Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems

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ABSTRACT

Even though organic management practices are intended to enhance soil performance by altering the quantity or quality of soil organic matter (SOM), there is no consensus on how to measure or manage SOM status. We investigated the veracity of common perceptions about SOM quantity in organically and conventionally managed soils by evaluating the relative responsiveness to organic management of particulate organic matter (POM) and the Illinois Soil N Test (IL-N), which has been proposed as a direct measure of labile N. Soil samples were obtained from nine farming systems trials in the USA. Soil organic C (SOC), total N (TN), POM-C, POM-N, and IL-N were compared among manure + legume-based organic, legume-based organic, and conventional farming systems. The organic systems had higher SOC and TN concentrations than conventional systems whether or not manure was applied. The POM-C, POM-N, and IL-N concentrations did not differ between manure + legume- and legume-based organic systems. The amount of N recovered in POM and IL-N was similar. Organic management enriched soil POM-C and -N by 30 to 40% relative to the conventional control and this level of enrichment was two to four times greater than that in any other fraction. The IL-N fraction was not a good measure of labile N as it was less enriched than POM and included recalcitrant components. This is evidenced by the strong correlation between IL-N and SOC, TN, climate and textural characteristics. Particulate organic matter provided clearer evidence of SOM and labile N accrual under organic management. Direct links between POM status and soil N supply and physical condition are being pursued to help farmers manage biologically based fertility.

Soil organic matter is thought to underlie the productivity of organically managed farming systems, but there are few fertility management tools available to organic farmers to evaluate SOM and fertility status. Although SOM is the N reservoir for organic farming systems, it is primarily composed of biologically recalcitrant materials with mean turnover times of hundreds to thousands of years (Stevenson, 1994). Stocks reflect climate and soil texture as well as land management and so SOM has found little use as a management tool. Total SOC is not suitable for tracking the changes in biologically based soil fertility occurring during the 3- to 4-yr transition period following conversion to organic management (Wander et al., 1994). Soil organic matter is used to a limited extent in management of conventional systems, where N credits are sometimes given for SOM levels considered for N fertilizer recommendations; however, SOM as a whole has not been found to be well correlated with N response (Mulvaney et al., 2001) or plant uptake of soil N (Schnier et al., 1987). Biologically active SOM fractions that are important for nutrient cycling and supply are likely to be controlled by management to a much greater extent than total SOM. By isolating and quantifying sensitive or responsive SOM fractions one can view the effects of management on SOM and better provide information about fertility status. Two SOM fractions in particular, POM, and amino sugar N, are potential fertility indices due to their sensitivity to management and association with N supply.

Particulate organic matter obtained by density or size fractionation methods has been used to identify the effects of organic practices on SOM in many studies (references cited in Wander, 2004). The POM-C and -N concentrations have been found to be elevated in farming systems relying on organic fertility compared with those using synthetic fertilizers (Wander et al., 1994; Willson et al., 2001; Fortuna et al., 2003; Nissen and Wander, 2003). Composed of partially decomposed plant and animal residues, POM is thought to be an energy source for microorganisms (Janzen et al., 1992; Stevenson, 1994; Christensen, 2001) and has been connected to other indices of N supply and nutrient cycling. Both POM-C and -N, when combined with information about recently incorporated crop residues, were found to be good predictors of N mineralization potential in systems using conventional, legume-based organic, and manure-based organic fertility management (Willson et al., 2001). Soil POM-C contents were also found to be positively correlated with the amount of soil-derived N taken up by crops as well as with the amount of fertilizer N retained in soil (Nissen and Wander, 2003).

The IL-N is a newly developed test reputed to measure plant-available N. The test has a strong possibility for development into a fertility management tool for organic growers. This simple soil test was created after research showed that sites where crop yield was either responsive or nonresponsive to N fertilizer application could be differentiated on the basis of their amino sugar N content (Mulvaney et al., 2001). To determine amino sugar N, soil is subject to hydrolysis in 6 M HCl at approximately 115°C for 12 h and subsequent filtration, neutralization, and fractionation of the hydrolysate. The test was developed to estimate amino sugar plus exchangeable NH_4^+–N by hydrolysis in 2 M NaOH for 5 h at approximately 49°C (Khan et al., 2001). It is likely that this process also liberates some α-amino N (Greenfield, 2001) and possibly other chemically labile N forms. Other work showing that amino sugars, which

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Abbreviations: FCTE, Field Crop Organic Transition Experiment; FST, Field System Trial; IL-N, Illinois soil N test; MAP, mean annual precipitation; MAT, mean annual temperature; NSF–LTER, NSF–Long-term Ecological Research; POM, particulate organic matter; SOC, soil organic carbon; SOM, soil organic matter.

are microbial residues derived primarily from bacterial and fungal cell wall materials, are responsive to changes in land management practices support the use of amino and hydrolyzable-N based assays as measures of labile N. For example, amino sugar N was disproportionately depleted as SOM declined on initial cultivation of both forests (Solomon et al., 2001) and prairies (Zhang et al., 1997; Amelung et al., 2001), and accumulated faster than total SOM in land under Conservation Reserve Program management (Amelung et al., 2001). Amino sugars have been found to be the N fraction with the greatest percentage of enrichment after cultivation of legumes or incorporation of leguminous residues or manure (Praveen-Kumar et al., 2002) and, along with amino N, are known sources of mineralizable N (Mengel, 1996).

