Nutr Cycl Agroecosyst (2011) 90:253–266
DOI 10.1007/s10705-011-9426-4

ORIGINAL ARTICLE

Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems

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Received: 29 September 2010 / Accepted: 31 January 2011 / Published online: 20 February 2011

Abstract Sustainable soil fertility management depends on long-term integrated strategies that build and maintain soil organic matter and mineralizable soil N levels. These strategies increase the portion of crop N needs met by soil N and reduce dependence on external N inputs required for crop production. To better understand the impact of management on soil N dynamics, we conducted field and laboratory research on five diverse management systems at a long-term study in Maryland, the USDA- Agricultural Research Service Beltsville Farming Systems Project (FSP). The FSP is comprised of a conventional no-till corn (*Zea mays* L.)–soybean (*Glycine max* L.)–wheat (*Triticum aestivum* L.)/double-crop soybean rotation (NT), a conventional chisel-till corn–soybean–wheat/soybean rotation (CT), a 2 year organic corn–soybean rotation (Org2), a 3 year organic corn–soybean–wheat rotation (Org3), and a 6 year organic corn–soybean–wheat–alfalfa (*Medicago sativa* L.) (3 years) rotation (Org6). We found that total potentially mineralizable N in organic systems (average 315 kg N ha^{-1}) was significantly greater than the conventional systems (average 235 kg N ha^{-1}). Particulate organic matter (POM)–C and –N also tended to be greater in organic than conventional cropping systems. Average corn yield and N uptake from unamended (minus N) field microplots were 40 and 48%, respectively, greater in organic than conventional grain cropping systems. Among the three organic systems, all measures of N availability tended to increase with increasing frequency of manure application and crop rotation length (Org2 $<$ Org3 $\leq$ Org6) while most measures were similar between NT and CT. Our results demonstrate that organic soil fertility management increases soil N availability by increasing labile soil organic matter. Relatively high levels of mineralizable soil N must be considered when developing soil fertility management plans for organic systems.

Keywords Chemically-labile organic matter (CLOM) · Organic farming · Particulate organic matter (POM) · Soil mineralizable nitrogen

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Introduction

Nitrogen is generally recognized as the most limiting nutrient required for the production of world food supply (Smil 2001). Optimizing N use efficiency (NUE) by tightening the N cycle is a fundamental goal of sustainable agriculture (Cassman et al. 2002). Achieving this goal will improve the economic performance of agroecosystems by better matching N inputs with crop N needs and reduce negative environmental impacts of excessive N applications such as contamination of ground water and hypoxia in surface waters (Follett and Hatfield 2001)

Soil organic C and N dynamics are tightly linked in agroecosystems. Management practices that build soil organic matter tend to increase the soil's capacity to meet crop N needs through mineralization of soil organic N. For example, the addition of animal manure (Beegle et al. 2008; Mallory and Griffin 2007), use of legumes in the rotation (Oyer and Touchton 1990; Clark et al. 2007), and continuous no-till (House et al. 1984; Franzluebbers et al. 1994) all tend to increase labile pools of soil organic C and mineralizable N. As the portion of crop N needs met by soil N increases, external N inputs can be reduced. This approach requires knowledge of the soil's capacity to meet crop N needs so that supplementary additions of N may be adjusted accordingly.

There has been considerable work done over the past several decades to improve N management in agroecosystems (Meisinger et al. 2008; Raun and Johnson 1999; Cassman et al. 2002); however, little of this research has addressed N dynamics in organic grain cropping systems, which tend to use multiple sources of N additions to soil. The number of certified organic crop hectares in the United States increased, on average, by 24% per year between 1992 and 2003 in response to consumer demand for organic products (Green 2006). Organic grain prices have been up to two times those of conventional grains, even as conventional grain prices have fluctuated widely during the last few years (USDA-ERS 2008). These economic conditions have attracted the interest of conventional grain farmers who are considering adopting organic production methods. Improving NUE in organic grain cropping systems is becoming more important as the number of hectares managed organically increases.

Challenges during transition to organic production, including soil fertility and weed management, have hindered the success of grain farmers transitioning to organic methods. Yields of grain crops are often, though not always, lower in organic than in conventional systems (Porter et al. 2003; Delate and Cambardella 2004; Archer et al. 2007; Cavigelli et al. 2008). Nitrogen limitations are often an important factor limiting corn grain yield in organic systems (Berry et al. 2002; Cavigelli et al. 2008). Nitrogen management in organic cropping systems requires an integrated strategy of incorporating crop and cover crop residues and animal manures into soil to build and maintain soil organic matter and mineralizable soil N levels (Gaskell and Smith 2007; Berry et al. 2002). Managing these systems sustainably requires that the buildup of mineralizable soil N be taken into consideration so that sufficient, but not excessive, rates of N inputs can be determined.

Measuring the amount of N released from soil organic matter pools has challenged soil scientists for decades due to the dynamic nature of soil N transformations and the chemical complexity of soil organic matter. Since total soil organic matter is primarily composed of recalcitrant humus with mean turnover times ranging from hundreds to thousands of years (Stevenson 1994), total organic C or N are of limited use for quantifying the impact of management on the quality or functionality of SOM. A number of approaches have been used to estimate soil N release from soil organic matter pools. One of the most common and direct methods is to quantify potentially mineralizable organic N using long-term aerobic incubations (Stanford and Smith 1972; Christensen and Olesen 1998; Mallory and Griffin 2007). Another classic approach is to measure crop N uptake or yield from unfertilized field plots (Meisinger et al. 2008; Egelkraut et al. 2003). Other measures of labile soil organic matter have also been used to estimate soil N release. Two fractions that are sensitive to management and are potential indices of N mineralization potential are particulate organic matter (POM, organic C and N < 2.0 mm and >53 μm) (Marriott and Wander 2006; Nissen and Wander 2003; Christensen 2001) and oxidizable organic matter (i.e., chemically labile organic matter [CLOM], soil organic C oxidized by 0.02 M $KMnO_4$) (Weil et al. 2003; Mirsky et al. 2008; Blair et al. 1995; Min et al. 2003).

