available (Robinson, 1993). To assess changes in SOC across time, we compared our SOC concentrations for 0 to 15 cm measured in 2002 with concentrations reported by Robinson (1993) for the same depth and treatments in 1990: CC (0-N and 180-N), CS (180-N), CCOA (180-N), and COAA (180-N, Kanawha only). At Nashua, measurements in 1990 and 2002 correspond to Years 11 and 23 of the experiment. At Kanawha, the 0-N treatment had been in effect since 1954, so these measurements correspond to Years 36 (by 1990) and 48 (by 2002) without N fertilization. In the 1990 study, SOC was determined by the Walkley-Black (WB) method (Robinson et al., 1996), whereas we used dry combustion, the CE method. Thus, to make comparisons between sample dates, it was necessary to determine site-specific conversion factors between the two methods. We analyzed SOC by both WB and CE in two cropping systems (CS and CCOA), two N levels (0- and 180-N), and two depths (0–5 and 5–15 cm) for all blocks at Nashua (24 samples total) and Kanawha (16 samples). We assumed a constant factor of 1.724 for conversion of soil organic matter (SOM) determined by WB to SOC (Nelson and Sommers, 1996). The relationships between SOC (g kg^{-1}) estimated by the two methods were: Nashua, CE = 1.05 × WB − 6.19 (R^2 = 0.989); Kanawha, CE = 0.892 × WB − 5.56 (R^2 = 0.984). Historical data for WB conversion factors were not available, so the untested assumption was that there was no change.

Potentially mineralizable C was assayed by measures of CO_2–C released during 28-d laboratory incubations at 23°C (Paul et al., 2001, Russell et al., 2004). For the 2001 samples, field-moist soil was sieved (4 mm) and kept refrigerated until incubations began, within 48 h of collection. For each sample time and plot, 20 g of soil were incubated in vials placed in a one-pint (473 mL) Ball jar. Approximately 1.5 mL of distilled water was added to the bottom of each Ball jar to keep the atmosphere hydrated. Duplicates were run on all samples. Soil moisture was low at all sampling times from May to November, so distilled water was added to adjust samples to 50% water-filled pore space before incubations in those months. Subsamples were dried at 105°C to determine moist-to-dry-weight conversion factors. Rate of CO_2–C released was measured periodically (before CO_2 concentrations reached 4%) by flushing the jar headspace through an infrared gas analyzer for 2001 samples (IRGA, Rosemount Analytical, Inc., Orrville, OH) (Paul et al., 2001). In 2002, the same principles but slightly different methods were applied to accommodate the extensiveness of the field sampling and to conform to protocols of a multisite project. The depths sampled were 0 to 15 cm in 2001 and 5 to 15 cm in 2002. Because these soils were moldboard and chisel plowed, the top 15 cm was well homogenized; preliminary SOC data indicated that the two sampled layers did not differ significantly. In the 2002 sampling, air-dried 2-mm-sieved soils were used in the assays of 5-g samples with three laboratory replicates using an IRGA (Model 3300, Automated Custom Systems, Orange, CA). Soil samples were hydrated to 50% water-filled pore space before incubation. The PMC was high in the prairie soils, so to avoid surpassing the measurement capacity of the IRGA, sample masses were reduced to 3 g, and six replicates were analyzed. Incubation-tube atmosphere was kept hydrated by piping the air supply through a water bath.

Particulate organic C was quantified according the method of Cambardella and Elliott (1992). A single 10-g sample per plot was first dispersed by shaking 18 h on a reciprocal shaker in 30 mL of 5 g L^{-1} sodium metaphosphate. The sample was rinsed thoroughly with distilled water and passed through a 53-μm sieve. The (silt + clay) material that passed through the sieves was captured in a receiving pan, dried at 70°C, ground with mortar and pestle, and analyzed for SOC and TN. The amount retained on the sieve (POC plus sand) was dried at 50°C and weighed. The POC was calculated as the difference between SOC and silt + clay SOC, corrected for the amount recovered. Particulate OC was analyzed in the samples taken from April to July.

The passive or resistant soil C fraction was determined by refluxing 1 g soil in 5 mL 6 *M* HCl at 115°C for 18 h in a temperature-controlled digestion block (Paul et al., 2001). Refluxed samples were washed in 1000 mL deionized water, dried at 55°C, and ground in a mortar and pestle for analyses of C and N. Values were corrected for non-C content lost during hydrolysis. Although material in this fraction is relatively old, it may also contain newer SOC from modern plant lignin that is not hydrolyzed (Paul et al., 2001).

