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THE EFFECTS OF COMPOST AND CROP ROTATIONS ON CARBON TURNOVER AND THE PARTICULATE ORGANIC MATTER FRACTION

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Management practices that influence the quantity of C inputs returned to the soil from cropping systems and compost applications alter subsequent biotic activity broadly, contribute to seasonal fluctuations in nutrient dynamics, and may increase C sequestration. The effects of crop rotations and compost applications on soil-C sequestration and decompostion, and the turnover time of C_4-derived corn C were assessed via changes in the C content and ^{13}C values of particulate organic matter (POM) and total soil organic C (SOC). The majority of organic inputs entered the POM fraction, defined as the sand-sized soil separates remaining on a 53-μm sieve after removal of residues (>2 mm), dispersion in 5% sodium polyphosphate, and 12 h of shaking. Before the application of compost to soil, 85% of the C in the compost material was classified as POM. Measurements of POM-C in the soil were 45% higher and SOC was 16% greater where compost was applied in place of N fertilizer. Addition of compost to POM-C diminished the value of POM as an indicator of short-term changes in nutrient dynamics. However, POM-C remaining from compost applications made during the period 1993 to 1997 may be an indicator of enhanced macroaggregate stability: improved soil tilth and the retention of soil C and N. The turnover time of C_4-derived C in the POM fraction was 11 years compared with 22 years in SOC. The presence of compost C did not affect the turnover time of corn-derived C. High cropping intensity and chisel plow management increased C sequestration relative to the preceding alfalfa management. (Soil Science 2003;168:434–444)

Key words: Compost, rotation, POM, ^{13}C natural abundance, C_4-C, turnover time, SOC.

MANAGEMENT systems that utilize organic amendments such as crop residues and/or waste materials can increase the level of soil C that may improve soil quality and increase the potential for C sequestration (Lal et al., 1999). Agricultural practices that increase the quantity of plant residues returned and/or decrease the turnover rate of C inputs augment C sequestration. Greater cropping diversity and intensity, coupled with a reduction in tillage, have been shown to build up stores of soil C (Campbell et al., 1991; Sanchez et al., 2001). Sufficient N fertilizer levels are required to increase vegetative growth and maintain C inputs provided by crop residues, as well as for the stabilization of soil organic matter (Paul and Clark, 1996). Application of N fertilizer to continuous corn for 27 years increased total soil organic C (SOC) by 7 Mg C ha^{-1} above that of an unfertilized control (Gregorich et al., 1996). Combining a management practice that provides N and augments SOC, e.g. manuring coupled with a reduction in residue removal and tillage, can have an additive effect on C sequestration (Grant et al., 2001).

Increases in SOC are long term, requiring several growing seasons to effect a change. POM-C (50–2000 μm) is associated with the sand size fraction and contains the most recent additions of

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plant material. Aggregate dispersion and physical separation of POM is rapid and has proven to be a sensitive indicator of seasonal changes in soil C and N associated with management (Cambardella and Elliott, 1993). Portions of material added as manure and paper sludge also enter the system as particulate material associated with the sand-size fraction, persist, and may become the core of enhanced macro-aggregate structure (Aoyama et al., 1999; Chantigny et al., 1999). Therefore, POM-C measurements in some instances can be indicative of future changes in SOC, depending on the origin of the POM material (Wander et al., 1998; Six et al., 1999).

Studies that combine particle size fractionation with ^{13}C tracer techniques enable researchers to determine the location and turnover time of plant residues (Balesdent and Mariotti, 1987; Bonde et al., 1992). A study that followed the incorporation of sugar cane into various particle-size fractions revealed that initially residues entered the POM fraction, underwent decomposition, and then became mineral associated (Bonde et al., 1992).

The majority of research has focused on POM-C contributed by plant residues. It was hypothesized that humic materials in compost would persist in the POM fraction beyond a growing season, potentially altering the decomposition rate of plant residues and the turnover time of POM. Previous research in the Living Field Lab (LFL) at the Kellogg Biological Station (KBS) in MI revealed that POM-C was a sensitive indicator of seasonal changes in soil C and N (Willson et al., 2001). Accumulated inorganic N at Day 150 of a laboratory incubation was correlated with original POM-C (>53 μm) (r = 0.64). Forty-one percent of the total N content of compost was contained in the POM fraction, and compost additions increased POM-C by 25% in the year of application (Willson et al., 2001). However, the steady-state turnover time estimate of POM during the study was 20 to 40 years. Thus, knowledge of long-term changes in POM-C can facilitate management of nutrients from organic amendments. The objective of our study was to monitor the impact of crop rotations and compost applications on C sequestration, soil organic matter (SOM) decomposition, and the turnover time of C_4-derived C in the soil via changes in the C content and ^{13}C values of POM.