In addition to accumulation of labile SOM fractions, organically managed soils can accumulate SOM stocks relative to their conventional counter parts (Armstrong Brown et al., 1995; Pulleman et al., 2000; Stockdale et al., 2001). Conversion to organic management may be a way to increase soil C sequestration. However increases in SOM derived from use of organic amendments, crop rotation, and legumes might be undercut by organic systems' reliance on tillage (Macilwain, 2004). The ability of organic practices to increase SOM sequestration may hinge on nutrient cycling characteristics. Stockdale et al. (2002) suggest that differences in nutrient retention in organic and conventional systems can be explained by quantity and quality of organic inputs. Results from Rodale's Farming Systems Trial have shown that inputs alone cannot explain SOM accumulation (Wander et al., 1994; Drinkwater et al., 1998). At that site, organic systems have retained more SOM than the conventional counterpart even though they maintain greater biological activity and receive similar amounts of aboveground organic inputs. On-farm research in California also indicates that organic systems can maintain or enhance SOM levels relative to conventional systems at the same time that they increase N mineralization potentials (Drinkwater et al., 1995). This ability to supply nutrients and conserve them is also suggested by Poudel et al. (2002). They found that despite receiving greater N inputs and having a larger pool of potentially mineralizable N, an organic tomato system in California had an N turnover rate that was 50% lower than its conventional counterpart. They computed their rate constant by fitting N mineralization data to a single compartment exponential model. In that work, the organic system was also found to have lower N losses and greater N storage capacity than the conventional systems.

Legume- and animal-based organic systems may differ in their C and N cycling and SOM characteristics. Many consider livestock and the use of animal manures as soil amendments to be essential to sustainable agriculture (Koepf et al., 1976; Hanley, 1980). Sir Albert Howard (1956), one of the early patrons of organic agriculture, asserted that "no permanent or effective system of agriculture has ever been devised without the animal." Certainly, the ability of legumes to build SOM is less well established than that of manure (Paustian et al., 1997). Robertson et al. (2000) found SOM levels in the legume-based organic system in the NSF–LTER were midway between the conventional and no-till systems 10 yr after treatment initiation even though the organic plots including rotary hoeing to control weeds. At Rodale's Farming Systems Trial, soils under the manure-based organic system supported greater soil respiration and N mineralization and this was related to the characteristics of POM obtained by density separation (Wander et al., 1994). The POM obtained from the manured system was more biologically labile than POM obtained from the legume-based organic system. Moreover, the legume-based system tended to be more retentive of organic inputs than the manure-based system.

The characteristics of labile SOM fractions are more likely to reveal differences in fertility source than total SOM. Addition of organic amendments is likely to alter those fractions more rapidly than they do SOM as a whole. For example, Fortuna et al. (2003) found management systems relying solely on compost for fertility had 44% more POM-C than systems receiving synthetic fertilizers after 4 yr of differential management while compost additions increased SOC contents just 16% relative to the fertilized control. Manure-based and legume-based organic systems may need to be considered separately when describing the SOM characteristics of organic systems or developing management tools suitable for organic farmers.

Factors other than management, such as climate and soil texture, are known to be important influences on overall SOM concentrations. These factors also may affect labile fraction concentrations to varying degrees. The effects of soil texture on SOC and POM-C concentrations in farming systems under different tillage regimes were investigated by Needelman et al. (1999). They found SOC, but not POM-C, concentrations to be strongly affected by clay content. Although sand content did affect the influence of tillage on the vertical distribution of SOC and POM-C, the overall concentrations of SOC and POM-C were not affected. In cultivated prairie soils, Zhang et al. (1997) found concentrations of amino sugars to be strongly correlated with mean annual temperature (MAT), percentage of clay, and percentage of silt. Additionally, they found that the proportion of amino sugar-N in total N was significantly related to MAT. Comparing the relationships among SOM fractions and climate and texture variables may provide additional information about the relative sensitivity of these variables to management.

Our main objectives were to compare the SOM concentrations of a number of established trials comparing organic and conventional farming systems and to assess the sensitivity of POM and IL-N to management by examining the relative responsiveness of these fractions and the extent to which these fractions are influenced by other factors such as climate and soil texture. Additionally, we were interested in seeing if organic systems using manure could be distinguished from legume-based systems using POM and amino sugar N characteristics. Soils from a number of trials with different climatic, soil, and specific management characteristics were used in this study so that we could form generalizations about the influence of organic management systems. Toward that end, sites were used as experimental blocks and treatment by site interactions were not examined. Here we provide a preliminary examination of selected SOM fractions with potential to be used as fertility indices for organic farmers. While expressions of the data are not directly related to yield, the information provided by this kind of assessment is a needed step in the development of N fertility measures for systems relying on biologically based fertility.

MATERIALS AND METHODS

This study involved nine established farming systems trials that have comparisons of organic and conventional farming systems. Farming systems trials were located across the USA and represented a variety of soil types (Table 1). All but one trial, which was established 3 yr before sample collection, were well past the 3-yr transition period required for organic certification. Farming systems were categorized based on fertility source as manure + legume-based organic, legume-based organic, or conventional (Table 2). The organic farming systems using manure received various types of raw or composted manure in addition to residues from legumes in the crop rotation. Legume-based organic farming systems used legumes as cover crops or green manures for their primary N fertility source with supplements of rock phosphate and K as K_2O added as needed. Conventional farming systems relied on synthetic fertilizers for fertility with amendments made as needed.

Composite soil samples of at least five randomly collected soil cores were obtained from the surface depth, generally 0 to 25 cm, in the spring of 2002 and/or 2003 from the trials. Samples from at least three replicates of each main plot (farming system) were obtained from each trial. Soil samples were air-dried and ground to pass a 2-mm sieve. Recognizable organic residues $>$2 mm were removed by hand. Soils were tested for carbonates by treatment with acid and none were found. Soil organic C and TN were determined for whole soil samples by combustion analysis (Costech Analytical Elemental Combustion System 4010, Valencia, CA).