Statistical Analyses and Calculations

Analyses of variance for testing cropping system and N fertilization effects on measurements were conducted for a split-plot randomized block design using PROC GLM of SAS (SAS Institute, 1990) with all effects treated as fixed (Littell et al., 1991). Treatment means were compared using Tukey's studentized (HSD) multiple-comparison test. Planned comparisons within a cropping system were unfertilized (0-N) vs. fertilized treatments (90-N, 180-N, and 270-N). At Kanawha, planned comparisons within an N treatment consisted of contrasts between cropping systems with and without alfalfa in the rotation (CC and CS vs. CCOA and COAA). For the response variables measured at monthly intervals in 2001 (POC, PMC, and resistant C), ANOVA was first conducted using a repeated measures design to test for differences among the monthly sampling times (Littell et al., 1991). Relationships between PMC and SOC were assessed using correlation analysis (SAS Institute, 1990).

Gross and net C sequestration were calculated as described by Schlesinger (2000), using a factor of 1.4 to represent the full accounting of emissions of CO_2 associated with all aspects involved in N fertilizer production, transportation, and application (Cole et al., 1993; Izaurralde et al., 1998). Nitrogen fertilization effects on SOC were calculated as the difference between SOC in fertilized and unfertilized plots sampled in 2002 because no data were available from the beginning of the experiment.

RESULTS AND DISCUSSION

Soil profiles differed among the two agricultural sites and the native prairie, with regard to SOC and SIC concentrations, C/N ratio, and ρ_b (Fig. 1). In the 0- to

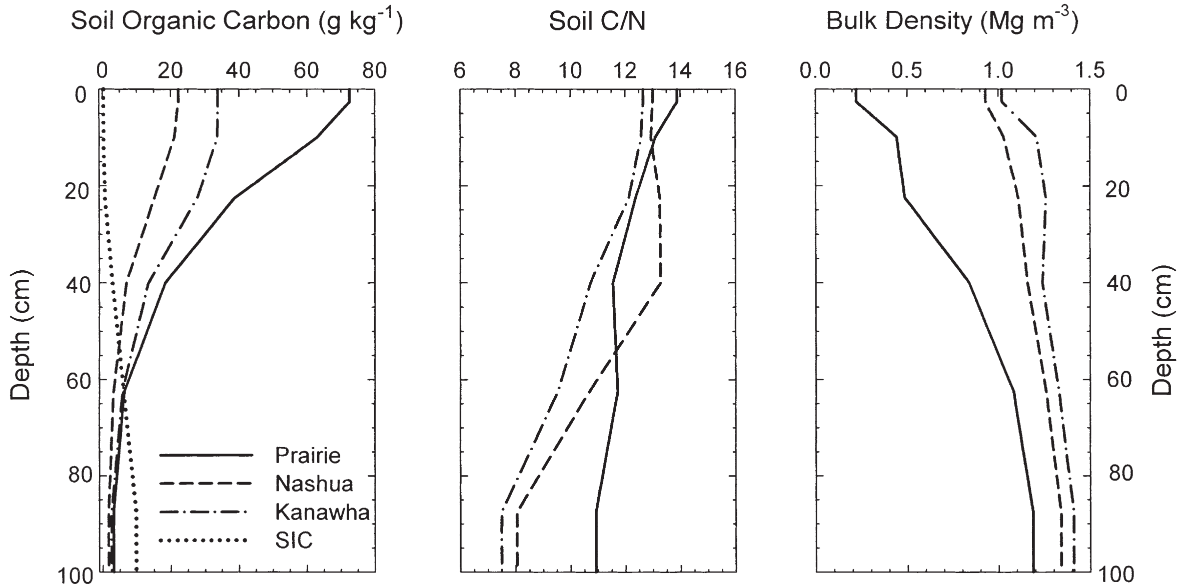

Fig. 1. Average soil organic C concentrations, C/N ratio, and bulk density, 0–100 cm at two long-term cropping system experiments conducted in north central (Kanawha) and northeast (Nashua) Iowa, and a native undisturbed prairie site located 50 km from the Nashua cropping system experiment. Data for soil inorganic C (SIC, g kg^{-1}) are for Kanawha, the only site with measurable concentration of carbonates.