MATERIALS AND METHODS

Field Sites

Field sites are located in Hickory Corners, Michigan, on a Kalamazoo loam and on a similar Oshtemo sandy loam (coarse-loamy, mixed, mesic, Typic Hapludalfs). The Living Field Lab was designed to compare the effects of several best-management practices on crop yield and soil biogeochemical processes. Management practices were compost and chemical fertilizer, substitution of a corn (*Zea mays* L.)-corn-soybean (*Glycine max* L.)-wheat (*Triticum aestivum* L.) rotation in place of continuous corn, and the use of a cover crop within each cropping system. The cover crop treatments were not used in the current study. The LFL was blocked by nutrient management, fertilizer, and compost. Nutrient management was further divided into four replicated split-split plots, each 15 × 4.5 m. Main plot treatments consisted of a continuous corn and a corn-corn-soybean-wheat rotation, including all entry points each year. The final split was a cover-no cover treatment.

The current study included data from the LFL in 1994, 1998, and 1999 the 2nd, 6th, and 7th years of the field study. Data were collected on the no cover crop plots. Plots were chisel plowed in April of each year in all cropping systems except winter wheat, which was chisel plowed in October. Banded herbicides and cultivation were used in both managements.

A total of 170 kg N ha^{-1} yr^{-1} was applied to corn in fertilizer treatments at preplant (April) and sidedress (June) each year. The compost management utilized compost as the only nutrient input. Compost material contained ~50% oak leaves (*Quercus rubra*) and ~50% dairy manure on a dry weight basis. Materials were composted for a minimum of 1 year. Application rates were adjusted to compensate for variations in moisture content such that the rotation and 4 years of continuous corn received the equivalent of 4480 kg ha^{-1} yr^{-1} compost on a dry weight basis. Compost was applied in late April of each year to all crops other than winter wheat. Compost was applied to winter wheat in October of each year. The total amount of N applied in the form of compost to continuous and 1st year corn was 117 kg N ha^{-1} yr^{-1}. The compost application was doubled in 2nd year corn because of the treatment's supplemental N requirement. Compost was not applied to the soybean crop. The total amount of compost applied over the rotation was equal to the quantity of compost applied during 4 years of continuous corn. Cumulatively, compost applied plus previous compost applications provided 40 to 53 kg N ha^{-1} yr^{-1} inorganic N (T.C. Willson, personal communication, 1998). A previously tilled successional grassland treatment located on an adjacent Long-term Ecological Research (LTER) site, which was in its 10th and 11th years in 1998 and 1999, was contrasted with that of the agronomic systems.

Soil Sampling

Soil samples were collected as composite samples of 12 or more 2-cm diameter cores at a 0–25-cm depth from each plot. Soil samples were collected from 10 × 30-m subplots within each of the four replicate, 1-ha plots on the adjacent LTER in April 1998 and 1999. Sampling dates on the LFL were April 1994, 1998, and 1999 prior to compost application and chisel plowing. Surface crop residues had been carefully eliminated before sampling. The fertilizer management and the compost management in the 1st year corn and soybean entry points on the no cover sub-sub plot were sampled in April 1994 (Table 1). The April 1998 and 1999 samples included fertilizer and compost management in the continuous corn system, and 1st year corn and soybean entry points in the rotation on no cover sub-sub plots (Table 1).

Total Organic Soil C

Soil samples collected in April 1994, 1998, and 1999 (Table 1) were measured by dry combustion on a Carlo Erba N A 1500 Series 2 N/C/S analyzer (C.E. Instruments, Milan, Italy). Total soil C measurements taken in 1994 at 25 cm in the successional grassland treatment and the soil sampling protocol were obtained from the KBS-LTER database (http://lter.kbs.msu.edu/Data/DataCatalog.html).

In Situ Soil Litter Incubation

Soil samples to be used in an *in situ* soil/residue incubation were collected as described previously in April of 1998 and 1999 prior to chisel plowing and compost application. Soil was sieved through a 4-mm screen and stored at 4 °C. Before application of a known residue mass, residue materials were removed from the soil by passing samples through a 2-mm screen. One hundred grams of sieved soil were placed in each nylon pouch along with one of the residues. The pouches were sealed with a glue gun, fitted with plastic tags, and buried on May 12, 1998 and April 13, 1999. There were two sampling dates each year, June 26 and November 25, 1998 and June 26 and December 3, 1999 for pouch recovery from the field. On each sample date, 32 pouches were recovered from the LFL (four replicates for each nutrient management by cropping system by residue type) and eight pouches from the LTER previously tilled successional grassland.