The overall objective of this research was to characterize soil N availability in response to five diverse management systems (two conventional and three organic) of a long-term study in Maryland, the USDA-Agricultural Research Service Beltsville Farming Systems Project (FSP). Our specific objectives were: (i) to quantify the effects of management history on potentially mineralizable soil organic N, POM, CLOM, and crop yield and N uptake in each cropping system; and (ii) to evaluate the relationships among these various measures of soil N availability.

Materials and methods

Study site

The FSP was established in 1996 to evaluate sustainability of five diverse crop production management systems. The study site is 16 ha in size and is at the western edge of the Atlantic Coastal Plain at the USDA-Agricultural Research Service Beltsville Agricultural Research Center in Beltsville, MD (39.03°N, 76.90°W). The 30 year average annual precipitation at the site is 1110 mm, distributed approximately evenly through the year. Average annual temperature is 12.8°C. The dominant soil types are Christiana (fine, kaolinitic, mesic Typic Paleudults), Matapeake (fine-silty, mixed, semiactive, mesic Typic Hapludults), Keyport (fine, mixed, semiactive, mesic Aquic Hapludults), and Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults) silt loams. Prior to establishment of the FSP, the site was a row crop production field that had been managed using continuous no-till for at least 11 years.

The FSP includes two conventional and three organic management systems (Table 1). The two conventional systems differ only in seedbed preparation, employing either a primary tillage operation, referred to as chisel-tillage (CT), or no-tillage (NT) management. The three organic cropping systems (Org2, Org3, and Org6) differ in crop rotation length and complexity. Every phase of each crop rotation is represented every year. Cropping systems are replicated four times in a split-plot design with system assigned to whole plots and crop rotation entry point assigned to subplots. Each of the 68 total subplots (17 rotation entry point subplots replicated four times) is 9.1 m wide and 111 m long (0.1 ha in size). Commercial-scale farm equipment is used for all field management operations. Corn, soybean and wheat are harvested for grain from all systems. Wheat straw is baled and harvested from CT and NT but not Org3 and Org6. In Org6, alfalfa is harvested three to five times per year depending on weather conditions. Cereal rye (*Secale cereale* L.) is planted as a cover crop following corn harvest in all management systems.

The two conventional systems, CT and NT, are managed using standard practices for grain production in the mid-Atlantic region. All soil fertility needs are met using commercial fertilizers. Both fertilizer and herbicide applications are based on University of Maryland recommendations. Fertilizer N rates for corn and wheat have averaged 175 kg N $ha^{-1}$and 100 kg N ha^{-1}, respectively. Tillage in the CT system includes one pass with a chisel plow followed by one to two passes with a disk before corn, or one pass with a chisel plow, disk or field cultivator before full season soybean and wheat. Double-crop soybean is direct seeded without tillage in the CT system.

Green manure crops serve as a significant N source for corn in the three organic systems. Hairy vetch (*Vicia villosa* Roth) is planted in early September following a fallow period after wheat harvest in Org3 and in October in Org2 following soybean harvest. In the spring prior to planting corn in Org6 alfalfa is

Table 1 Summary of cropping system management

Management practice	Cropping systems				
	No till	Chisel till	2 year organic	3 year organic	6 year organic
Crop rotation†	C-r-S-W/S	C-r-S-W/S	C-r-S-hv	C-r-S-W-hv	C-r-S-W-A-A-A
Primary tillage‡	None	Ch	D, MB, or Ch	D, MB, or Ch	D, MB, or Ch
Weed control§	Herbicides	Herbicides	RH, RC	RH, RC	RH, RC
Fertility¶	N, P, K	N, P, K	GM, AM, K	GM, AM, K	GM, AM, K

† *C* corn, *S* soybean, *W* wheat, *W/S* wheat followed by double-cropped soybean, *A* alfalfa; *r* rye cover crop, *hv* hairy vetch. No till and chisel till followed a 2 year C-W/S rotation from 1996 to 2000

‡ D disk, *MB* moldboard plow, *Ch* chisel plow

§ *RH* rotary hoe, *RC* row cultivator

¶ *N* urea ammonium nitrate, *P* triple super phosphate, *K* potassium sulfate, *GM* green manures, *AM* animal manures plowed under as green manure rather than being harvested. Animal manures are used to supplement green manure N to satisfy corn N needs. Animal manures are the sole source of N for wheat in Org3 and Org6. The source of manure has varied, depending on local availability, but has generally been poultry litter with a few dairy slurry applications. The rate of animal manure was dictated by estimated available N from green manure and sustainable nutrient management considerations to avoid a build-up of excessive soil P. A typical application rate of poultry litter for both corn and wheat in the organic systems is between 3.2 and 4.8 Mg ha^{-1} (dry weight equivalent; about 120 and 180 kg total N ha^{-1}, respectively). Primary tillage in the organic systems is similar to that used in the CT system (Table 1) with the exception that a moldboard plow is used to incorporate the green manure crop prior to corn. Typical weed control in organic corn and soybean crops consists of two passes with a rotary hoe about 5 and 10 days after planting, and two passes with a row cultivator about 3 and 4 week after planting. A more complete description of FSP management history and crop yields may be found in Cavigelli et al. (2009, 2008).