The POM was fractionated as SOM > 53 μm using a newly developed fractionation method. The technique parallels many others that rely on size to separate POM after soil has been dispersed (e.g., see Christensen, 2001) but, was developed with soil testing applications in mind. Twenty-gram soil samples were weighed into 30-mL plastic bottles. The mouth of the bottle was covered with 53-μm mesh fabric and then sealed with caps with 2-cm holes drilled in their tops. This assembly allowed materials $<$53 μm to pass from the 30-mL plastic bottle through the mesh fabric. The 30-mL bottle was placed in a 250-mL centrifuge bottle to which was added 150 mL of 5% (w/v) sodium hexametaphosphate. The sample was shaken for 1 h on a reciprocal shaker at approximately 180 oscillations min^{-1}. The sodium hexametaphosphate and suspended fine particles were replaced with 150 mL of tap water and the sample was shaken for 20 min. This step was repeated two times resulting in a total of 120 min of shaking time. The final 150 mL of tap water and suspended fines were discarded and the POM was transferred to a larger piece of 53-μm mesh fabric and rinsed with tap water until the water ran clear. The POM was then dried at 50°C for 24 h, weighed, and ground to powder consistency in a disk mill. Particulate organic matter samples were analyzed for organic C and N by combustion analysis (Costech Analytical Elemental Combustion System 4010, Valencia, CA).

Plant-available N was estimated in whole soils using IL-N (Khan et al., 2001) to measure alkali-labile N. This test is thought to recover amino sugar-N plus exchangeable NH_4^+–N (Khan et al., 2001), although it is likely that some α-amino-N is also released (Greenfield, 2001). One-gram soil samples were hydrolyzed with 2 *M* NaOH for 5 h at 48 to 50°C. The N liberated was collected by diffusion in a 4% (v/v) boric acid-indicator solution as NH_4^+ and quantified by titration with dilute H_2SO_4. Exchangeable NH_4^+ also was analyzed colorimetrically using an improved Berthelot method (Rhine et al., 1998) to confirm that exchangeable NH_4^+ was not the primary component of the IL-N fraction. Briefly, soil extracts, obtained

Table 1. Summary of long-term trials considered in this study.

Long-term trial names and locations	Latitude and longitude	Year initiated	Soil series†	Soil taxonomic family
Field Crops Organic Transition Experiment, Wooster, OH	40°48′ N, 81°56′ W	2000	Wooster sil	fine-loamy, mixed, active, mesic Oxyaquic Fragiudalfs
Farming Systems Project, Beltsville, MD	39°02′ N, 76°54′ W	1996	Christiana sil	fine, kaolinitic, mesic Typic Paleudults
			Keyport sil	fine, mixed, semiactive, mesic Aquic Hapludults
			Keyport variant	fine, mixed, semiactive, mesic Aeric Ochraquults
			Matapeake sil	fine-silty, mixed, semiactive, mesic Typic Hapludults
			Mattapex sil	fine-silty, mixed, active, mesic Aquic Hapludults
Farming Systems Trial, Kutztown, PA	40°31′ N, 75°47′ W	1981	Comly channery sil	fine-loamy, mixed, active, mesic Oxyaquic Fragiudalfs
Living Field Lab, Hickory Corners, MI	42°26′ N, 85°23′ W	1993	Kalamazoo l	fine-loamy, mixed, semiactive, mesic Typic Hapludalfs
			Oshtemo sl	coarse-loamy, mixed, active, mesic Typic Hapludalfs
Long-Term Ecological Research in Row Crop Agriculture, Hickory Corners, MI	42°26′ N, 85°23′ W	1989	Kalamazoo l	fine-loamy, mixed, semiactive, mesic Typic Hapludalfs
			Oshtemo sl	coarse-loamy, mixed, active, mesic Typic Hapludalfs
Long Term Research on Agricultural Systems, Davis, CA	38°33′ N, 121°44′ W	1994	Yolo sil	fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents
			Rincon sicl	fine, smectitic thermic Mollic Haploxeralfs
Muscatine Island Research and Demonstration Farm, Fruitland, IA	41°21′ N, 91°08′ W	1998	Fruitland coarse s	coarse-loamy, mixed, superactive, calcareous, mesic Typic Torriorthents
Neely-Kinyon Long-Term Agroecological Research, Greenfield, IA	41°18′ N, 94°28′ W	1998	Macksburg sicl	fine, smectitic, mesic Aquic Argiudolls
			Shelby cl	fine-loamy, mixed, superactive, mesic Typic Argiudolls
Wisconsin Integrated Cropping Systems Trial, Arlington, WI	43°20′ N, 89°23′ W	1990	Plano sil	fine-silty, mixed, mesic Typic Arguidoll

† Abbreviations following series names refer to the textural class of the A horizon: sil, silt loam; l, loam; sl, sandy loam; sicl, silty clay loam; s, sand; cl, clay loam.

Table 2. Treatment descriptions and soil pH for nine long-term farming system trials in the USA.