Initial measurements of ^{13}C in soil at 0–25-cm depth (−23‰) were influenced by previous cropping to alfalfa, a C_3-C pathway plant (Table 2). All non-corn C – alfalfa, wheat, soybean, clover, and compost – had C_3 pathway isotopic signatures (Table 3). Plant tissue samples were

TABLE 1

Description of treatments and analyses completed on soil samples from each set of management practices on the Living Field Lab, Hickory Corners, MI, U.S.A.†

Nutrient Management	Total Soil organic C	^{13}C in whole soil	In-situ incubation	Residue in pouch: corn	Residue in pouch: clover	Residue in pouch: wheat	POM-C‡	^{13}C in POM-C
Nitrogen Fertilizer								
Cropping System								
Continuous corn-no cover	'94, '98, '99	'94, '98	'98, '99	'98, '99	'98, '99		'94, '98, '99	'94, '98, '99
1st Year corn-no cover	'94, '98, '99	'94, '98	'98, '99			'98, '99	'94, '98, '99	'94, '98, '99
Soybean-no cover	'94, '98, '99	'94, '98	'98, '99	'98, '99			'94, '98, '99	'94, '98, '99
Compost								
Continuous corn-no cover	'94, '98, '99	'94, '98	'98, '99	'98, '99,	'98, '99		'94, '98, '99	'94, '98, '99
1st Year corn-no cover	'94, '98, '99	'94, '98	'98, '99			'98, '99	'94, '98, '99	'94, '98, '99
Soybean-no cover	'94, '98, '99	'94, '98	'98, '99	'98, '99			'94, '98, '99	'94, '98, '99

†1994, 1998, 1999 = the years soil samples were taken from the field. All samples are from a 0- to 25-cm depth.
‡POM-C = particulate organic matter carbon.

TABLE 2.

Initial ^{13}C values of soil in the Living Field Lab

Management†	Soil ^{13}C (‰)‡ 1994
N Fertilizer	
1st yr corn	−23.4
Soybean	−23.3
Composite	
1st yr corn	−23.2
Soybean	−23.2

†Soil samples (0–25 cm) were collected in continuous corn and plots to be cropped to 1st year corn and soybean rotations.

‡The precision for the mass spectrometer for five identical samples in delta notation is C ~ 0.05.

bulked over field replicates to insure a uniform residue source for the *in situ* incubations. The ^{13}C content of bulked plant samples was run in duplicate. The precision of the mass spectrometer for five identical samples in delta notation is 0.05 per mil use unit. The difference in the C_4-derived isotopic signature of corn-derived C and all other C_3-derived C inputs allowed us to determine the rate at which corn-derived C was incorporated into SOC and POM in the presence or absence of compost and/or C_3 residues.

Treatments containing *in situ* incubations were selected from N fertilizer and compost management on the LFL. The cropping systems included: the continuous corn no cover treatment with red clover (*Trifolium pratense* L.) residue (7.5 Mg ha^{-1}) and corn residues (26 Mg ha^{-1}) added to separate pouches; 1st year corn, no cover, with wheat residue additions (12 Mg ha^{-1}); and the soybean no cover treatment with corn residue (26 Mg ha^{-1}) (Table 1). Residue additions applied to soil in pouches were in lieu of the normal surface residue incorporation through tillage. Red clover (7.5 Mg ha^{-1}) and corn residues (26 Mg ha^{-1}) were added to separate pouches of soil from the previously tilled successional grassland on the LTER.

Intact soil cores 13.5 cm × 13.5 cm × 15 cm were removed with a cup cutter at approximately 1-m intervals in the NW corner of each subplot. A nylon pouch was placed in each hole at a 15-cm depth, and the soil core was placed above it. Each time a pouch was excavated, a soil sample was taken adjacent to the incubation site for determination of soil moisture. Pouches were stored at 4 °C after recovery from the field. Within 2 weeks after removal from the field, pouches were opened, sieved through a 2-mm screen, and left to air dry.

TABLE 3

The ^{13}C content of organic amendments

Organic Amendments†	^{13}C (‰)§
Compost	−26.4
Compost POM‡	−25.0
Clover residue	−28.0
Corn residue	−13.0
Wheat residue	−26.8

†Organic amendments were oven dried at 60 °C.

‡Particulate organic matter (POM) in compost

§The precision for the mass spectrometer for five identical samples in delta notation is C ~ 0.05.

Particulate Organic Matter (POM)

POM was defined as the sand-sized soil separates remaining on a 53-μm sieve after removal of residues (>2 mm), dispersion in 5% sodium polyphosphate, and 12 h of shaking (Willson et al., 2001). The sand-sized soil separates were dried at 60 °C and ground with a mortar and pestle. After grinding, POM was passed through a 60-μm mesh. Total C was measured in POM samples recovered on June 26 1998, November 25, 1998, June 26, 1999, and December 3, 1999 (Table 1). POM-C was also separated from archived soil samples taken in April 1994 at a 0- to 25-cm depth (Table 1). The quantity of total C and/or N in POM was determined by dry combustion on a Leco Carbon Analyzer (Leco Corp., St Joseph, MI) or using a Carlo Erba N A 1500 Series 2 N/C/S analyzer (C.E. Instruments, Milan, Italy).

