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Optimizing nutrient availability and potential carbon sequestration in an agroecosystem

A. Fortuna[a,*], R. Harwood[b], K. Kizilkaya[c], E.A. Paul[d]

[a]*USDA-Agricultural Research Service, New England Plant, Soil and Water Laboratory, University of Maine, Orono, ME 04469-5753, USA*

[b]*Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824, USA*

[c]*Department of Animal Science, Adnan Menderes University, Aydin 09100, Turkey*

[d]*Laboratory Natural Resources Ecology, NESB, Colorado State University, Fort Collins, CO 80523, USA*

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Abstract

The uniformity, low cost and ease of application associated with inorganic fertilizers have diminished the use of organic nutrient sources. Concern for food safety, the environment and the need to dispose of animal and municipal wastes have focused attention on organic sources of N such as animal-derived amendments, green manures, and crop rotations. Managing organic N sources to provide sufficient N for crop growth requires knowledge of C and N decomposition over several years, particularly where manure and compost are applied. We report a comparison of compost and chemical fertilizer, use of a corn–corn–soybean–wheat rotation compared to continuous corn and the use of cover crops. Nitrogen (150 d) and C incubations (317 d) were conducted to determine the effect of cropping system and nutrient management on: N mineralization potential (NMP), the mineralizable organic N pool (N_o), the mean residence time (MRT) of No, C mineralization (C_{min}), and soil organic carbon (SOC) pool sizes and fluxes. Compost applications over 6 y increased the resistant pool of C by 30% and the slow pool of C by 10%. The compost treatment contained 14% greater soil organic C than the fertilizer management. Nitrogen was limiting on all compost treatments with the exception of first year corn following wheat fallow and clover cover crop. The clover cover crop and wheat-fallow increased inorganic N in both nutrient managements. We recommend that growers adjust their N fertilizer recommendation to reflect the quantity and timing of N mineralized from organic N sources and the N immobilization that can be associated with compost or other residue applications. Proper management of nutrients from compost, cover crops and rotations can maintain soil fertility and increase C sequestration.

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Keywords: N and C mineralization; Carbon sequestration; Compost; Crop rotation; Cover crops; Residue decomposition; Best management practices

1. Introduction

The potential of agricultural land to mitigate greenhouse gases and sequester C may be an added benefit of maintaining soil fertility levels through the use of best management practices. Cropland constitutes 19.4% of the land in the United States. Lal et al. (1999) estimated that the C sequestration potential of crop residues was 22,510,940 Mg C y^{-1}. Additional C inputs from organic manures have the potential to sequester 66–22 kg C ha^{-1} y^{-1}. A recent study of global warming potential (GWP) on a coarse-textured soil found that land farmed using best-management practices had nearly zero net impact on the GWP increase of N_2O emissions from all sites (Robertson et al., 2000).

Maintenance of soil quality, fertility, and SOC require management of N fertilizer and organic inputs. The use of rotations that include cover crops can increase total soil N (TSN) while minimizing N loss to leaching (Poudel et al., 2001). Organic sources of N such as green manures have been shown to have a substantial residual effect on soil N. Corn uptake of N from ^{15}N labeled clover was lower (17%) and its retention in the soil greater (47%) than that of labeled fertilizer N (Harris et al., 1994). Forty percent of fertilizer N was recovered in the corn crop and 17% in the soil during the year of application. Increases in N fertilizer up to the yield sufficiency level have been shown to increase residue returned to the soil which may lead to greater SOC and TSN (Gregorich et al., 1996). A direct relationship was

* Corresponding author. Tel.: +1-207-581-3365; fax: +1-207-866-0464.
E-mail address: eann-marie.fortuna@maine.edu (A. Fortuna).

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found between residue returned and the mineralizable organic N pool (No) in several 20 y cropping systems (Christenson and Butt, 1997). A 1 mg kg^{-1} change in No required 0.33 Mg ha^{-1} of crop residue.

Survey information on SOM content as a function of long-term land use history revealed that SOM content was higher in organic systems as compared to land in conventional, arable use (Pulleman et al., 2000). Organic systems received greater manure input than the conventional systems. The MRT of N and C pools has been shown to increase with application of sludge, compost or manure. Sewage sludge contains little soluble C. Continuous application of sewage sludge for 8 y decreased soil nitrification potential and retained N in microbial cells (a labile N fraction) for more than 4 y (Boyle and Paul, 1989). Thus, greater SOC and TSN can lead to immobilization of inorganic N if not properly managed.