15-cm depth interval, the prairie's SOC (66.1 ± 1.2 g kg^{-1}) was 2.8 times higher than the highest SOC for the cropping systems at Nashua, CCOA, whether fertilized or not (22.7 ± 0.3 g C kg^{-1} in 0-N and 23.6 ± 0.7 g C kg^{-1} in 270-N). Throughout the entire 100-cm profile, ρ_b was substantially lower in the prairie, and C/N tended to be higher.

Among all combinations of treatments, SOC stocks (0–100 cm, fixed-volume basis) at Nashua were lowest in CS (0-N), 76 Mg C ha^{-1}, and highest in CCOA (270-N), 119 Mg C ha^{-1} (Table 1). At Kanawha, SOC ranged from a low of 120 Mg C ha^{-1} in CC (90-N) to a high of 186 Mg C ha^{-1} in the CCOA (0-N) system. On an equivalent-mass basis, Nashua SOC ranged from 69 to 108 Mg C ha^{-1}, in comparison with SOC stocks of 121 Mg C ha^{-1} in the prairie.

Effects of Nitrogen Fertilization on Soil Organic Carbon Stocks

The effect of N fertilization on SOC stocks differed among cropping systems, and between depth intervals and sites (Table 1). At Nashua, for the 0- to 15-cm depth, the effect of N fertilization on SOC stocks (averaged across all cropping systems) was significant (P = 0.007). Within a cropping system, however, SOC increased significantly with N fertilization only in the CC system (Table 1). For the 15- to 100-cm depth, the effect of N fertilization across all cropping systems was not significant (P = 0.814), such that SOC to a 1-m depth was not significantly influenced by N fertilization (P = 0.612). At Kanawha, N fertilization effects across all cropping systems were not significant for the 0- to 15-, 15- to 100-, or 0- to 100-cm depths (P = 0.664, 0.724, and 0.896, respectively). At Nashua, mean SOC (Mg C ha^{-1}, 0–100 cm), averaged across all cropping systems for the 0-, 90-, 180-, and 270-N treatments were 110, 101, 104, and 119, respectively; at Kanawha, the respective values were 179, 178, 147, and 163.

High variability in SOC, relative to differences among treatments, contributed to the lack of statistical significance. At Kanawha, other factors contributed to the lack of significant effect of N fertilization: only two replicates for each treatment, high variability between the two blocks, and a high buffering capacity of the soil due to the high soil clay content. Omay et al. (1997) found no significant increase in SOC with N fertilization at two long-term sites in Kansas. Neither N fertilization nor cropping system influenced concentrations of SIC at Kanawha (Fig. 1), the only site in which soils contained carbonates.

Effects of Cropping System on Soil Organic Carbon Stocks

At both sites, cropping systems influenced SOC stocks, but the effects depended on N fertilization and depth (Table 1). At Nashua, in the 0- to 15-cm depth, mean SOC stocks (across all N treatments) increased significantly (P = 0.032) for cropping systems in the following order: CS ≪ CC < CCOA. Soil OC stocks were significantly lower in CS than in CCOA at the 0- and 270-N level (Table 1). At Kanawha, the effect of cropping system was not significant (P = 0.21 for 0–15 cm). In pooled comparisons, however, cropping systems that contained alfalfa in the rotation (CCOA and COAA) had significantly higher SOC stocks than systems without alfalfa (CC and CS) at all N levels except 180-N (Table 1). Omay et al. (1997) had similar results in that SOC was lower under CS compared with CC at two long-term sites in Kansas, on irrigated soils with lower SOC than at our sites. In the 15- to 100-cm depth, across all N treatments, the effect of cropping system was not significant at either site (P = 0.222 and 0.181, Nashua

Table 1. Long-term effects of cropping system and N fertilization on stocks of total soil organic carbon (SOC) for two depth intervals at the Nashua and Kanawha, IA, long-term experimental sites.