Our research on N dynamics was limited to the corn phase of the rotation since corn is the most N-responsive crop in the study. In order to quantify the impact of cropping system management legacy on plant available soil N, minus N experimental treatments were imposed on 4.6 m by 9.1 m microplots within corn subplots of each system during the 2009 growing season. All sources of managed external N were withheld from minus N microplots. In Org2 and Org3 hairy vetch was terminated shortly after establishment in September 2008 using a flame weeder (Model 550, Flame Weeders, Greenville, WV). In Org6 alfalfa was killed shortly after the last cutting in October 2008 with glyphosate (2.2 kg a.i. ha^{-1}). Poultry litter was excluded from organic microplots by covering them with a tarpaulin when poultry litter was spread over the subplots. In the conventional systems the minus N treatments were established by withholding starter and sidedress fertilizer N. To ensure that N was the only limiting nutrient both P and K were applied to plots in CT and NT based on soil tests and University of Maryland recommendations (46.5 kg P ha^{-1} as triple-super phosphate, 140 kg K ha^{-1} as K_2SO_4) (Table 2).

Typically, corn in the conventional systems is planted a few weeks earlier than in the organic systems. The later planting date in the organic systems is used to maximize production of green manure biomass and facilitate weed control. In order to allow comparisons across systems we elected to plant corn in all microplots on the same day using the typical planting date for the organic systems. Due to an abnormally wet spring, corn (Blue River 33N73, 92 day relative maturity) was planted on 29 June 2009, about a month later than is typical even for the organic systems. Corn was planted in rows spaced 76 cm apart (6 rows per microplot) at an average seeding rate of 67,600 seeds ha^{-1}. Standard weed control was supplemented by hand weeding in every system to maintain microplots weed-free.

Grain yield was determined by hand harvesting 3 m of two of the center rows at physiological maturity. Yield data were adjusted to 150 g kg^{-1}

Table 2 Summary of selected soil properties for each cropping system

Cropping system†	Soil pH	Mehlich 3 extractable			
		P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
CT	6.8ab‡ ± 0.19	46.3a ± 9.6	63.0b ± 9.1	1167a ± 114	165ab ± 23.8
NT	6.5b ± 0.17	46.0a ± 3.9	57.3b ± 7.2	1156a ± 90.7	158b ± 21.0
Org2	7.0a ± 0.18	54.3a ± 5.9	101a ± 2.9	1319a ± 65.6	185ab ± 17.8
Org3	6.9a ± 0.05	63.0a ± 6.4	102a ± 6.4	1248a ± 18.4	184ab ± 8.1
Org6	7.0a ± 0.04	61.0a ± 10.5	78.3a ± 10.3	1207a ± 49.5	193a ± 7.8

† *CT* chisel till corn—soybean—wheat/soybean rotation, *NT* no-till corn—soybean—wheat/soybean rotation, *Org2* organically managed 2 year corn—soybean rotation, *Org3* organically managed 3 year corn—soybean—wheat rotation, *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

‡ Means within columns followed by the same letter are not significantly different ($P < 0.05$); ± one standard error

moisture content. In order to quantify total N uptake, whole corn plants, cut at the soil surface, were collected from 3 m of one of the center rows. Corn biomass samples were oven dried (60° C), ground (<1 mm) and analyzed for total N by the Kjeldahl procedure (Bremner 1965).

Soil sample collection and analysis

We conducted a 210 days soil incubation to directly measure mineralizable soil N in all systems. Soil for the incubation was collected from the surface 20 cm from minus N microplots in each of the five cropping systems 2 weeks prior to planting corn. Eight cores were collected (5 cm dia.), composited in the field, and held at 4°C until they were processed (less than 24 h). Whole samples were weighed and subsampled for moisture determination to calculate bulk density. Field moist soil was gently passed through a 5 mm sieve and held at 4°C for 1 week before the start of the incubation. Sieved soil was subsampled for determination of moisture content at field capacity (−0.03 MPa) using the pressure plate method (Klute 1986). At the initiation of the incubation, approximately 300 g of soil were air-dried and ground to pass a 2 mm sieve and stored in sealed plastic bags prior to analysis of total and labile soil organic C and N.

Quantification of potentially mineralizable N

In order to allow for destructive sampling during incubation, nine subsamples (50 g dry weight equivalent) of field moist soil from each microplot were placed in 237 ml (8- oz.) glass canning jars and moistened to field capacity (−0.03 MPa). Jars were covered with lids with a 1 cm hole cut in the center. A small piece of polyfilm was placed over the hole in the lid to limit water loss but allow gas exchange during incubation. Containers were randomized and incubated in the dark for up to 210 days at 25°C. Moisture content of incubated soil was maintained at field capacity throughout the incubation by periodically adding water after weighing jars.

Incubation jars of soil from each microplot were destructively sampled 7, 14, 28, 42, 63, 84, 112, 154, and 210 days after initiation of the incubation. At initiation of the incubation and at each sampling date thereafter, soil from each destructively sampled jar was thoroughly mixed and subsampled for determination of $[NH_4 + NO_3] - N$ by extracting duplicate 5 g subsamples (dry weight equivalents) within 4 h of sampling using 50 ml of 1 *M* KCl for 1 h. Soil KCl extracts were stored frozen until they were analyzed for $[NH_4 + NO_3] - N$ colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments, Milwaukee, WI). Soil moisture content at each sampling interval was determined by drying a 10 g subsample from each jar at 105°C.