The work of Sanchez et al. (2001) has shown that crop rotations including a legume cover crop and/or organic amendments can increase organic N in soil. The addition of clover residues and wheat-fallow in the rotation increased the supply of soil inorganic N. Greater N was mineralized from simultaneous application of compost and clover then a single application of compost or clover. Previous substrate diversity did not affect decomposition of added substrate by soil organisms. Management of organic N sources to provide sufficient N at the time of maximum crop growth requires knowledge of C and N decomposition over several years particularly when compost is utilized as a nutrient source. Additional C added as compost can increase C sequestration but must be managed to prevent N immobilization. The current study was designed to assess the multi-seasonal effect of N fertilizer management and crop diversity on: (i) the supply of inorganic N to row crops, (ii) the MRT of N and C in soil organic matter (SOM) pools and (iii) C sequestration. The effect of residues and residual organic amendment applications on the quantity of available N must be quantified and used to adjust N recommendations when applying organic or inorganic N fertilizers. Modeling of C and N inputs for ecosystem fluxes and global climate change calculations also requires a better understanding of the dynamics of plant residues and other organic amendments.

2. Materials and methods

2.1. Field site

The living field lab (LFL) located at the Kellogg Biological Station in Hickory Corners, MI, USA was designed to test the effects of best management practices on crop yield and soil biogeochemical processes. The trial is located on a Kalamazoo loam and Oshtemo sandy loam (Haplic Luvisols). Practices include: comparison of compost and chemical fertilizer, use of a corn–corn–soybean–wheat rotation compared to continuous corn and the addition of a cover crop within each cropping system (Table 1). The compost system utilizes compost as a N fertilizer source and banded herbicide with cultivation. The fertilizer management utilizes fertilizer as a nutrient source, banded herbicides, and cultivation. Both use rootworm insecticide on corn as needed. A more detailed discussion of management practices on the LFL can be found in Jones et al. (1998).

Table 1
Experimental units sampled in the LFL, Hickory Corners, Michigan, USA

Nutrient management	Cropping system	Cover crop
Fertilizer	Continuous corn	Crimson clover no cover crop
	Rotation (corn–corn–soybean–wheat) first year corn	Crimson clover
		No cover crop
	Soybean	No current cover crop
		No cover crop
	Wheat	Red clover
		No cover crop
Compost	Continuous corn	Crimson clover
		No cover crop
	Rotation (corn–corn–soybean–wheat) first year corn	Crimson clover
		No cover crop
	Soybean	No current cover crop
		No cover crop
	Wheat	Red clover
		No cover crop

The field was in alfalfa for 6 years prior to the start of the LFL experiment in 1993.

The statistical design of the LFL is a split–split-plot, randomized complete block. Split–split-plots are 15 × 4.5 m. Main plot treatments consist of a continuous corn (*Zea mays* L.) and a corn–corn–soybean–wheat rotation including all entry points each year. This study includes information from 1994 to 1998, the second and sixth year of the crop rotation. Individual crop split plots are subdivided into non-randomized cover crop and control subplots. Crimson clover (*Trifolium incarnatum* L.) is sown into standing corn in late July after final cultivation. Red clover (*Trifolium pratense* L.) is frost seeded into wheat (*Triticum aestivum* L.) in late March. Soybean (*Glycine max* L.) contains no cover crop during the soybean season.

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 y. The moisture content of the compost varied. Compost application rates were adjusted to compensate for variations in moisture content such that the rotation and 4 y of continuous corn received the equivalent of 4480 kg ha^{-1} y^{-1} of dried compost. The total amount of N applied in the form of compost to continuous and first year corn was 117 kg N ha^{-1} y^{-1}. The compost application was doubled in second year corn due to the treatment's supplemental N requirement. Compost was not applied to the soybean crop. This made the total compost input over the rotation equal to that of continuous corn. Cumulatively, compost applied plus previous compost applications provided 40–53 kg N ha^{-1} y^{-1} inorganic N (T.C. Willson, PhD Thesis, Michigan State University, 1998). Nitrogen was applied as ammonium nitrate to treatments in corn under N fertilizer management at a rate of 170 kg N ha^{-1} y^{-1}. Dolomitic limestone was applied to the LFL at a rate of 4.48 Mg ha^{-1} on March 30th 1998.