Cropping system†	N treatment, kg N ha^{-1}‡ 0	90	180	270	MSD§	P	P_{CN}¶
	SOC, Mg ha^{-1}						
Nashua, 0–15 cm							
CS	31.4a#	34.1	32.8	34.4a	5.5	0.311	0.116
CC	35.1abA	37.8AB	38.4AB	39.5bB	3.5	0.022	0.005
CCOA	39.0b	38.8	38.5	40.5b	3.9	0.369	0.799
MSD	5.4	6.6	6.9	4.8			
P	0.019	0.132	0.068	0.020			
Nashua, 15–100 cm							
CS	45.1	57.5	55.7	51.2a	33.4	0.604	0.262
CC	68.0	60.3	67.6	63.3ab	27.3	0.732	0.524
CCOA	71.1	62.2	65.2	78.3b	21.6	0.148	0.640
MSD	29.1	42.8	52.6	24.8			
P	0.062	0.928	0.717	0.043			
Kanawha, 0–15 cm							
CS	46.0	46.3	48.0	43.9	28.7	0.920	0.991
CC	42.4	46.2	51.3	47.8	24.6	0.481	0.240
CCOA	56.5	50.7	54.2	55.5	16.6	0.471	0.364
COAA	49.8	58.2	53.4	55.9	23.7	0.481	0.231
MSD	22.4	36.1	13.1	20.6			
P	0.173	0.459	0.277	0.151			
P_{CC}††	0.045	0.021	0.111	0.020			
Kanawha, 15–100 cm							
CS	102.7	85.4	96.7	84.5	111.6	0.828	0.516
CC	85.5	73.4	103.8	79.9	109.3	0.626	0.990
CCOA	129.0	129.8	112.2	127.3	94.6	0.787	0.736
COAA	129.3	119.9	94.0	107.5	117.5	0.574	0.347
MSD	100.4	138.2	35.7	48.6			
P	0.277	0.324	0.244	0.048			
P_{CC}	0.098	0.111	0.628	0.016			

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ N fertilizer added in corn phase only.
§ MSD = minimum significant difference, Tukey's test.
¶ P_{CN} = Significance ($P > F$) of planned contrasts between unfertilized and fertilized treatments.
# Values within a column (N rate) followed by the same lowercase letter do not differ significantly among cropping systems (P = 0.05). Values within a row followed by the same uppercase letter do no differ significantly among N treatments.
†† P_{CC} = Significance of planned contrast between cropping systems with and without alfalfa in the rotation (CC and CS vs. CCOA and COAA).

and Kanawha, respectively). Within the 270-N treatment, however, systems that contained alfalfa had significantly greater SOC stocks than did CS (both sites) and CC (Kanawha only) (Table 1).

The fact that tillage, as well as cropping system, influences SOC stocks is well documented (Lal et al., 1997; Robertson et al., 2000; Hao et al., 2002). In our study, because crop effects are confounded with tillage-frequency effects, we cannot discern whether the increase in SOC stocks in systems containing oat and alfalfa was caused by traits of the crops in the sequence, or the absence of tillage during 2 to 3 yr of the 4-yr sequence.

Change in Soil Organic Carbon and Net Carbon Sequestration

During the 12 yr between the 1990 and 2002 samplings at Nashua, the rates of SOC loss (0–15 cm) in the CS (180-N) and CC (0-N), and gains in CC and CCOA (180-N) did not differ significantly from zero (Table 2). During the same 12 yr at Kanawha, SOC increased for all systems, but this increase was significant only in the fertilized CC and COAA cropping systems. The two sites had similar trends among cropping systems in that the fertilized CS system had the lowest increase in SOC at Kanawha and the greatest decline at Nashua, even in comparison with unfertilized CC. Similarly, Studdert and Echeverría (2000) found that SOC loss increased with soybean in the rotation.

Paustian et al. (2002) incorporated detailed data sets regarding Iowa climate, soils, land use, and management practices into CENTURY, a process-based model that has been widely used to examine SOM dynamics (Parton et al., 1987). Paustian et al. (2002) estimated that the current sink for CO_2 in agricultural soils in Iowa is 3.1 MMTC yr^{-1}, ≈15% of CO_2 emissions from the state's fossil fuel emissions in 1997 (USEPA, 2001). These researchers estimated that Iowa's agricultural soils could sequester two to three times more C if the 50% of cropland now managed under conventional, intensive tillage were converted to no-till practices. They also predicted soil C gains of 0.25 Mg ha^{-1} yr^{-1} by changing from intensive- to moderate-till practices. The trends in our Nashua data were consistent with this latter prediction, although ours was not a straightforward test regarding effects of lower tillage frequency because residue inputs also differed (Table 2).