Characterization of labile soil organic matter

The concentrations of total soil organic C and N were determined by dry combustion analysis using a Costech ECS 4010 (Costech Analytical Technologies, Valencia, CA). Particulate organic matter was isolated from soil by dispersing duplicate 10 g subsamples of air-dry soil with 0.5% (w/v) $(NaPO_3)_6$ for 16 h on a reciprocating shaker and rinsing with deionized water through a 0.53 μm sieve (Sollins et al. 1999). Material remaining on the sieve was oven dried (60° C), weighed, and ground to a fine powder using a mortar and pestle. The concentrations of C and N were determined as described above. The CLOM analysis was conducted on duplicate subsamples of air-dry soil (Weil et al. 2003; Mirsky et al. 2008). Briefly, 10 ml of a 0.02 *M* $KMnO_4$-0.1 *M* $CaCl_2$ solution were added to 2.5 g of soil in 50 ml screw top plastic centrifuge tubes. The suspension was shaken for 2 min on a reciprocating shaker (180 rpm) then allowed to settle for 10 min. A 500 μL aliquot was diluted to 50 ml and absorbance measured on a split-beam spectrophotometer (550 nm). The quantity of C oxidized was determined using a standard curve developed by measuring absorbance of standard $KMnO_4$ solutions ranging from 0 to 0.02 *M* and assuming stoichiometric oxidation (0.75 mol C oxidized per mol $KMnO_4$).

Calculations and statistics

Net N mineralization in incubated soil during each time period was calculated by subtracting inorganic N content at time zero from that at time *t*. Mineralization data were modeled using a two-component first-order model:

$$N_{min} = N_a(1 - e^{-kat}) + N_s(1 - e^{-kst}), \quad (1)$$

where N_{min} is cumulative N mineralized at time *t*; N_a and N_s are the active and slow N pools, respectively;

and k_a and k_s are rate constants for the active and slow N pools, respectively. We used the modified double exponential model recommended by Wang et al. (2004), using fixed rate constants to generate N pool size estimates not influenced by incubation conditions, as occurs when all four parameters are fitted simultaneously (Cabrera and Kissel 1988; Sierra 1990; Dou et al. 1996; Dendooven et al. 1997). We used a similar approach as Christensen and Olesen (1998) to determine mineralization rate constants k_a and k_s. Based on model fitting of Eq. 1 and visual inspection of cumulative N mineralization, half lives of 7 and 120 days were used to describe mineralization kinetics of N_a and N_s, respectively ($k_a = 0.099\ d^{-1}$, and $k_s = 0.00578\ d^{-1}$). This approach allows soil N mineralization capacity to be expressed explicitly in terms of pool size by eliminating potentially confounding effects of variable rate constants (Wang et al. 2004; Mallory and Griffin 2007).

Model parameters N_a and N_s were estimated for each microplot using the PROC NLIN procedure of SAS using the Marquardt option (SAS Institute 2002). Total mineralizable N (N_o) was calculated as the sum of N_a and N_s. A step-down bootstrap adjustment was used for means comparisons of N_a, N_s, and N_o using PROC MULTTEST of SAS. Analysis of variance for all other parameters was performed using PROC MIXED of SAS. Means separation of cropping system effects was performed using the PDIFF option of the LSMEANS statement ($P < 0.05$) when the F test was significant. All proportions data were $\sin^{-1}(x)^{1/2}$ transformed prior to analysis of variance to meet normality and homogeneity of variance assumptions. The relationships between selected properties were analyzed using PROC REG of SAS.

Results and discussion

Potentially mineralizable soil N

Long-term aerobic incubations were conducted to determine the effect of management history on mineralizable soil N among cropping systems. The modified double exponential model fit the soil N mineralization data for the five cropping systems very well ($R^2 \geq 0.98$; Fig. 1, Table 3). Estimated size of N_a was similar among all systems except Org3, which had a significantly greater N_a than CT, NT, and Org2 but not Org6. The estimated size of N_s was similar among the three organic systems and significantly greater than the conventional systems. Total potentially mineralizable N (N_o), the sum of N_a and N_s, followed the same pattern as N_s. These findings are similar to those of Poudel et al. (2002) who showed greater mineralizable N in organic than conventional systems in a long-term project in California, and to those of Drinkwater et al. (1995) who found greater mineralizable N in organic than conventional farms in California. Our study is one of the first to show greater mineralizable N in organic than in no-till systems.

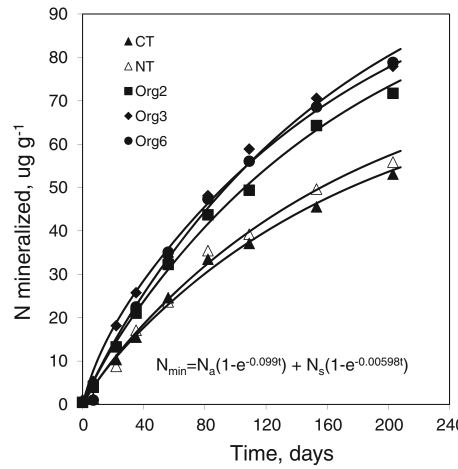

Fig. 1 Net N mineralization during laboratory incubations of soil collected from unamended (minus N) microplots within each of the cropping systems. Active (N_a) and slow (N_s) mineralizable N pools estimated using the double exponential model with fixed rate coefficients of 0.099 $days^{-1}$ for the active pool (k_a) and 0.00578 $days^{-1}$ for the slow pool (k_s). Parameter estimates for N_a and N_s and model R^2 are summarized in Table 3. *CT* chisel till corn—soybean—wheat/soybean rotation; *NT* no-till corn—soybean—wheat/soybean rotation; *Org2* organically managed 2 year corn—soybean rotation; *Org3* organically managed 3 year corn—soybean—wheat rotation; *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

Much of the difference in the size of mineralizable N pools between organic and conventional cropping systems is likely due to the addition of manure. Only a fraction of the organic N in manure is mineralized during the season of application, while the remainder decomposes slowly over many years (Endelman et al. 2010; Habteselassie et al. 2006; Whitmore and Schröder 1996). Thus, repeated applications of manure result in the accumulation of mineralizable