Analysis of ^{13}C Natural Abundance

Whole soil, POM, and organic amendments were analyzed for $\delta^{13}C$ (Table 1) on a Europa Model 2020 continuous flow mass spectrometer (Europa Scientific, Crewe, UK). Each of the treatments contained four replicate POM and whole soil samples. Plant tissue samples were bulked and run in duplicate. Standards were sugar beet sucrose (−25.68‰ V-PDB) calibrated against NBS-22 (−29.74‰ V-PDB) and sugar cane sucrose (−10.45‰ V-PDB) calibrated against (IAEA-C-6, −10.43‰ V-PDB) (Collins et al., 2000). The precision of the mass spectrometer for five identical samples in delta notation was 0.05 per mil use unit.

The fraction (f) of corn (C_4)-derived C in the soil was calculated using the equation:

$$f = (\delta_t - \delta_0)/(\delta_c - \delta_0) \qquad (1)$$

where $\delta_t = \delta^{13}C$ at time t, δ_0 = initial $\delta^{13}C$ of the C_3-derived soil organic matter (SOM) at time $t = 0$, and $\delta_c = \delta^{13}C$ of corn residue (Balesdent and Balabane, 1992).

Turnover Rate

The turnover rate of C_4-derived POM-C was calculated based on the fraction of corn C (C_4-derived C) in the soil on the continuous corn, fertilizer management in 1994 vs 1998 using a single pool first-order model:

$$k = -\ln(A_t/A_0)/t \tag{2}$$

where $A_0 = C_3$-derived C at time 0 (1994), A_t is the C_3-derived C at time t [$A_t = (1 - f)$POM-C] or C_4 derived C at time t [$A_t = f$(POM-C)], t = 4 yr, and k = the decomposition rate of POM C (yr^{-1}). The mean residence time (MRT) of the POM = $1/k$.

Crop Residue C

Average crop residue C was based on the above ground biomass at maturity of the corn, wheat, and soybean crop minus grain yield. A description of the sampling procedure for above ground biomass can be found in Fortuna et al. (2003a). The average C content of above ground residues was 40% (Fortuna et al., 2003a). Below ground biomass of crops was estimated using root-C for corn = crop residue C $\times$ 0.53 and root-C for soybean = crop residue C $\times$ 0.47 (Paul et al., 1999). The root-C for wheat residue was based on measured above ground biomass at maturity, a shoot/root ratio of 1.13, and a root C content of 30% (Buyanovsky and Wagner, 1997).

Statistical Analyses

Variations in SOC, POM-C, and $\delta^{13}C$ values of POM and POM as a percent of SOC were analyzed using SAS Proc Mixed (SAS Institute, 1997). The effect of N fertilizer management, cropping system, residue type, date, and year, as well as the interactions between individual effects, was determined for each of the previously mentioned data sets.

RESULTS

Carbon Inputs

Four years of compost applications, 1994–1997, increased SOC by 16% relative to N fertilizer management. In 1994, the amount of total C measured to a 25-cm depth on the previously tilled successional grassland (LTER) treatment was significantly greater than that of the LFL (Table 4). Although C on the agronomic and grassland managed areas increased from 1994 to the spring of 1998, increases in SOC were larger in the successional grassland where no plant residues were removed and no tillage occurred.

The quantity of biomass C returned to the soil from 1993 to 1997 was estimated in the spring of 1998. The amount of biomass C returned to the soil in the rotation management was (24.1 Mg C ha^{-1}) on the compost treatment and (24.6 Mg C ha^{-1}) on the N fertilizer treatment for the same period. Continuous corn treatments receiving N fertilizer produced 31.8 Mg ha^{-1} corn residue C at maturity from 1993 to 1997 (Table 5). Continuous corn biomass production was 31.3 Mg C ha^{-1} in the compost treatment during this period. A total of 7.5 Mg C ha^{-1} of compost C was applied, and an average of 27.7 Mg residue C ha^{-1} across the rotation and continuous corn treatments was returned to the LFL between November 1993 and April 1998 (Table 5).

Particulate Organic Matter

POM-C constituted 15 to 20% of SOC in the 0- to 25-cm depth under N fertilizer management (Table 6). Between 23 and 26% of SOC was contained in the POM fraction where compost was applied (Table 6). The quantity of POM-C was greatest ($P = 0.01$) in treatments where compost was substituted for N fertilizer in 1998 and 1999 (Table 6) and (Fig. 1). Carbon inputs from residues plus compost were, on average, 25% higher than C inputs from residues in the fertilizer management (Table 5). After application of compost from 1993 to 1997, POM-C increased an average of 44.5% (Fig. 1). The quan-

TABLE 4

Total Soil Organic Carbon†

	1994 (Mg C ha^{-1})‡	1998 (Mg C ha^{-1})
Agronomic system		
(Living Field Lab)		
N fertilizer	35.2 a	42.6 b
compost	35.5 a	49.6 d
Successional grassland		
(Long-term ecological research site)	48.1 c	61.0 e

†Total C values 0–25-cm depth for 1998 and 1994. Samples in 1994 were taken 1 yr after the start of the Living Field Lab.