Our analysis of changes in soil C stocks was limited to the last 12 yr of the experiments and the nine treatments for which we have historical data. To compare net SOC sequestration (0–15 cm) among all fertilized treatments during the entire course of the experiment, we used the unfertilized treatments within each site and cropping system as the baseline for comparison of SOC stocks in the fertilized treatments. In general, with such small differences in soil C storage between fertilized and unfertilized treatments, the calculated emissions of

Table 2. Change in soil organic carbon (SOC, 0–15 cm) between 1990 and 2002 at the Nashua and Kanawha, IA, long-term experimental sites.

Site	Cropping system†	N treatment	SOC change‡	SOC rate of change	P_0§
		kg N ha^{-1}	mg C g^{-1}	Mg C ha^{-1} yr^{-1}	
Nashua	CS	180	−1.47 (0.86)	−0.21 (0.13)	0.304
	CC	0	−1.23 (1.01)	−0.18 (0.15)	0.480
	CC	180	0.47 (1.43)	0.07 (0.21)	0.722
	CCOA	180	1.63 (1.77)	0.24 (0.25)	0.280
Kanawha	CS	180	2.40 (1.90)	0.30 (0.24)	0.373
	CC	0	4.05 (3.25)	0.51 (0.41)	0.402
	CC	180	5.10 (1.50)	0.64 (0.19)	0.041
	CCOA	180	3.15 (0.35)	0.39 (0.04)	0.107
	COAA	180	6.15 (0.25)	0.77 (0.03)	0.002

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ Changes during 12 yr were calculated using data from Robinson (1993), August sampling, assuming no change in bulk density.
§ P_0 = significance of rate of change across time (within cropping system and N treatment).

CO_2 from fertilizer production nearly equaled or exceeded the increase in soil C accumulated in 17 out of 21 of our cropping systems under the three fertilization levels (Table 3). By Schlesinger's (2000) method of calculation, as much as 793% of the increase in soil C stored was released as CO_2 during the fertilizer production. The analysis was not meaningful in six of the systems due to a negative difference in SOC stocks (i.e., SOC stocks were higher under the unfertilized treatment). The only system that showed a net gain in SOC at Nashua was the CS under 90-N treatment. At Kanawha, the CC (90-N and 180-N) and COAA (all three N levels) had net gains in SOC. With N fertilizer added only once every 4 yr, the COAA system probably achieved a favorable balance because the CO_2 emissions associated with fertilizer production and use were low due to lower N inputs, and did not offset the increase in SOC from the cropping system. Our analyses by Schlesinger's (2000) method differed from recent studies of C emissions in agriculture in that we accounted for CO_2 emissions associated only with N fertilizer, and our conversion factor (1.4) was higher than in other studies (West and Marland, 2002). Nevertheless, our estimates of net C flux were only 2% higher than the average reported for corn under conventional tillage (West and Marland 2002), and our estimates of CO_2 emissions fall within the range expected due to variability among sites (Marland et al., 2003).

Constraints to Soil Organic Carbon Sequestration

Sequestration of SOC is determined by the difference between inputs of organic C and losses via decomposition. The N fertilization treatments applied to corn in the two experiments increased corn yield (compared with the unfertilized check) of the CC and CS systems in all years of the studies. Fertilizer N also increased oat yield of the CCOA in many years, while yields of soybean, alfalfa, and oat for the COAA system (at Kanawha) were not affected (Mallarino and Pecinovsky,

Table 3. Proportion of apparent C sink in soil that is released during N fertilizer production at the Nashua and Kanawha, IA, long-term experimental sites.

Cropping system†	N treatment‡	Cumulative N application§	Cumulative C cost¶	CO_2–C released¶
	kg ha^{-1}	mol N m^{-2}	g C m^{-2}	% of sequestration
Nashua				
CC	90	14.8	249	92
	180	29.6	497	149
	270	44.3	746	167
CS	90	7.4	124	46
	180	14.8	249	172
	270	22.2	373	125
CCOA	90	7.4	124	NM#
	180	14.8	249	NM
	270	22.2	373	251
Kanawha				
CC	90	25.9	436	114
	180	52.0	875	98
	270	57.6	968	177
CS	90	13.0	218	793
	180	26.0	438	222
	270	28.8	484	NM
CCOA	90	13.0	218	NM
	180	26.0	438	NM
	270	28.8	484	NM
COAA	90	6.5	109	13
	180	13.0	219	61
	270	14.4	242	40

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ N fertilizer added in corn phase only.
§ Based on the history of N application since 1979 at Nashua and 1948 at Kanawha.
¶ Calculation described by Schlesinger (2000).
# NM = not meaningful due to negative value (less soil C in fertilized treatment).