Table 3 Active (N_a), slow (N_s), and total (N_o) mineralizable N pools determined using a 210 day laboratory incubation of soil collected from unamended (minus N) microplots within each cropping system

Cropping system†	Mineralizable N pools‡			Model R^2
	N_a (kg ha^{-1})	N_s (kg ha^{-1})	N_o (kg ha^{-1})	
CT	6.89b§ ± 2.1	222b ± 7.0	229b ± 6.9	0.99
NT	5.03b ± 3.0	236b ± 8.6	241b ± 9.3	0.99
Org2	10.1b ± 3.5	287a ± 8.2	297a ± 11	0.99
Org3	23.7a ± 2.3	299a ± 9.8	323a ± 11	0.99
Org6	11.3ab ± 8.4	312a ± 12	325a ± 11	0.98

† CT = chisel till corn—soybean—wheat/soybean rotation; NT = no-till corn—soybean—wheat/soybean rotation; Org2 = organically managed 2 year corn—soybean rotation; Org3 = organically managed 3 year corn—soybean—wheat rotation; Org6 = organically managed 6 year corn—soybean—wheat—alfalfa rotation

‡ N_a and N_s estimated using the double exponential model with fixed rate coefficients of 0.099 days^{-1} for the active pool (k_a) and 0.00578 days^{-1} for the slow pool (k_s). N_o is the sum of N_a and N_s

§ Means within columns followed by the same letter are not significantly different ($P < 0.05$); ±one standard error

organic N in soil. The larger size of N_a in Org3 compared to Org2 is likely a result of the frequency with which Org3 and Org2 receive manure (2 out of 3 years for Org3 and 1 out of 2 years for Org2). It is interesting that even though Org6 received manure less frequently (2 out of 6 years) than either Org2 or Org3 it had similar levels of N_a as Org3 and similar levels of N_s as both Org2 and Org3. The likely reason for this result was the inclusion of alfalfa in the Org6 rotation. Decomposition of alfalfa crowns and roots remaining after alfalfa was harvested and killed the previous fall likely contributed a significant quantity of mineralizable N. Research conducted in Michigan by Harris and Hesterman (1990) to quantify N release from ^{15}N labeled alfalfa roots found that 14–21% of alfalfa root and crown N was recovered in a succeeding corn crop and 60–61% remained in soil as inorganic N (1–2%), microbial biomass N (6–8%), and organic N (37–44%).

There were no differences in any of the mineralizable N pools between NT and CT. This was somewhat surprising, as mineralizable soil N is generally expected to increase with continuous no-till management (Sharifi et al. 2008; Wienhold and Halvorson 1999; Franzluebbers et al. 1994).

Soil carbon and nitrogen fractions

Carbon and N cycling in agroecosystems is tightly linked, especially in organic grain cropping systems where soil fertility is managed using animal and green manures (Berry et al. 2002; Stockdale et al. 2002), and in conventional high residue continuous no-till grain cropping systems (Spargo et al. 2008b; Franzluebbers et al. 1994). Total soil organic C and N concentrations for each cropping system are presented in Table 4. Total soil organic C was 10% greater in Org3 than CT but similar among the other cropping systems. Total soil organic N was more sensitive to management than total organic C; NT, Org3, and Org6 all had significantly higher concentrations of N than CT. Total organic C:N ratio was highest in CT, lowest in Org3 and Org6 and intermediate in NT and Org2.

The concentration of POM-C was significantly higher in Org3 and Org6 (average 3.65 g kg^{-1}) than in CT and NT (average 2.90 g kg^{-1}), while POM-C in Org2 (3.10 g kg^{-1}) was intermediate to (and not statistically different) than these two groups (Table 4). The concentration of POM-N followed a similar trend, with the exception that POM-N in Org6 was significantly greater than in Org2. Other researchers have also found greater POM-C and POM-N in organic compared to conventional systems (Marriott and Wander 2006; Willson et al. 2001; Wander et al. 1994) but this is one of the first studies that include a no-till treatment. The C:N ratio of POM, reflecting the quality of this pool of soil organic matter, followed the trend Org6 < Org3 < Org2 < NT < CT.

Levels of CLOM-C were statistically similar among all systems except that CLOM-C in Org3 (0.483 g C kg^{-1}) was 12% greater than the average of CLOM-C in CT, NT, Org2 and Org6 (0.433 g C kg^{-1}; Table 4). The higher concentration of CLOM-

Table 4 Total, particulate, and chemically labile (CLOM) oil organic matter fractions for each cropping system

Cropping System[†]	Total organic			Particulate organic matter			CLOM-C[‡]
	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C:N	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C:N	
CT	14.6b[§] ± 0.96	1.24b ± 0.06	11.8a ± 0.24	2.95b ± 0.16	0.148c ± 0.009	20.1a ± 1.27	0.419b ± 0.023
NT	15.8ab ± 0.73	1.40a ± 0.06	11.3abc ± 0.46	2.85b ± 0.07	0.153c ± 0.009	18.8ab ± 0.93	0.434b ± 0.020
Org2	15.3ab ± 0.49	1.34ab ± 0.05	11.4ab ± 0.30	3.10ab ± 0.20	0.171bc ± 0.014	18.3ab ± 1.08	0.434b ± 0.016
Org3	16.1a ± 1.44	1.48a ± 0.11	10.9c ± 0.16	3.65a ± 0.43	0.210ab ± 0.025	17.4bc ± 0.27	0.483a ± 0.030
Org6	15.8ab ± 0.56	1.45a ± 0.04	11.0bc ± 0.14	3.64a ± 0.03	0.222a ± 0.006	16.4c ± 0.35	0.446b ± 0.011