‡Values with the same lower case letter are not significantly different ($P = 0.01$) across the management and year.

TABLE 5

Estimated C inputs from crop residues and compost, Spring 1998

Cropping system	Carbon Inputs† ($Mg\ C\ ha^{-1}$)	
	N Fertilizer	Compost
Continuous Corn		
4 yrs of crop residues‡	**21.2**	**20.8**
Total C Inputs 1993–1997		
Crop residue C, 1993–1997	31.8	31.3
Compost C, 1993–1997		7.5
	31.8	**38.8**
Rotation		
1st yr corn	5.40	5.73
2nd yr corn	5.04	4.81
Soybean	2.50	2.35
Wheat§	1.31	0.72
Total crop residues 4 yr. Rotation‡	**14.20**	**13.60**
Total C Inputs 1993–1997		
Crop residue C 1993–1997	24.6	24.1
Compost C 1993–1997		7.5
	24.6	**31.6**

†Total C Inputs include crop biomass and compost in the compost management.
‡Crop biomass values are the average above ground biomass measured plus estimated below ground biomass.
§Wheat straw (above ground biomass) was harvested in the wheat rotation.

tity of POM-C ranged from 6.36 to 7.66 Mg C ha^{-1} under N fertilizer management and from 10.0 to 12.2 Mg C ha^{-1} in the compost treatment from 1998 to 1999 (Table 6). Sampling date ($P = 0.004$) and N management ($P = 0.04$) had significant effects on the percent of POM contained in SOC during 1999. The same interactions were not significant in 1998. After compost was dispersed with Na hexametaphosphate and sieved through a 53-μm mesh, 84% of the compost material was contained in the POM fraction before application to the soil.

The C:N ratio of POM on the LFL increased over time (Table 7). The C:N ratio of POM on the LFL in 1994 was 15.6. The POM separated from compost before soil application had a C:N ratio of 13 (data not shown). Crop inputs from predominantly nonleguminous crops had wider C:N ratios (33.6–90.6) than alfalfa residue (23.0), leading to an increase in the C:N ratio of POM (17.4) by June 1998 (Table 7 and 8). The successional grassland management had the widest C:N ratio, 19.9 in June 1998 (Table 7).

^{13}C Natural Abundance

One year after establishment of the LFL in 1994, the $\delta^{13}C$ value of soil after 9 years of alfalfa was −23‰ at a 0- to 25-cm depth (Table 2). All C inputs to the LFL were dominated by C_3-C sources, which, with the exception of corn (−13.0‰), ranged from −25.0 to −28.0‰. The soils under successional grassland management (8 years of continual C_3 inputs) had a $\delta^{13}C$ value of −22.3‰.

TABLE 6

Corn-derived carbon in the particulate organic matter fraction (POM)

Cropping system	Nutrient management	Organic C in POM	POM in SOC‡	C_4-C	Corn C	^{13}C of the POM
		($Mg\ C\ ha^{-1}$)†	**(%)**	**($Mg\ C\ ha^{-1}$)**	**(%)§**	**(‰)§**
1st yr corn						
Wheat residue	N fertilizer	6.3	15	1.5	24	−22.5
Wheat residue	compost	11.0	25	1.7	16	−23.5
Soybean						
Corn residue	N fertilizer	7.4	20	2.2	30	−21.6
Corn residue	compost	10.0	23	2.4	24	−22.3
Continuous corn						
Clover residue	N fertilizer	7.6	20	3.7	48	−19.8
Corn residue	N fertilizer	7.5	19	3.5	45	−19.4
Clover residue	compost	12.0	26	4.0	33	−21.9
Corn residue	compost	12.0	26	3.4	28	−21.3

†Soil was from the 0–25 cm depth. A bulk density of 1.3 $Mg\ m^{-3}$ was assumed. Samples were averaged across 1998 & 1999. Fertilizer management * crop was significant at the ($P = 0.02$) probability level in 1999. Fertilizer management was significant at the ($P = 0.01$) probability level in 1998.
‡SOC = soil organic carbon
§Estimate of the fraction of corn derived C was calculated using $f = \delta_t - \delta_0/\delta_c - \delta_0$. Where $\delta_t = \delta^{13}C$ of corn crop and $\delta_0 = \delta^{13}C$ of the initial C_3 derived from soil organic matter at the time t = 0. The precision for the mass spectrometer for five identical samples in delta notation is C ~ 0.05.