Table 4. Correlations between corn yields and soil organic carbon (SOC) stocks (0–100 cm) in three cropping systems under four N treatments at the Nashua and Kanawha, IA, long-term experimental sites.

Site	Cropping system†	Correlation of SOC with yield‡	
		r§	*P*
Nashua	CC	0.148	0.852
	CS	0.841	0.159
	CCOA	0.038	0.962
Kanawha	CC	0.344	0.655
	CS	−0.621	0.379
	CCOA	−0.489	0.511

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ Average first-crop corn yield data for Nashua are from 1979–1998, and from Kanawha, 1985–1998; SOC data are from 2002.
§ Pearson's correlations coefficient, $n = 4$ in each comparison.

1999; Mallarino and Rueber, 1999). Measurements of corn biomass production that we conducted in 2001 and 2002 at both sites at the physiological maturity growth stage indicated, as expected, that N fertilization increased residue inputs (Russell, unpublished data, 2001 for Nashua and 2002 for Kanawha). In spite of large grain yield response to N fertilization, yield was not significantly correlated with SOC stocks (0–100 cm) under any cropping system, at either site (Table 4). Also, corn yields across all cropping systems within a site were uncorrelated with SOC stocks ($r = 0.080$, $n = 12$, $P = 0.806$ at Nashua; $r = 0.262$, $n = 16$, $P = 0.327$ at Kanawha). These results suggest that differences among systems in SOC sequestration (Table 2) were not related to quantity of residue inputs alone.

At Nashua, the lack of significant change in SOC concentrations during the last 12 yr of the experiment, and SOC levels well below those of the native prairie, suggest that constraints to SOC sequestration exist in these systems. One explanation for this, and for the lack of correlation between quantities of inputs and SOC stocks, is that decomposition processes play a relatively important role in C sequestration in these systems. By examining various aspects of SOC quality and mineralization, we evaluated the potential for cropping system and N fertilization to influence SOM decomposition differentially.

Soil Organic Carbon Mineralization

Soil C/N ratios provide insight into SOC quality and relative 'decomposability'. Soil C/N ratios were higher under native prairie than the agricultural systems, and remained relatively constant with depth, whereas C/N ratios decreased substantially with depth in agricultural systems (Fig. 1). Among the agricultural soils at Nashua, C/N ratios were higher under CC than CS and CCOA (Table 5). Variability in soil C/N between blocks was high at Kanawha, such that differences were not significant. The high C/N ratios in the prairie soils and the soils under CC at Nashua suggest that the SOC was relatively less decomposed in these systems relative to the CS and CCOA systems. However, C/N ratios tell only part of the story.

Averaged across the whole growing season (2001), PMC determined by 28-d aerobic incubations did not differ significantly among cropping systems ($P = 0.104$) or N treatments ($P = 0.293$) (Crop × N rate, $P = 0.421$). However, PMC varied significantly during the course of the growing season ($P = 0.001$), and effects of cropping system depended on the N treatment and month (Table 6). During the summer months at Nashua, PMC was significantly lower in the CC cropping system than under CCOA (June–August 2001) and CS (June 2001 only) (Table 6). With seasonal data from only 1 yr, we could not evaluate the strengths of the seasonal relationships. Because our sampling was limited to plots in the first corn rotation, these differences in trends in mineralization may reflect the decomposability of residue from the previous crop (i.e., soy for CS, corn for CC, and alfalfa for CCOA). Nevertheless, by fall, for which we have 2 yr of data, cropping systems did not differ in PMC in either year. This suggested that relatively labile OM from the previous year had been mineralized by the end of the growing season, regardless of the quality of the residue inputs in the previous year. At Kanawha, PMC was significantly higher under COAA than under CS, but we do not have insights into the seasonal dynamics at that site. In long-term studies in CC and CS rotations in Kansas, PMC in fall samples was not influenced by crop rotation (Omay et al., 1997). Ajwa et al. (1998)

Table 5. Long-term effects of cropping systems and N fertilization on soil C/N at the Nashua and Kanawha, IA, long-term experimental sites.