[†] *CT* chisel till corn—soybean—wheat/soybean rotation, *NT* no-till corn—soybean—wheat/soybean rotation, *Org2* organically managed 2 year corn—soybean rotation, *Org3* organically managed 3 year corn—soybean—wheat rotation, *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

[‡] Chemically-labile organic matter carbon

[§] Means within columns followed by the same letter are not significantly different ($P < 0.05$); ±one standard error

C in Org3 is, again, likely due to the higher frequency of manure application in Org3 than in the other systems. It is interesting that we did not measure significant differences among the other treatments despite the diversity of fertility management and crop rotations among systems. Min et al. (2003) found significant differences in CLOM-C between soils with a history of two different levels of dairy manure application and mineral fertilizer and between soils under orchardgrass (*Dactylis glomerata* L.) vs. alfalfa in Maryland. In Pennsylvania, Mirsky et al. (2008) found CLOM-C to be more sensitive to fertility management (mineral fertilizer, and two levels of manure application), and crop rotation (corn-soybean, continuous corn, 4 years corn-4 years alfalfa, and corn-oats-wheat-2 years red clover hay) than POM-C. There is insufficient data to determine why that was not the case here, but it is not uncommon to have different conclusions arise among sites when data are derived from the action of strong chemical agents (e.g. $KMnO_4$) reacting with soil organic matter (Keeney and Bremner 1966; Nommik 1976; Fox and Piekielek 1978; Stanford and Smith 1978).

Management legacy also impacted the relative fraction of labile C and N (i.e., labile/total; Table 5). The proportion of total organic N isolated as POM-N was similar between Org3 and Org6 (average 0.148 g POM-N g^{-1} total organic N) and significantly higher than NT and CT (average 0.115 g POM-N g^{-1} total organic N). Marriot and Wander (2006) found similar

Table 5 Soil organic matter fractions as proportions of total soil C and N for each cropping system

Cropping System[†]	Proportion of total N		Proportion of total C	
	POM-N[‡] ($g\ g^{-1}$)	N_o[§] ($g\ g^{-1}$)	POM-C[‡] ($g\ g^{-1}$)	CLOM-C[¶] ($g\ g^{-1}$)
CT	0.120c[#] ± 0.0047	0.0628b ± 0.0033	0.203bc ± 0.0067	0.0288ab ± 0.00048
NT	0.109c ± 0.0063.	0.0590b ± 0.0031	0.181d ± 0.0047.	0.0275b ± 0.0010
Org2	0.127bc ± 0.0068	0.0761a ± 0.0025	0.202c ± 0.0073	0.0284b ± 0.00052
Org3	0.141ab ± 0.0068	0.0752a ± 0.0044	0.226ab ± 0.0092	0.0302a ± 0.00079
Org6	0.154a ± 0.0068	0.0770a ± 0.0035	0.230a ± 0.0086	0.0282b ± 0.00040

[†] *CT* chisel till corn—soybean—wheat/soybean rotation, *NT* no-till corn—soybean—wheat/soybean rotation, *Org2* organically managed 2 year corn—soybean rotation, *Org3* organically managed 3 year corn—soybean—wheat rotation, *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

[‡] Particulate organic matter-N and -C

[§] Total potentially mineralizable-N

[¶] Chemically-labile organic matter-C

[#] Means within columns followed by the same letter are not significantly different ($P < 0.05$); ±one standard error results, where the proportion of total soil organic N as POM-N in organically managed cropping systems with a history of manure was significantly higher than conventionally managed cropping systems with no manure (0.133 g POM-N g^{-1} total organic N vs. 0.099 g POM-N g^{-1} total organic N, respectively). We found organic management also disproportionally enriched the N_o fraction of total organic N compared to conventional management; N_o, expressed as a fraction of total organic N, was similar among all organic systems (average 0.0761 g N_o g^{-1} total organic N) and 25% greater than in conventional systems (average 0.0609 g N_o g^{-1} total organic N). The fraction POM-C/total C was similar between Org3 and Org6 (average 0.228 g g^{-1}) and significantly greater than in Org2 (0.202 g g^{-1}). The fraction POM-C/total C for CT (0.203 g g^{-1}) was similar to that in Org2 and Org3 but less than that in Org6, while that in NT (0.181 g g^{-1}) was significantly lower than in all other systems. We were surprised that soil organic C in CT was more enriched with POM-C than NT; we expected the inverse to be true. The CLOM-C/total C was no more sensitive to management than CLOM-C alone, further illustrating its limited utility in this study to detect changes in labile C due to management.

While differences in labile organic matter among organic systems were not as distinct as those between the organic and conventional systems, we did observe a few interesting patterns. The trend, where evident, was for labile fractions of organic matter (e.g., POM-N, POM-C:N, POM-N/total N, POM-C/total C) to increase with length of the crop rotation (Org2 < Org3 ≤ Org6). As previously discussed, differences between Org2 and Org3 (i.e., N_a, total soil organic C:N, POM-C/total C) are likely due to the higher frequency of animal manure application in Org3 (2 out of 3 years) compared to Org2 (1 out of 2 years). However, frequency of animal manure application does not explain the greater POM-N and lower POM-C:N in Org6 compared to Org2. Animal manure was applied 2 out of 6 years in Org6, indicating that the inclusion of a perennial legume in the Org6 rotation for 3 of 6 years had a greater impact on POM-N than did the relatively frequent application of manure in Org2. The impact of alfalfa on POM-N may be due in part to greater quantities of plant residues returned to the soil under forage than under annual grain and cover crops (Min et al. 2003). It is also likely that the elimination of tillage in Org6 during the perennial phase of the rotation reduced turnover of labile organic matter.