Site†	Treatment‡	Crop rotation§	N Fertility	Tillage	Reps	Soil pH¶
FCTE	M	*c-sb-o-rc/ti h	raw strawpack beef manure (corn: 27000 kg ha^{-1}, oat: 1800 kg ha^{-1}) and daylay poultry compost (corn: 2800 kg ha-1, daylay poultry compost 1800 kg ha^{-1})	moldboard plow 6″, disked, harrowed, cultivated, spring toothed tined	6	6.1
	C	*c-sb	synthetic fertilizer (≈150kg ha^{-1}), starter and sidedress N	chisel plow, field cultivated, no till soybean	6	6.0
FSP	M	c/r-*sb-w/v or cc	raw broiler litter (6720 kg ha^{-1} wheat)	disk, roller, flail mowed, cultivator	4	6.9
	C	c-*sb-w/sb	synthetic fertilizer (85–120 kg ha^{-1} N on corn and 75 kg ha-1 N on wheat)	chisel, disk, cultivator	4	6.7
FST	M	w/rc/a-rc/a-*c/r-r/*sb-cs/w	aged cattle manure (18 000 kg ha^{-1} before corn grain and 27 000 kg ha^{-1} before silage	moldboard plow, disk, harrow, cultipacker; rotary hoe, sweep cultivators	4	6.2
	L	v/*c/r-*sb/w-w/v	hairy vetch cover crop	moldboard plow, disk, harrow, cultipacker; rotary hoe, sweep cultivators	4	6.0
	C	*c-c-*sb-c-sb	synthetic fertilizer on corn (146 kg ha^{-1} as 33.6 kg as starter fertilizer (30–30–10), and 112.4 kg as UAN liquid sidedress)	moldboard plow, disk, harrow, cultipacker;	4	6.2
NSF-LFL	M	*c/cc-c/ar-*sb-w/rc	dairy manure-oak leaf compost (4480 kg ha^{-1} yr^{-1})	chisel plow, cultivation for weed control	4	6.9
	C	*c-c-sb-w	synthetic fertilizer (170 kg N ha^{-1} as ammonium nitrate or liquid 28)	chisel plow	4	6.3
NSF-LTER	L	*c-sb-w/rc	red clover cover crop	chisel plow, cultivation for weed control	6	6.1
	C	*c-sb-w	synthetic fertilizer (≈123 kg N ha^{-1} before corn and ≈56 kg N ha^{-1} before wheat)	chisel plow	6	6.2
LTRAS	M	v/p/*c-v/p/t	composted poultry litter (≈373 kg N ha^{-1} on corn and ≈214 on tomato)	conventional tillage, hand-hoeing	3	7.2
	C	*c-t	synthetic fertilizer (235 kg N ha^{-1} on tom and 160 kg N ha^{-1} on tomato).	conventional tillage, hand-hoeing	3	7.5
MIRDF	M	r/hv-*pp	poultry manure compost (112 kg N ha^{-1} yr^{-1})	rototilled, disked, machine/hand cultivated	4	7.4
	C	r-*pp	synthetic fertilizer (112 kg N ha^{-1} yr^{-1})	rototilled, disked	4	7.3
N-K	M	*c-sb-o/a and *c-sb-o/a-a	composted swine manure (135 kg N ha^{-1} on corn and 60 kg ha^{-1} on oats)	moldboard plowed after alfalfa, tandem disk, field cultivator, rotary hoed/harrowed	4	6.8
	C	*c-sb	synthetic fertilizer (135 kg N ha^{-1} as urea on corn)	field cultivator, row cultivator, tandem disk	4	6.4
WICST	M	*c-o/p/a-a	dairy manure (22400 kg ha^{-1} yr^{-1})	chisel plow, cultivated, rotary hoe	4	6.6
	L	*c-*sb-w/rc	red clover cover crop	chisel plow, cultivated, rotary hoe, finisher	4	6.6
	C	*c-*sb	synthetic fertilizer (135 kg N ha^{-1} as anhydrous on corn)	no till	4	6.5

† FCTE, Field Crops Organic Transition Experiment; FSP, Farming Systems Project; FST, Farming Systems Trial; NSF-LFL, National Science Foundation Living Field Lab; NSF–LTER National Science Foundation Long-Term Ecological Research in Row Crop Agriculture; LTRAS, Long Term Research on Agricultural Systems; MIDRF, Muscatine Island Research and Demonstration Farm; N-K, Neely-Kinyon Long-Term Agroecological Research; WICST, Wisconsin Integrated Cropping Systems Trial.

‡ M, manure + legume-based organic farming system; L, legume-based organic farming system; C, conventional farming system relying on inorganic fertilizers.

§ Asteriks indicate crop entry points that were sampled. c, corn; sb, soybean; o, oats; rc, red clover; ti, timothy; h, hay; w, wheat; a, alfalfa; r, rye; cs, corn silage; v, vetch; cc, crimson clover; ar, annual ryegrass; p, pea; t, tomato; pp, pepper.

¶ Soil/water ratio, 1:1.

using 2 *M* KCl, were reacted with a citrate reagent, followed by a 2-phenylphenol-nitroprusside reagent and a buffered hypochlorite reagent. Absorbance was determined at 660 nm and calibrated with standards to obtain NH_4^+ concentration. Soil texture and pH were determined using composites representing each site by treatment (farming system) combination. Soil texture was determined on 50-g samples using the Hydrometer method (Gee and Bauder, 1986). Soil pH was determined on 5-g composite samples using a 1:1 soil/water ratio.

The percentage of relative enrichment of C and N in SOM fractions due to organic management was calculated by taking the difference between fraction C or N concentrations in organic and conventional systems and dividing that difference by the concentration in the conventional soil from the same experimental block. If the site experimental design did not include blocks, then relative enrichment was calculated using site treatment means for each fraction.