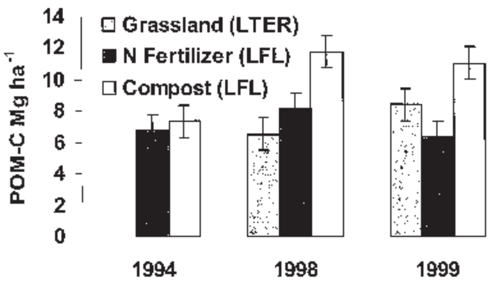

Fig. 1. Particulate organic matter (POM) C under varying management in 1994, 1998, and 1999

The percentage of C_4-C, (corn-derived C) in SOC was calculated using the $\delta^{13}C$ values of soil and corn residues (Table 2 and 3). A shift of 1‰ in a soil ^{13}C value was considered to be significant at the ecosystem level, although changes in isotope ratios of <1‰ can be statistically significant. Five years of rotations and compost applications from 1993 to 1997 reduced the $\delta^{13}C$ value of soil on the LFL (−23‰) by more than 1‰ on all treatments in the N fertilizer system and in all but one compost management (Table 9).

The continuous corn, fertilizer treatment contained 26% C_4-C in 1998 (Table 9). The fertilizer rotation treatments contained 10 and 12% corn-derived C. Approximately 25% of the residue C inputs in the rotation were C_3-derived. Compost treatments cropped to continuous corn contained 10% corn-derived C. Carbon inputs from compost were C_3-derived and equal to 25% of the total C residue inputs for the period 1993–1997.

Turnover rates (1/k) of corn-derived C were calculated based on the fraction of (C_4) derived C in soil samples taken from 1994 and 1998. Application of compost and the diversity of residue types within rotation treatments did not affect the turnover rate of corn-derived C. The turnover time (k) of C_4-C in SOM was 22 years, irrespective of N fertilizer and cropping system.

TABLE 7.

The C:N ratio of soil and particulate organic matter

Soil	Management	1994 C:N	1998 C:N
	Agronomic LFL		
	N Fertilizer	10.3 a	10.7 a
	Compost	10.6 a	12.4 a
	Successional Grassland LTER		19.9
POM†	**Agronomic LFL**	15.6	17.4

†POM = Particulate organic matter fraction, the sand-sized soil separates remaining on a 53-μm sieve after removal of residues (>2 mm), dispersion in 5% sodium polyphosphate and 12 hr of shaking.

TABLE 8

The C:N ratio of residue in the Living Field Lab (LFL)

C:N Alfalfa prior to LFL†	Nutrient management	C:N of Residue CC‡	FYC	Wheat
23.0	**N fertilizer**	52.5	67.8	33.6
	Compost	90.6	82.0	42.4

†The C:N ratio for alfalfa was not measured on the Living Field Lab but is from a separate site in an adjacent field.
‡Abbreviations: CC = continuous corn; FYC = 1st year corn.

Compost and crop residue inputs had a significant effect on $\delta^{13}C$ measurements in POM during 1998. The average $\delta^{13}C$ value of the N fertilizer management was −20.8‰ and −22.2‰ for the compost management (data not shown). The 1st year corn compost treatment in the rotation after wheat contained the lowest $\delta^{13}C$ value, −23.5‰, and followed two C_3 pathway crops (Table 6). The fertilizer continuous corn management contained the highest $\delta^{13}C$ value −19.4‰ (Table 6).

Measurements of $\delta^{13}C$ in the POM fraction were used to calculate the quantity of C_3− and C_4 (corn) derived POM-C in 1998. By the end of the 7th year of the rotation, N fertilizer treatments contained 20 to 38% more corn-derived C than compost treatments. The fertilizer continuous corn treatment contained the highest percent of corn-derived C, nearly 50% (Table 6). The compost treatment in 1st year corn contained the lowest percent corn-derived C because of lowered corn yields and dilution of C_3-C from compost (Table 6). The application of compost from 1993 to 1997 increased the average amount of C_3-C in POM by 4 Mg C ha^{-1} relative to the N fertilizer management.

Turnover rates (1/k) of corn-derived C were calculated based on the fraction of (C_4) derived C in POM extracted from soils sampled in 1994 and 1998. Application of compost and the diversity of residue types within rotation treatments did not affect the turnover rate of corn-derived C in POM. The average turnover time (k) of corn-derived C in the POM fraction 1994–1998 was 11 years.

DISCUSSION

The higher SOC build up in the LTER previously tilled successional grassland indicated that LFL soils have not yet reached their saturation capacity with regard to C and will continue to se-

TABLE 9

Corn-derived carbon in soil organic carbon (SOC), 1998

Cropping system	Nutrient management	SOC (Mg C ha^{-1})†	C_4-C (Mg C ha^{-1})	Corn C (%)‡	^{13}C of the soil (‰)§
1st yr corn					
Wheat residue	N fertilizer	42	5.1	12	−22.2
Wheat residue	compost	44		0	−23.2
Soybean					
Corn residue	N fertilizer	38	3.8	10	−22.3
Corn residue	compost	43	4.3	10	−22.1
Continuous corn					
Clover residue	N fertilizer	38	10.0	26	−20.6
Clover residue	compost	47	4.7	10	−22.1

†Samples placed in pouches were from the 0–25-cm depth. A bulk density of 1.3 Mg m^{-3} was assumed. Fertilizer management was significant at the ($P = 0.01$) probability level.