It is interesting that we found few differences in labile organic matter between NT and CT. By incorporating crop residues, decreasing soil albedo, aerating soil, and destroying soil aggregates, tillage increases decomposition of soil organic matter and decreases the soil's ability to conserve N (Carter and Rennie 1984; Follett and Schimel 1989; Franzluebbers 2004). Continuous no-till management has generally been found to increase total and labile soil organic matter (Franzluebbers 2005; West and Post 2002); however, this is not always the case (Blanco-Canqui and Lal 2008; Venterea et al. 2006). Accumulation of soil organic matter in no-till soils has been found to be limited where crop residues are removed or biomass production is limited by extended fallow periods (Blanco-Canqui and Lal 2008; Venterea et al. 2006). For example, West and Post (2002) found that no-till management did not significantly increase soil C in wheat-fallow rotations. Harvest of wheat straw from the conventional systems of the FSP reduced the quantity of residue returned to the soil but biomass residues from corn, soybean and the rye cover crop are recycled so it seems unlikely that this limited the capacity of no-till to conserve organic matter. In addition, crop yields and biomass returned to the soil have been similar in NT and CT (Cavigelli et al. 2008; unpublished data), indicating that reduced crop yields in NT relative to CT are not an explanation for similar soil C and N pools in CT and NT, as others have found in cooler climates (Venterea et al. 2006). That we did not detect a significant increase in any measure of total or labile soil organic matter (except total soil N) in NT relative to CT could be due to Type II errors reducing our ability to detect any differences in those cases where mean values are greater in NT than CT (Tables 3, 4, 5). It is well established that no-till management has a significant impact on the distribution of soil organic matter within the profile, with no-till leading to the accumulation of organic matter at or near the soil surface (Spargo et al. 2008a; Franzluebbers 2002a; Kay and VandenBygaart 2002; Needelman et al. 1999). While we did not measure the depth distribution of soil organic matter in this study we do recognize its role in improving soil quality, and reducing runoff and erosion in no-till systems (Franzluebbers 2002b).

Relationships between soil parameters and corn yield response

Average corn grain yield in minus N microplots was similar among organic cropping systems (mean of 9.61 Mg ha^{-1}) and significantly greater than for NT and CT (mean of 6.87 Mg ha^{-1}; Table 6). Average corn grain yield in the minus N plots of the organic systems was near the yield potential observed in the first 11 years of the study (1996–2005) across all systems (Cavigelli et al. 2008) and not significantly different from observations made in adjacent weed-free sections of subplots in 2009 receiving full fertility (legume biomass, and poultry litter; data not shown), indicating that mineralization of soil organic N met most, if not all, corn N needs. Total N uptake by corn followed a similar trend where average N uptake in organic cropping systems (195 kg N ha^{-1}) was 44% greater than average N uptake in conventional cropping systems (132 kg N ha^{-1}). It is worth noting that N was identified as an important limiting factor for corn production in the organic cropping systems during earlier years of the experiment (Cavigelli et al. 2008). Our current results suggest that earlier N limitation in these systems has likely been alleviated by additional years of organic management. However, since we did not make similar measurements in earlier years of this project, it is not possible to determine the trajectory of change in soil N fractions during the development of these organic systems. Such information, however, could prove useful to organic farmers and others who rely on organic inputs, so they can adjust their management to reflect changes in soil N_o over time.

A useful index of labile organic matter (or soil quality) should be both sensitive to management and related to some functional aspects of the soil. Potentially mineralizable N (N_o) was strongly correlated with corn grain yield ($r = 0.87$, $P < 0.0001$; Fig. 2) and N uptake ($r = 0.83$, $P < 0.0001$; Fig. 3), illustrating the relative value of soil N as a source of fertility in each of these systems. The sensitivity of N_o to organic vs. conventional management and its high degree of correlation with both corn grain yield and N uptake illustrates this relationship well. We also found that POM-N was strongly correlated with corn grain yield ($r = 0.72$, $P = 0.0008$) and N uptake ($r = 0.63$, $P = 0.004$), and that POM-N and N_o were strongly correlated ($r = 0.83$, $P < 0.0001$; Fig. 4). Thus, POM-N, which is more easily measured than N_o, might have greater potential than N_o as a measure of soil N availability for organic systems as also suggested by Willson et al. (2001). Particulate organic matter-C was also significantly correlated with corn grain yield ($r = 0.59$, $P = 0.01$) and N

Table 6 Corn grain yield and N uptake from unamended (minus N) microplots within each of the cropping systems

Cropping system[†]	Grain yield[‡] (Mg ha^{-1})	Total N uptake (kg ha^{-1})
CT	7.12b[§] ± 0.39	119b ± 14
NT	6.62b ± 0.25	144b ± 13
Org2	9.23a ± 0.44	183a ± 5
Org3	10.2a ± 0.48	196a ± 11
Org6	9.41a ± 0.84	207a ± 13

[†] *CT* chisel till corn—soybean—wheat/soybean rotation, *NT* no-till corn—soybean—wheat/soybean rotation, *Org2* organically managed 2 year corn—soybean rotation, *Org3* organically managed 3 year corn—soybean—wheat rotation, *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

[‡] Grain yield adjusted to 150 g kg^{-1} moisture content

[§] Means within columns followed by the same letter are not significantly different ($P < 0.05$); ±one standard error