This multi-site study employed a systems approach to compare the general SOM characteristics associated with different types of farming systems. The categories we consider, legume- and manure + legume-based organic systems and conventional systems, vary among the sites we studied as they do in the real world. Differences exist in the mix and sequence of crops, rotation length, in the fertility rates and sources, as well as in the types and frequencies of tillage-based disturbance. This type of comparison of intact, realistic farming systems allows us to document emergent properties and processes that result from interactions among system components (Delate, 2002). A disadvantage of this approach is that it is not possible to identify specific cause-effect relationships between individual factors (e.g., tillage intensity or amendment rate) and outcomes (Drinkwater, 2002), and thus we make no attempts at this. Farming system effects on SOM fractions were analyzed using PROC MIXED (SAS Institute, 1999). Since we were not interested in the specific effects of location on SOM fractions, but rather in the general influence of farming systems on SOM fractions, we treated each site as an environment as suggested by Carmer et al. (1989) and considered site and site by system interactions as random effects. We view the sites included in this study as a random selection from a larger theoretical population of possible sites, allowing us to make inferences about farming system effects on SOM fractions across the population of possible sites. Residuals were examined to evaluate assumptions of normality and equality of variance. If these assumptions were not met, as in the case of SOC, TN, IL-N, POM-C, and POM-N, variables were transformed using $\log_{10}$ and reanalyzed. System means were separated using LSMEANS post hoc test. To compare N concentrations in POM and IL-N, systems were analyzed separately (PROC MIXED, SAS Institute, 1999) and N concentration was log-transformed to improve normality. Site and site by fraction interactions were treated as random effects and system means were separated using LSMEANS post hoc test. Differences in the percentage of relative enrichment among SOM fractions were analyzed using PROC MIXED (SAS Institute, 1999). Again, site and site by fraction interactions were treated as random effects. Examination of residuals showed that the percentage of relative enrichment did not meet assumptions for normality and equality of variance and so this variable was transformed according to the following equation:

$$\text{Percentage of relative enrichment transformed} = (\text{percentage of relative enrichment} + 200)^{-1} \times 1000 \quad [1]$$

The mean percentage of relative enrichments of SOM fractions were separated using LSMEANS post hoc test.

The degree of association between SOM fractions was investigated using simple linear correlation analyses (PROC CORR, SAS Institute, 1999). The relative importance of mean annual precipitation (MAP) and temperature (MAT), soil texture, and farming system trial age in influencing concentrations of SOM fractions was evaluated using stepwise multiple regression analyses (PROC REG, SAS Institute, 1999). The significance level to enter the model was 0.50, and the significance level to stay in the model was 0.05. Results from all three farming systems were included in that analysis to allow us to investigate fraction sensitivity to management. When a strong relationship was observed between variables and texture/climate factors despite the fact that all three different management systems were included in the analysis, we assumed this indicated that those SOM fractions had rather low sensitivity to management. Mean annual temperature and MAP were used to represent climatic differences. The percentage of clay and the percentage of silt were used to compare soil textural effects on SOM fractions. Residuals were examined to confirm that assumptions of normality and equality of variance were met. Collinearity between independent variables was evaluated using the condition index (COLLIN, SAS Institute, 1999). In all cases, the condition index was <30 indicating that moderate or severe collinearity was not a problem. Simple linear regressions were performed between the percentage of relative enrichment of SOM fractions, which was transformed according to Eq. [1], and age of farming system trial using PROC REG (SAS Institute, 1999). Only the organic systems were included in the analyses of age affects on increases in SOM concentrations.

RESULTS

Concentrations of C and N in all soil organic matter fractions examined were significantly affected by management and site (Table 3). Farming system had no effect on exchangeable NH_4^+ concentrations. Site by system interactions were not significant for any SOM fraction examined (Table 3), indicating that farming system differences were consistent across sites. Since the Field Crops Organic Transition Experiment (FCTE) site had been underway for a shorter period of time (3 yr) than all other sites at the time of sampling and changes in SOM fractions are time dependent, this analysis was repeated without the FCTE site. Even though there was some small fluctuation in mean values, the overall results were the same as with all sites included (data not shown).

Table 3. Statistical results for analysis of farming system effects on soil organic matter fraction concentrations.

Independent variable	Dependent variable Log_{10} SOC†	Log_{10} TN	Log_{10} POM-C	Log_{10} POM-N	Log_{10} IL-N	NH_4^+
	F or Z value					
Farming system	4.88*	8.14**	14.00**	12.10**	7.65*	2.59
Site	1.97*	1.99*	1.90*	1.94*	1.98*	1.74*
Site × system	0.94	0.54	1.18	1.39	0.49	1.03

† SOC, soil organic C; TN, total N; POM, particulate organic matter; IL-N, Illinois Soil N Test-N; NH_4^+, exchangeable NH_4^+.

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

Organic management significantly increased average SOC and TN concentrations compared with conventional systems (Fig. 1a and 1b). The organic systems also had greater concentrations of POM-C, POM-N, and IL-N than the conventional systems (Fig. 1c and 1d). The small quantity of N in the exchangeable NH_4^+ fraction and similar concentrations of this fraction in all farming systems indicated that differences among the systems' IL-N concentrations were primarily due to organic

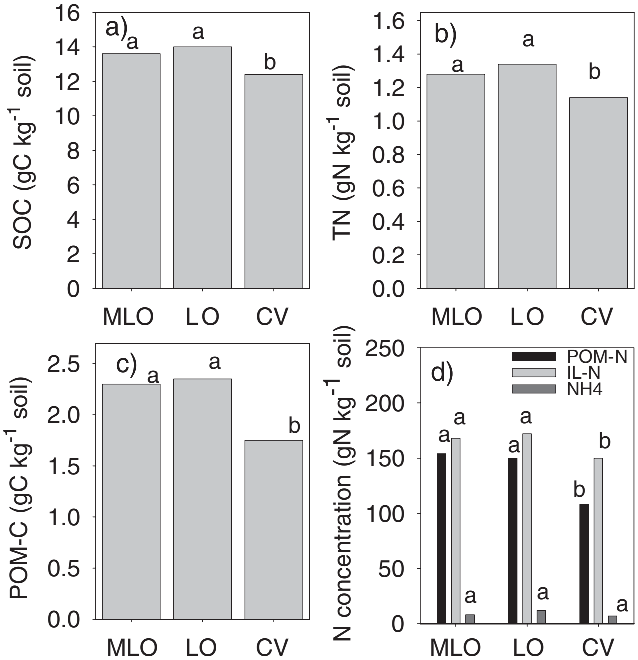

Fig. 1. Influence of farming systems on soil organic matter fractions in surface soils (generally 0 to 25 cm) collected from nine long-term farming systems trials located across the USA. Shown are (a) soil organic C (SOC), (b) total N (TN), (c) particulate organic matter C (POM-C), and (d) particulate organic matter (POM-N), Illinois Soil N Test-N (IL-N), and exchangeable NH_4^+–N concentrations of manure-based organic (MLO: eight sites), legume-based organic (LO: three sites), and conventional (CV: nine sites) farming systems. Different letters within a fraction show significant differences among farming systems at the $p < 0.05$ level. Statistical analyses for SOC, TN, IL-N, and POM fractions were conducted on log_{10} transformed data to improve normality and equality of variances. Untransformed data are presented in the figure.