‡Estimate of the fraction of corn derived C was calculated using $f = \delta_t - \delta_0/\delta_c - \delta_0$. Where δ_t = the δ^{13}C of the corn crop at time t, δ^{13}C of corn crop, and $\delta_0 = \delta^{13}$C of the initial C_3-derived C from soil organic matter at time $t = 0$.

§The precision for the mass spectrometer for five identical samples in delta notation is C ~ 0.05.

quester both C and N. Total soil organic C on the LFL increased from 1993 to 1998 as a result of greater crop residue inputs in the corn-based systems after 9 years of alfalfa. Studies conducted in eastern Canada have illustrated that initial increases in SOC from corn-derived C are rapid in the first 12 years of continuous corn production, followed by a marked decrease (Liang et al., 1998). Compost additions to the LFL from 1993 to 1997 increased C inputs by 25%, resulting in a 16% gain in SOC on the compost management relative to that of N fertilizer. Total soil C values increased significantly but were highly variable because of the heterogeneity of the soils, residue distributions, and sampling techniques. Stored LFL samples from 1994 and 1998 were analyzed for total C concurrently to reduce analytical error.

Sieving soil through a 4-mm mesh did not remove all fine root material. Root residue not removed by sieving was included in SOC measurements and may have contributed to elevated SOC levels in our study. Measurements of SOC in treatments dominated by a plant(s) with a fibrous root system, such as the winter wheat entry point in the rotation and the successional grassland, would be affected to a greater degree than treatments dominated by plants with tap roots containing fewer fine roots, such as corn. Greater crop diversity resulted in variations in the quantity, pattern, and depth of root residues. These variations affect residue decomposition rates (Ghidey and Alberts, 1993) and, over time, may alter SOC patterns. Chisel plowing plots added additional heterogeneity. Residue distribution resulting from chisel plowing is less uniform relative to no-till and moldboard plow managements (Colvin et al., 1986).

Field plots were located on Oshtemo and Kalamazoo series. These soils were formed in glacial till, a highly heterogeneous material. The depth of the B_t layer varied throughout the LFL and, in some instances, within a plot. Total C on an adjacent LTER wheat plot located on the same soils was auto-correlated at a distance of less than 2 m^2 (Stoyan et al., 2000).

The turnover time of corn-derived C in sandy loam soils across nutrient management and cropping systems on the LFL was 22 years in 1998. The turnover time of SOC in a silt clay soil after 13 years of continuous corn production was 35 years (Balesdent and Mariotti, 1987). The turnover time of SOC has been shown to be longer where the silt + clay content is greater than 50% (Liang et al., 1998). Differences in the turnover time of SOC and corn-derived SOC in the same soil were not unexpected. Carbon decay is exponential, and SOC contains older C relative to corn inputs. Therefore, the turnover time of SOC was projected to be greater than that of corn-derived SOC on the LFL.

Increases in SOC associated with LFL management practices were caused by changes in the quality and quantity of residues returned and the addition of humic materials contained in compost. The rotation and monocrop corn treatments returned a greater quantity of residues that mineralized more slowly than alfalfa root residue. Above ground residues were removed by alfalfa harvest. Use of a chisel plow rather than a moldboard plow decreased the potential for C loss.

Organic C levels in whole soil on chisel plow treatments have been shown to be intermediate between that of no-till and moldboard plow managements at a 0- to 15-cm depth (Hussain et al., 1999). A 6-year no-till treatment adjacent to the LFL contained approximately 16% more SOC (20 cm) than the moldboard plow treatment (Collins et al., 2000). This study verified that soils on the LFL had not yet reached their saturation capacity with respect to C and will continue to sequester both C and N if no-till management practices are implemented.

^{13}C Natural Abundance and C Turnover in Soil and POM

The C:N ratio of POM increased from 15.6 in 1994 to 17.4 in 1998, showing the effect of inputs with a wider C:N ratio. Our values were similar to data from a site in continuous corn production for 25 years (18.8), stubble mulch (19.5), and bare fallow managements (18.4) (Lehmann, et al., 1998; Solomon, et al., 2002). Past C:N measurements of POM on the LFL in 1994 were 15 to 16 (Willson et al., 2001). The LFL fertilizer management and previously tilled successional grassland (LTER) may have had similar quantities of POM-C as a result of high levels of crop residues returned and reduced tillage on LFL agronomic treatments. The tillage history of the LFL included 5 years of chisel plow management and 9 years without tillage while plots were in alfalfa before establishment of the research trial.