2.2. Soil measurements

Soil samples were collected as composite samples of 12 or more 2 cm diameter cores from each plot, cooled, sieved through a 4 mm screen and stored at 4 °C prior to N analysis. Samples were collected from 0 to 25 cm in April of 1994 and 1998 prior to aboveground residue incorporation, compost application and planting. Samples were further subdivided into 0–10 and 10–25 cm increments in 1994. The separate depths were combined into one 0–25 cm increment on a weight by volume basis. Treatments included in the present study from the 1994 sample date are fertilizer and compost treatments at two points in the rotation, first year corn and soybean on cover/no cover splits. The plots that had been in corn in 1993, and were designated as continuous corn plots were included. Samples in 1998 included the above-mentioned treatments and fertilizer and compost plots cropped to continuous corn cover and no cover.

Soil samples were analyzed for moisture content, initial inorganic N ($NH_4 + NO_3$) concentration, and total C and N. Inorganic N ($NH_4^+ + NO_3^-$)-N was extracted from 20 g soil samples with 1N KCl. Aliquots were run on an auto analyzer to determine the concentration of ($NH_4^+ + NO_3^-$)-N (Lachat Instruments Inc. Milwaukee, WI). TSN and the C and N content of residues was measured on a Carlo Erba N A 1500 Series 2 N/C/S analyzer (CE Instruments Milan, Italy). Total soil C was measured 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 (CE Instruments Milan, Italy).

2.3. Laboratory incubations

A portion of the soil samples collected on April 10th 1998 were used to conduct two, 150 d N incubations in the laboratory. One incubation contained unamended soil; the second a series of residue applications. Residues were 4 cm in length and dried at 60 °C. Nitrogen in plant tissue was applied at a rate of 78 mg red clover N kg^{-1} soil, 40 mg wheat N kg^{-1} soil, and 40 mg corn N kg^{-1} soil. Carbon was applied at a rate of 833 mg red clover C kg^{-1} soil, 1333 mg wheat C kg^{-1} soil, and 2889 mg corn C kg^{-1} soil. Plant materials were added to incubations to determine the N mineralization pattern of the previous seasons crop residues. Corn and clover residue included root residues. The shoot/root ratios used were 1.42 for corn and 1.15 for clover (Buyanovsky and Wagner, 1997; Kunelius et al., 1992). A 25 g soil sample was weighed into each specimen vial for a 150 d N incubation. Incubations were run at 25 °C and 50% of water holding capacity (WHC) (Paul et al., 2001). A set of specimen vials were removed at day 0, 10, 21, 30, 50, 70, 98, 122, and 150. Inorganic N ($NH_4^+ + NO_3^-$)-N was extracted with 1N KCl and aliquots were run on an auto analyzer (Lachat Instruments Inc. Milwaukee, WI).

Nitrogen incubation data from 1994 was obtained from T.C. Willson, PhD Thesis, Michigan State University, (1998). Cumulative N mineralization curves from 1998 and the 1994 data sets were fit using a single pool first order exponential model Eq. (1) with the SAS NLIN procedure (SAS Inst., 1988, 1997; T.C. Willson, PhD Thesis, Michigan State University, 1998).

$$N_t = N_i + N_o(1 - e^{-t/\mathrm{MRT}}) \quad (1)$$

The parameter N_i is the initial inorganic N content, N_t is the quantity of extractable inorganic N at time t, and MRT is the steady state MRT of the mineralizable organic N pool (N_o). A sum of square reduction test was used to determine whether fertilizer, cropping system, and or cover crop management were significant at $P = 0.05$.

Carbon incubations were conducted in the laboratory for 317 d at 50% WHC estimated via the funnel method (Paul et al., 2001). Soils were preincubated for 2 w upon rewetting of air dried soil. Twenty-five gram soil samples were incubated in 500 ml jars in a darkened room at 25 °C. The CO_2 content in the headspace of each jar was measured using an infrared gas analyzer (LI-COR, Lincoln, NE). Jars were degassed with CO_2-free air when CO_2 levels in the headspace of the majority of samples reached 5–6%.