Table 4. Statistical results for comparison of N concentrations in particulate organic matter and Illinois Soil N Test among three types of farming systems.

Independent variable	Manure-based organic	Legume-based organic	Conventional
	N concentration		
	F or Z value		
N fraction	**0.16**	**0.02**	**5.03**
Site	**1.42**	**0.85**	**1.61**
Site × fraction	**1.81***	**0.97**	**1.88***

* Significant at the 0.05 probability level.

forms of N and not affected much, if at all, by the presence of inorganic N (Fig. 1d). The manure + legume-based and legume-based organic systems had similar concentrations of all SOM fractions considered (Fig. 1).

The concentrations of POM-N and IL-N were compared in each farming system to determine if there were differences between these fractions within each system. The legume-based organic systems had similar quantities of N in the POM-N and IL-N fractions (approximately 180 mg N kg^{-1} soil, Table 4). Site by fraction interactions were significant ($p < 0.05$) for both the manure + legume-based organic systems and the conventional systems, indicating that the relative ranking of these fractions was site specific and not generalizable at the farming system level (Table 4).

Soil and POM C/N ratios did not differ among the farming systems (Table 5). The POM-C fraction comprised roughly 3% more of the SOC in the organic than in the conventionally managed soils (Table 5). The POM-N and IL-N fractions each comprised between 12 and 14% of TN (Table 5). The percentage of TN found in the IL-N fraction did not differ among the three types of systems while more TN was found in the POM-N fraction in the manure + legume-based organic system than the conventional system (Table 5).

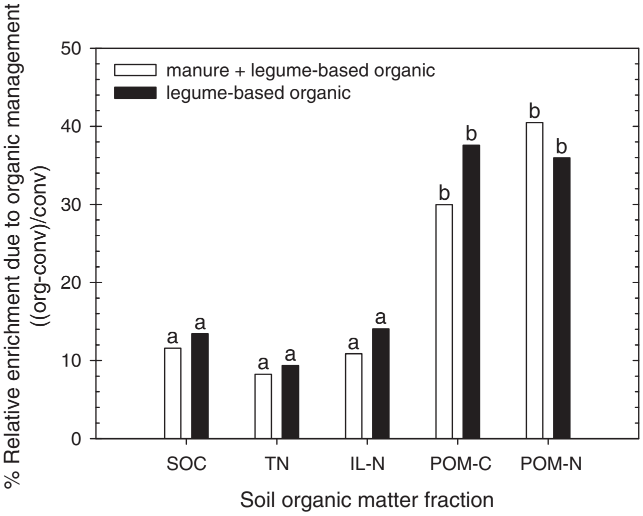

Fig. 2. Mean percentage of relative enrichment of soil organic C (SOC), total N (TN), particulate organic matter (POM)-C, POM-N, and Illinois Soil N Test-N (IL-N) fractions in surface soils (generally 0 to 25 cm) of organic farming systems relative to conventional farming systems at nine long-term farming systems trials in the USA. The percentage of relative enrichment calculations were made on paired sets of soil organic matter fraction concentrations (g kg^{-1} or mg kg^{-1}) in conventional and organic systems within sites. Different lowercase letters indicate significant differences among fractions at the $p < 0.05$ level. Statistical analysis was conducted on transformed data [$(\text{enrichment} + 200)^{-1}$] to improve normality and equality of variance; untransformed means are presented in the figure.

To assess the ability of organic farming systems to enhance SOM and to evaluate the sensitivity of POM and IL-N fractions to management, we calculated the percentage of relative enrichment. Differences between organic and conventional SOM concentrations were normalized by SOM in the conventional systems. We compared the responses of POM and IL-N fractions to those of SOC and TN. The POM-C and-N fractions in both organic systems showed 30 to 40% enrichment due to organic management; this was two to four times greater than the enrichment shown by SOC, TN, or IL-N (Fig. 2). There were no differences between the two types of organic systems in the percentage of relative enrichment of any SOM fraction. As with the analysis of variance of SOM fraction concentrations, this analysis was repeated without the FCTE site and again there were no major changes in the overall results (data not shown).

Illinois Soil N Test-N was highly correlated with SOC and the strength of the association between these two variables was similar in all three types of farming sys-

Table 5. Statistical results and means for whole soil and particulate organic matter (POM) C/N ratios, percentage of soil organic C (SOC) comprised of POM-C, and percentages of total N (TN) comprised of POM-N and Illinois Soil N Test-N (IL-N).

Independent variables	Whole soil C/N ratio	POM C/N ratio	POM-C/SOC	POM-N/TN	IL-N/TN
	Dependent variables				
			%		
	F or Z value				
Farming system	**0.74**	**1.11**	**13.3****	**7.87***	**1.64**
Site	**1.95***	**1.98***	**1.94***	**1.79***	**1.96***
Site × system	**0.91**	**0.99**	**0.58**	**1.39**	**0.21**
	Mean ± 1 standard error†				
Manure + legume-based organic	**11.2 ± 0.57**	**16.1 ± 1.90**	**18.2a ± 2.04**	**13.3a ± 1.30**	**13.5 ± 0.76**
Legume-based organic	**11.0 ± 0.59**	**16.3 ± 1.94**	**17.5a ± 2.14**	**12.0ab ± 1.59**	**13.5 ± 0.78**
Conventional	**10.9 ± 0.57**	**16.7 ± 1.89**	**14.9b ± 2.03**	**9.9b ± 1.28**	**13.2 ± 0.76**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Different letters within a column indicate significant differences at $p < 0.05$.