Site	Cropping system†	N treatment, kg N ha^{-1}				MSD‡	*P*
		0	90	180	270		
		C/N, 0–15 cm					
Nashua	CS	12.26b§	12.34	12.20	12.07	1.11	0.860
	CC	13.27a	13.03	13.11	12.94	0.56	0.283
	CCOA	12.57b	12.40	12.46	12.69	0.54	0.341
	MSD	0.55	0.78	1.12	1.30		
	P	0.007	0.060	0.098	0.158		
Prairie		13.24					
Kanawha	CS	13.37	13.61	13.35	13.02	2.12	0.667
	CC	13.22	12.76	13.19	12.81	1.96	0.602
	CCOA	12.95	12.82	12.82	12.86	1.26	0.941
	COAA	12.63	12.99	12.58	12.77	1.62	0.651
	MSD	2.41	3.61	0.82	1.10		
	P	0.562	0.805	0.060	0.839		

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ MSD = minimum significant difference, Tukey's test.
§ Values within a column followed by the same lowercase letter do not differ significantly among cropping systems ($P = 0.05$). Prairie data are not included in ANOVA.

Table 6. Potential mineralization of carbon (PMC) at the Nashua and Kanawha, IA, long-term experimental sites: Significant effects of cropping system and N fertilization.

Site	Date	PMC				MSD†	*P*
		mg kg^{-1}					
		Cropping system‡					
		CS	CC	CCOA	COAA		
Nashua	June 2001§	379b¶	329a	379b	–	51	0.038
	July 2001	345a	362a	423b	–	31	0.002
	August 2001	242a	252a	286b	–	30	0.013
	October 2001	255	282	298	–	98	0.376
	October 2002	301	340	335	–	46	0.071
Kanawha	October 2002	295a	359ab	363ab	426b	93	0.025
		N treatment, kg N ha^{-1}					
		0	90	180	270		
Nashua	April 2001	204	–	254	–	46	0.035
	June 2001	384	–	340	–	36	0.024
	July 2001	404	–	349	–	33	0.006
	October 2001	282	–	274	–	47	0.376
	October 2002	321	328	321	330	36	0.837
Kanawha	October 2002	365	361	352	363	30	0.606

† MSD = minimum significant difference, Tukey's test.
‡ C = corn, S = soybean, O = oat, A = alfalfa.
§ Data for 2001 are from the 5- to 15-cm depth, and for 2002 from the 5- to 15-cm depth interval. The PMC in the prairie reference site (for Nashua) was 863 mg kg^{-1} in August 2002.
¶ Values within rows followed by the same lowercase letter do not differ significantly between cropping systems (*P* = 0.05). Each value represents the mean across N treatments. Native prairie was not included in the ANOVA.

found that management practices influenced mineralization potentials in both surface and subsurface soils collected in April. In the 2001 study at Nashua, the PMC/SOC ratio varied among months ($P = 0.001$), but not in interaction with cropping system or N fertilization. Trends among cropping systems in PMC did not reflect trends in soil C/N ratios, suggesting that SOC mineralization is also influenced by other factors, such as weather, timing of leaf drop and root turnover, physical and chemical structure of the biomass, and optimal C/N ratio for decomposers (Huggins et al., 1998). Nitrogen fertilization influenced the seasonal dynamics of PMC, with PMC significantly higher in April (before planting and fertilization), and significantly lower by early summer (Table 6). By late summer, PMC did not differ among fertilization regimes in either year at Nashua, or for either site in 2002. Omay et al. (1997) found that PMC pool size for samples collected in September increased by 32% with fertilizer addition, although the rate constant did not increase.

Potentially mineralizable C was 2.4 times higher in the prairie than in the highest cropping system, CCOA (Table 6). However, the ratio of PMC/SOC was lower in the prairie, 0.0137, compared with the agricultural systems, where the lowest value was 0.0141 in the 0-N CCOA. Thus, although the native prairie system had higher PMC, a relatively smaller fraction of the SOC was mineralized in comparison with the agricultural systems. The highest PMC/SOC ratio was 0.0175 in the 0-N CS system. Ajwa et al. (1998) also found that the ratio of PMC/SOC tended to be greater in agricultural sites compared with tallgrass prairie in Kansas. These data are consistent with the C/N ratio data and indicate that SOC in the native prairie is inherently more resistant to decomposition, whereas SOC in CS systems is less resistant to decomposition.