There was no significant change in POM-C in the N fertilizer management between 1994 and 1998. Measurements of POM-C in 1998 on the compost management were 44.5% higher than POM-C measurements taken from soils sampled in 1994. Eighty-four percent of the compost C was in the POM fraction prior to soil application. Thus, increases in POM-C were caused by application of compost from 1993 to 1997. The turnover time of corn-derived C did not very between the N fertilizer and compost treatments. If decomposition of plant material was equal across managements, as corn-derived C turnover times suggest, 63% of the POM-C applied to the soil as compost during the time 1994 to 1997 remained in the POM fraction in April 1998. Compost POM-C remained in the soil for a longer period of time as a result of the presence of humic materials. Aerobic composting of manure for 140 days was shown to increase the lignin content and double the quantity of humic substances in composted materials (Inbar et al., 1989). Manure applications have been shown to have a similar effect, increasing POM-C by 25% over a 10-year period (10 cm) (Aoyama et al., 1999).

Natural abundance differences in the C_4-C_3 plant switch and applied compost were used to calculate the turnover rate of C_4, corn-derived C in POM and SOC. The $\delta^{13}C$ value of the compost was $-26.4‰$, reflecting the mixture of leaf materials of oak origin and dairy manure. The $\delta^{13}C$ value of the oak leaves $-27.5‰$ was measured in a previous study (Collins et al., 2000). Both animal nutrition and the composting process have been shown to increase the proportion of lignin in remaining compost as other materials are removed (Inbar et al., 1989). Lignin is depleted 2–6‰ in ^{13}C relative to whole plant material (Benner et al., 1987).

The tracer study provided no specific information on the turnover rate of C_3-C. However, data from long-term C incubations and acid hydrolysis analysis of soil from the same site revealed that corn-based management and application of compost from 1993 to 1997 increased the size and mean residence time (MRT) of SOC pools at 0–25 cm. Soil organic C pools were defined as active (2 to 5% of SOC), slow (45–48% of SOC), and resistant (~50% of SOC) pools (Paul et al., 2001b). Application of compost to the corn-based cropping systems on the LFL increased the slow pool C by 75% and the resistant pool of C by 40% (Fortuna et al., 2003b). The field MRT of slow pool C in the compost management was 18 years, as defined by incubation rather than chemical fractionation to allow the microorganisms to fractionate the soil biologically. The independent ^{13}C analysis in this study shows that two different techniques have produced similar SOC dynamics. This lends credence to both methods of analysis.

Paul et al. (2003) have shown that the length of exposure in a tracer study influences the MRT measured as the recently added ^{13}C residues slowly equilibrate with the rest of the SOC that is much older. The MRT of the corn-derived C will become somewhat greater as this experiment continues. The C content of the residue of acid hydrolysis has been equated with the size of the resistant C pool and found to constitute approximately 50% of the SOC. The mean residence time of the resistant pool is 1500 years older than total organic soil C (Paul et al., 1997; Paul et al., 2001b). Therefore, it contributes little to soil fertility but is of major significance in soil quality and long-term C sequestration.

The turnover rate of corn-derived C was no different in the N fertilizer and compost managements, indicating that the decomposition of corn carbon was neither slowed down nor increased by the compost addition. Turnover times of corn-derived C (C_4-C) as measured with ^{13}C were 11 years in POM and 22 years in soil. This indicates that the corn C now found in the POM fraction was primarily in the slow pool as defined by Paul et al. (2001a). This shows that it is the slow pool, representing 45 to 48% of SOC, that must be managed for long-term soil fertility and for C sequestration.

CONCLUSIONS

Data collected from the current project indicate that compost applications and greater cropping intensity increased POM-C and SOC. Shifts in the quantity of POM-C were an early indicator of increases in SOC under compost management. Compost applications increased POM-C by 45% and SOC 16%. Before application of the compost material to soil, 85% of compost C was measured in the POM fraction. Compost materials and crop residues did not affect the turnover rate (1/k) of corn-derived C. The turnover time (k) of C_4-C in POM and soil revealed that corn-derived C persisted in the POM fraction nearly half as long (11 years) as C_4-C in SOC (22 years). Use of compost in intensely managed systems can increase C sequestration and allow growers to participate in future carbon credit programs.

Previous measurements of POM in agronomic systems focused on short-term turnover of N and C. The majority of POM-C in such agronomic systems is derived from plant residues and turns over fairly rapidly (Cambardella and Elliott, 1993). Few studies have included partially digested materials such as compost. Addition of C contained in humic materials did not decrease the turnover rate of corn-derived C in POM but did seem to reduce the decomposition of total POM-C. Addition of compost to POM-C diminished the value of POM as an indicator of short-term changes in nutrient dynamics. However, POM-C remaining from compost applications may be an indicator of enhanced macroaggregate stability, improved soil tilth, and the retention of soil C and N.

The compost we utilized was made from a mixture of oak leaves and dairy manure and would be expected to be more resistant to decomposition than materials made with less ligniferous materials. There is a great abundance of oak leaves in the eastern United States. Composting these and returning them to the soil could add greatly to C sequestration while minimizing the amount of waste transferred to landfills. Further research is needed to determine the effect of compost applications on soil aggregate structure. Estimates of turnover rates and the quantity of C_4-derived C associated with the silt and clay fractions would improve our understanding of the role of soil texture in C cycling.

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