Table 6. Correlations between soil organic matter (SOM) fraction concentrations from nine farming system trials.

	Coefficient of correlation with		
SOM fraction	**SOC**	**TN†**	**POM-C**
		All systems	
IL-N	0.982***	0.977***	0.501**
POM-C	0.581**		
		Manure + legume-based organic systems	
IL-N	0.978***	0.973***	0.294
POM-C	0.423		
		Legume-based organic systems	
IL-N	0.998***	0.983	0.750
POM-C	0.761		
		Conventional systems	
IL-N	0.980***	0.978***	0.496
POM-C	0.427		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The FST site was excluded from these analyses. A scatterplot of IL-N vs. TN revealed a shift in the intercept for this site due to high amounts of fixed NH_4^+ at this site. When the FST site was analyzed alone the coefficient of correlation between TN and IL-N was 0.953***.

tems (Table 6). The association between IL-N and TN was equally strong when the Farming Systems Trial (FST) site was excluded from the analysis. A scatterplot of IL-N versus TN revealed a shift in the intercept for the FST site, most likely due to the high amounts of fixed NH_4^+ present in the soil at this site (Wander and Traina, 1996). Although clay-fixed NH_4^+ is recovered in TN, little is solubilized during alkali hydrolysis (Greenfield, 2001). When the FST site was analyzed alone the coefficient of correlation between TN and IL-N was also very high (0.953***). In contrast to the IL-N fraction, the correlation between soil POM-C and SOC was much weaker and was significant only when all three systems were analyzed together (Table 6). The correlations between POM-C and IL-N were similar to those for POM-C and SOC and again, the association was only significant when all three systems were analyzed together (Table 6).

Soil organic C and IL-N were negatively correlated with MAT and positively correlated with the percentage of clay and the percentage of silt (Table 7). These climatic and textural variables explained nearly 80% of the variation in SOC and IL-N. However, POM-C was positively correlated with MAP only, which explained about 40% of the variation in POM-C. To determine if the elevated concentrations of SOM fractions in the organic systems were related to the length of time those systems had been in place, farming system trial age was added as an independent variable and the stepwise regression procedure was repeated using data from only the two organic systems. Age did not make a significant contribution to the models for SOC and IL-N; regression models were very similar to those fit when all systems were considered without acknowledgment of age (Table 7). In contrast, for POM-C, inclusion of trial age in the analysis yielded a stronger regression model, explaining about 60% of the variation in POM-C, in which age was the only significant independent variable (Table 7). When simple linear regression was used to examine the effect of trial age on the percentage of relative enrichment of SOM fractions in organic systems no significant relationship between trial age and any variable was found (data not shown).

DISCUSSION

Across the range of soil and climatic conditions present at these studies, organic management increased total SOM concentrations in surface soils. Generally, total SOM has not been found to be very responsive to differences in management in the short-term, but SOC and TN concentrations were significantly higher in the organic systems compared with the conventional systems. Organic management increased SOC concentrations approximately 14% above values found in conventional systems after an average of 10 yr. Without samples from the start of these farming systems trials, we cannot conclude whether these systems are resulting in net losses or gains of SOC. However, assuming that the experiments were laid out according to standard design practices at each site and the farming systems had similar SOC levels at the initiation of each trial, our results indicate that even though organic systems often involve intensive and frequent cultivation, they retain more SOC than conventional systems.

Table 7. Stepwise multiple regression results for effects of climate, soil texture, and farming system trial age on soil organic matter (SOM) fractions.

		Partial R^2 values‡					
Dependent variable†	**Model adjusted R^2 value**	**MAT**	**MAP**	**% clay**	**% silt**	**age**	**Regression equation**
					All systems		
SOC	0.788***	0.211	NS	0.514	0.086	n.a.	SOC = 14.9– 1.62MAT + 0.520clay + 0.122 silt
IL-N	0.789***	0.239	NS	0.450	0.123	n.a.	IL-N = 180– 21.5MAT + 6.17clay + 1.97silt
POM-C	0.398***	NS	0.420	NS	NS	n.a.	POM-C = −0.718 + 0.036MAP
					Organic systems		
SOC	0.851***	0.222	NS	0.608	0.049	NS	SOC = 15.2– 1.70MAT + 0.642clay + 0.096silt
IL-N	0.857***	0.231	NS	0.570	0.083	NS	IL-N = 171– 22.2MAT + 8.02clay + 1.71silt
POM-C	0.615***	NS	NS	NS	NS	0.639	POM-C = 1.56 + 0.110age

† SOC, soil organic C (g C kg^{-1} soil); IL-N, Illinois Soil N Test-N (mg N kg^{-1} soil); POM-C, particulate organic matter C (g C kg^{-1} soil).

‡ For significant ($p < 0.05$) independent variables. MAT, mean annual temperature; MAP, mean annual precipitation; age, age of farming system trial; n.a., independent variable was not included in analysis; NS, not significant ($p < 0.05$).