Our data are consistent with the concept that SOC sequestration is influenced by both inputs of organic C and decomposition losses (Tables 4, 6). At Nashua, SOC stocks were lowest in CS (86 Mg C ha^{-1}, mean across all N treatments, 0–100 cm), the cropping system with the lowest residue inputs (estimated from long-term yield data reported by Mallarino and Pecinovsky, 1999) and relatively high PMC in spring. Soil C stocks were intermediate (102 Mg C ha^{-1}) in CC, with intermediate yields and low PMC in spring. Stocks were highest (108 Mg C ha^{-1}) in CCOA, the system with the highest yields and relatively high PMC. Trends were similar at Kanawha, with SOC stocks high in CCOA and COAA (179 and 167 Mg C ha^{-1}) and low in CS and CC (138 and 133 Mg C ha^{-1}). Although yields were generally higher with N fertilization, higher PMC in spring may have offset SOC gains, as evidenced by the general lack of significant increase in SOC stocks with N fertilization.

Soil Organic Carbon Fractions

Both POC and resistant SOC increased in the order CS < CC < CCOA (Table 7). Particulate OC was significantly lower under CS than CC and CCOA (180-N only), and resistant C was significantly higher in CCOA than CS (0-N only). Neither POC nor resistant C was influenced by N fertilization. Liebig et al. (2002) studied several soil properties in a long-term cropping system in Nebraska and observed that N fertilization (180 kg ha^{-1} N) increased POC in only one of four cropping systems examined, the CC system. In our study, resistant C averaged 67% of SOC in the cropped systems, and 91% in the prairie. Particulate OC and resistant SOC concentrations in the prairie were 2.6 and 3.9 times higher, respectively, than the highest values measured for the cropping systems, the unfertilized plots of the CCOA system (Table 7).

Trends in SOC fractions were similar to those of total SOC, indicating that cropping systems impact both the quantity and the quality of SOC. Cropping systems that

Table 7. Long-term effects of cropping system and N fertilization on SOC fractions, particulate organic carbon (POC), and resistant C (0- to 15-cm depth) at the Nashua, IA, long-term experimental site.

Cropping system†	N treatment, kg N ha^{-1} 0	180	MSD‡	*P*
	POC§, g kg^{-1}			
CS	4.31	4.18a¶	2.66	0.862
CC	4.38	5.04b	1.35	0.170
CCOA	5.39	5.15b	0.62	0.243
MSD	2.70	0.78		
P	0.373	0.021		
Prairie	14.18			
	Resistant C§, g kg^{-1}			
CS	12.74a	13.41	1.97	0.281
CC	13.01ab	14.59	1.92	0.072
CCOA	15.35b	14.85	1.71	0.333
MSD	2.48	2.70		
P	0.036	0.244		
Prairie	60.02			

† C = corn, S = soybean, O = oat, A = alfalfa.
‡ MSD = minimum significant difference, Tukey's test.
§ Values represent means of monthly sampling (April–July 2001), except prairie values from August 2002.
¶ Values within a column followed by the same lowercase letter do not differ significantly between cropping systems ($P = 0.05$).

included oat and alfalfa in the rotation had the greatest potential to accumulate SOC and to accumulate more stabilized forms of SOC, whereas the CS system had the lowest potential. Furthermore, all four indices of quality indicated that SOC in the CS system was more labile relative to SOC under CC and CCOA. Nitrogen fertilization had little effect on indices of SOC quality other than to stimulate C mineralization during spring.

CONCLUSIONS

Our data indicate that the dominant cropping system of the upper Midwest, CS rotation with conventional tillage (chisel plowing for corn phase and disking for soybean phase) is not suitable for increasing SOC stocks. On the other hand, cropping systems that include alfalfa in 1 to 2 yr of a 4-yr rotation are a viable management option for increasing SOC stocks. This study was not designed, however, to test whether the increased SOC quantity and quality in the CCOA system were the result of crop traits per se, or reduction in tillage intensity. In this study, N fertilization had no significant effects on indices of SOC quality, with the exception of stimulation of mineralization in early spring. Nitrogen fertilization resulted in significantly higher SOC stocks for only one of four cropping systems studied, the CC, and at only one of two sites. Because of the C cost for N fertilizer production, N fertilization generally had a net negative effect on net C sequestration. There was no evidence that SOC stocks in these tile-drained Mollisols under agriculture will recover to levels found in a native prairie.

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