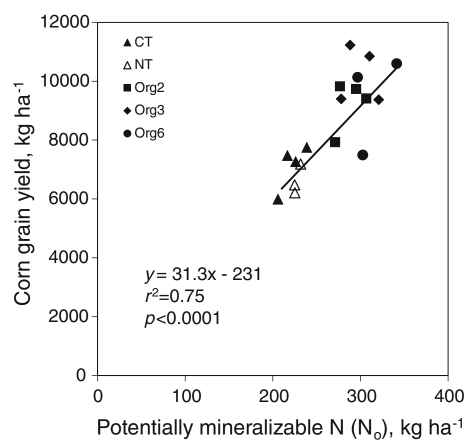

Fig. 2 Relationship between potentially mineralizable soil N (N_o) during laboratory incubations and corn grain yield from unamended (minus N) microplots within each of the cropping systems. *CT* chisel till corn—soybean—wheat/soybean rotation; *NT* no-till corn—soybean—wheat/soybean rotation; *Org2* organically managed 2 year corn—soybean rotation; *Org3* organically managed 3 year corn—soybean—wheat rotation; *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

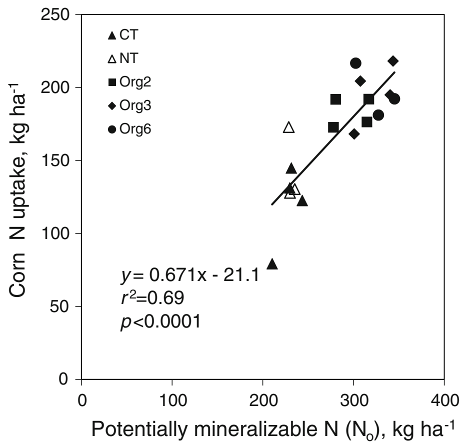

Fig. 3 Relationship between potentially mineralizable soil N (N_o) during laboratory incubations and total corn N uptake from unamended (minus N) microplots within each of the cropping systems. *CT* chisel till corn—soybean—wheat/soybean rotation; *NT* no-till corn—soybean—wheat/soybean rotation; *Org2* organically managed 2 years corn—soybean rotation; *Org3* organically managed 3 year corn—soybean—wheat rotation; *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

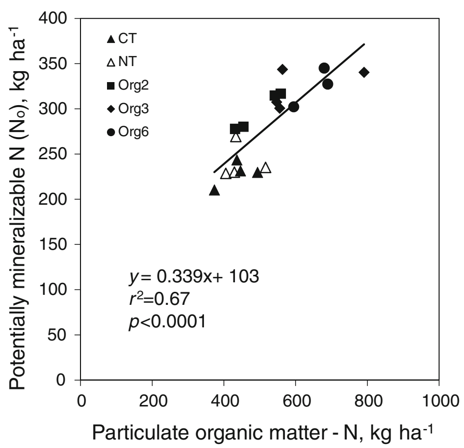

Fig. 4 Relationship between potentially mineralizable N (N_o) and particulate organic matter N from unamended (minus N) microplots within each of the cropping systems. *CT* chisel till corn—soybean—wheat/soybean rotation; *NT* no-till corn—soybean—wheat/soybean rotation; *Org2* organically managed 2 year corn—soybean rotation; *Org3* organically managed 3 year corn—soybean—wheat rotation; *Org6* organically managed 6 year corn—soybean—wheat—alfalfa rotation

uptake ($r = 0.51$, $P = 0.03$). Although CLOM-C was correlated with corn grain yield ($r = 0.48$, $P = 0.046$), it was not significantly related to N uptake ($r = 0.40$, $P = 0.09$).

One of the most important implications of our results pertains to the relative dependence of these systems on external fertility inputs. If crop N needs are viewed using a mass balance approach (Meisinger et al. 2008), external N needs (met by commercial fertilizers, animal manure, or green manure) are inversely proportional to N_o. Thirteen years of organic management have significantly increased N_o at the FSP, and corn grain yield and N uptake data suggest that mineralization of soil organic N in these systems is high enough to meet a substantial portion of crop N needs. This finding is important because meeting the N needs of high demand crops in organic grain systems using external sources can be very challenging. For example, the legume species that are adapted to the mid-Atlantic region (annuals and perennials) do not provide sufficient plant available N to satisfy all the needs of a subsequent grain crop in most seasons (Decker et al. 1994; Clark et al. 2007; Wagger 1989). In organic cropping systems, animal manures are often used to meet crop N needs not met by legumes and soil N mineralization. Sound nutrient management practices dictate that application rates of animal manures be determined by the balance of manure P concentration, soil P level, and crop P removal to avoid buildup of soil P and the associated risk of P enrichment of runoff (Spargo et al. 2006; Maguire et al. 2008). Though not excessively high, levels of soil P at the FSP tend to be greater in the organic than the conventional systems (Table 2). This is in spite of the fact that manure applications have been relatively conservative. In order to avoid increasing soil P to excessive levels, animal manure rates and soil P levels will need to be closely monitored. What is not clear is how much manure will be required both to meet the balance of crop N needs not satisfied by legume and soil N and to maintain levels of N_o.

Summary and conclusions

Soil C and N cycling are tightly linked, especially in organic cropping systems. In systems with a history of animal manure use and legume cover crops or perennial forages in rotation, mineralizable soil N is likely to build to levels high enough to meet a substantial portion of crop N needs in silt loam soils of the mid-Atlantic region. Mineralizable soil N was greater in three organic systems and POM-C and POM-N were greater in two of three organic systems than in a no-till system. These differences in soil N availability were reflected in corn yield and N uptake among systems. This source of plant available N needs to be considered when making fertility recommendations for organic cropping systems. Our results also suggest that animal manure applications could be reduced significantly once organic systems are well-established when legume cover crops are used. Further work, however, is needed to better understand what level of animal manures over the long term is required to maintain adequate N_o while not overloading soils with P in diverse organic cropping systems.

Acknowledgments The authors would like to extend their sincere gratitude to Chris Rasmann, Allegra Buyer, Grace Garst, Amelia Garcia, Aisha Parihar, and Sarah Emche for their significant contributions to this research.

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