*** Significant at the 0.001 probability level.

None of the SOM fractions examined was able to differentiate between organic systems receiving manure and those whose fertility is based solely on legumes. The similar SOC and TN concentrations found for these two types of systems indicated that legume-based organic management is as capable of building SOM as systems receiving manure or compost. The similarity of these systems may be due to the fact that legumes are an integral part of both systems. However, this study only included three sites with legume-only organic systems; a larger sample size may facilitate more detailed evaluation of potential differences between these types of organic systems. Although Wander et al. (1994), found differences in chemical quality of POM isolated from these two types of organic systems, those differences were not apparent when POM- C and-N concentrations were considered alone. In that work, POM was obtained using a density rather than a size based methodology. In general, the light fraction has been found to be more sensitive to input quality than has the coarse fraction (literature reviewed in Wander, 2004). Further investigation of the qualitative characteristics of SOM fractions might also differentiate between the manure + legume-based and legume-based organic systems.

Some have suggested the POM fraction is not a significant source of mineralizable N (Boone, 1994; Yakovchenko et al., 1998) while others have argued amino sugars and amino N (Mengel, 1996; Mulvaney et al., 2001) and base hydrolyzable N recovered at low temperatures (Mulvaney et al., 2006) are a substantial sources of mineralizable N. Accordingly, we were somewhat surprised to find POM-N concentrations to be at least as high as IL-N concentrations in most of the organic systems. Mean POM-N and IL-N concentrations found in these organic soils (170–190 mg N kg^{-1} soil), approach the minimum IL-N concentration (235 mg N kg^{-1}) found in conventionally farmed soils where corn was nonresponsive to N fertilization in IL (Khan et al., 2001). Our findings demonstrate POM-N is an important N reservoir where SOM is intentionally managed to increase soil N supply as is the case for organic systems. In conventional systems, where organic matter is being lost or at best maintained, IL-N or TN for that matter, might be better predictors of soil N supply than are depleted labile pools.

Although organic management was expected to result in disproportionate enrichment of the labile SOM fractions (POM-C, POM-N, and IL-N) compared with SOC and TN, this was only true for POM fractions. Both POM-C and -N were at least two times more enriched by organic management than any other fraction. The POM-C and -N made up a larger percentage of SOC and TN, respectively, in the organic than in the conventional systems. In contrast, the IL-N fraction was not preferentially enriched by organic management. Its response to management was quite similar to that of SOC and TN. The substantial enrichment of POM fractions in organic systems relative to conventional systems is even more striking when considering the additional tillage occurring in the organic systems. Particulate organic matter-C has been found to be preferentially depleted compared with SOC with increasing intensity of tillage (Cambardella and Elliott, 1992). Organic matter losses stimulated by tillage are offset by residue additions made in the form of manures or composts or contributed through the green manure or ley crop components of the rotations. Differences between the organic and conventional systems appear to be driven largely by the rotations used, which are more diverse and generally longer in duration. It may be important to note that some of the ‘organic systems’ are not long enough to qualify for USDA certification. It may also be significant that the manure and compost amendment rates used in these research-focused trials are, except for one, being made to supply crop demand and so may not represent outcomes seen in more intensive animal-based systems. Most of the manure + legume based organic farming systems considered here benefit from the greater winter coverage of the soil provided by the inclusion of a perennial hay crop while the legume-based systems rely on use of annual covers incorporated around, or double cropped with, a cash crop of some kind. As a result, the organic rotations are longer and more diverse. The amount, quality, and timing of organic residues added to the soil by the organic systems are sufficient to maintain SOC levels at or above levels achieved in the conventionally managed systems.

The greater sensitivity of the POM fraction to differences in management compared with the IL-N test also was shown by the correlations between these fractions and SOC. The strong correlation found between IL-N and SOC in all farming systems and the important influence of climate and texture on IL-N concentrations indicates that this test may recover some biologically recalcitrant N. Mulvaney et al. (2001) found a weaker correlation between SOC or TN and amino sugar N as determined directly by hydrolysis and diffusion. Their coefficients of correlation ranged from 0.65 to 0.74 as compared with values of 0.97 to 0.99 found in this study. Similar to our results for IL-N and SOC, MAT, percentage of clay, and percentage of silt explained 87% of the variation in amino sugar concentrations in cultivated soils of the North American Prairie (Zhang et al., 1997). The comparatively weak correlations between POM-C and SOC, and POM’s weaker relationship with climatic and textural variables emphasize the importance of management in controlling POM levels in soils. The fact that when trial age was included in the analysis with POM, no climatic or textural variables were significant underscores the influence of management on POM concentrations. If the differences in POM-C concentration between conventional and organic systems increased with time under differential management, then we would expect to find a positive relationship between the age of farming system trials and the percentage of relative enrichment of POM-C concentrations. The lack of a relationship between the percentage of relative enrichment of POM-C and trial age indicates that substantial increases in POM-C in organic systems relative to conventional systems can occur quite quickly (within 3 to 5 yr). However, other differences between these sites, such as crop rotation or tillage, which may affect the rate of POM build-up under organic management, may be obscuring the influence of time in our analysis.

In work examining the relationship between climate and texture and amino sugar concentrations, the accumulation of amino sugars in prairie soils was primarily influenced by MAT, but this influence was limited to particle-size fractions containing more decomposed SOM, that is, finer fractions (Zhang et al., 1998). Coarse fractions, which contain less decomposed materials, including POM, were not affected similarly. This suggests that further fractionation of IL-N (assuming that amino sugars are an important source of the N recovered in IL-N) may be helpful in isolating an organic N fraction that is more influenced by management.

CONCLUSIONS

Use of organic farming practices increased the SOC concentrations of surface soils by 14% compared with conventional counterparts. Legume-based and manure + legume-based organic management resulted in similar increases in SOM concentrations compared to conventional systems. Of the two labile SOM fractions examined, the POM fraction, which was enriched by 30 to 40% in organic systems, was more sensitive to organic management. Further refinement of the IL-N fraction to exclude recalcitrant components, and more detailed analysis of POM biochemistry and or substrate quality, may improve the utility of these fractions by increasing their ability to distinguish between systems receiving different organic inputs and describe soil C and N cycling characteristics.

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