A two-pool first-order constrained model, including an interval correction adapted from Ellert and Bettany (1988); Eq. (2) was used to estimate the size and turnover rates of individual pools.

$$C_{(\min)} = C_a(e^{(-k_a^* t_1)} - e^{(-k_a^* t_1 - k_a^* t_2)}) + (C_{t_1} - C_{r_1} - C_{a_1}) \times (e^{(-k_s^* t_1)} - e^{(-k_s^* t_1 - k_s^* t_2)}) \quad (2)$$

C_a, k_a = active pool; k_s = slow pool; C_r = resistant pool; t_1 = start of sample interval; t_2 = end of sample interval. The slow pool is defined as $C_s = (Ct_1 - Cr_1 - Ca_1)$ where Ct_1 is defined as initial total soil organic C and Ca_1 as initial active pool C. The resistant fraction (C_r) was equated to the total C content of the residue of acid hydrolysis (Paul et al., 2001). The decomposition rate of the active and slow pools are k_a and k_s, respectively. The MRT of the active and slow pools are $1/k_a$ and $1/k_s$. Curve fitting of the CO_2 evolved per unit time; $C_{(\min)}$ was performed using the NLIN procedure of SAS (SAS Inst., 1988, 1997). The MRT of each C pool

Table 2
Cumulative ($NH_4^+ + NO_3^-$)-N mineralized from a 150 d incubation 0–25 cm soils sampled April 1994

Nutrient management		Cumulative ($NH_4^+ + NO_3^-$)-N mineralized[a]			
		Second year corn planted to soybean (kg N ha^{-1})		Wheat planted to first year corn (kg N ha^{-1})	
		Cover	No cover	Cover	No cover
Fertilizer					
	Day 10	0.54	4.73	34.2	13.0
	Day 30	21.7	15.5	36.5	19.1
	Day 70	41.0	26.2	97.0	56.6
	Day 150	138.0	121.0	171.0	152.0
Compost					
	Day 10	11.3	29.2	31.4	25.3
	Day 30	34.1	46.5	54.1	35.0
	Day 70	57.0	78.0	88.5	82.2
	Day 150	133.0	116.0	158.0	143.0

Fertilizer management × sampling interval was significant ($P = 0.05$).
[a] NMP (also refered to as cumulative N mineralized) of soil previously cropped to wheat were highly significant ($P = 0.01$).

was adjusted to average field temperature by assuming a Q_{10} of 2 (Kätterer et al., 1998; Paul et al., 1999).

3. Results

3.1. Nitrogen mineralization potential (NMP)

The use of inorganic fertilizer from 1994 to 1998 decreased NMP in the fertilizer management relative to compost management (Tables 2 and 3). There was a significant nutrient management × sampling interval interaction at the ($P = 0.05$) probability level in 1998. The compost treatment contained greater mineralizable N than the fertilizer management ($P = 0.001$) at all time intervals (10, 30, 70, and 150) during incubation of field soils sampled in April 1998 (Table 3). Four years of compost application increased the total N pool: No, the MRT and NMP of LFL soil. The MRT of N in the compost system was 208 d in April 1998 (Table 4). The MRT of N in the fertilizer system was 149 d. The No of the compost treatment was greater (70 mg N kg^{-1} soil) than that of the N fertilizer management (44 mg N kg^{-1} soil). The goodness of fit of N incubation data was not affected by the cropping system or cover crop employed in 1994. Regression estimates for the full model provided unique parameter estimates for two or more treatments. These parameter estimates did not provide a significantly better fit ($P = 0.10$) to the data than a single set of parameters used to fit the full data set.

Application of corn and wheat residues initially resulted in immobilization of N in both nutrient managements (Table 5). Addition of clover to fertilizer continuous corn treatments doubled the amount of N mineralized. This was the only treatment in which residue additions increased N mineralization. Clover residues contained 78 mg N kg^{-1}. Corn residues that had remained in the field for ~6 months contained 40 mg N kg^{-1} and 2889 mg C kg^{-1} (C:N 72). Corn caused the greatest amount of N immobilization. The quantity of N immobilized was greater in compost treatments after application of corn residue than in N fertilizer treatments reflecting the lower N availability in the compost treatment. Application of wheat straw resulted in

Table 3
Cumulative ($NH_4^+ + NO_3^-$)-N mineralized from a 150 d incubation 0–25 cm sampled April 1998

Nutrient management		Cumulative ($NH_4^+ + NO_3^-$)-N mineralized[a]					
		Second year corn planted to soybean (kg N ha^{-1})		Wheat planted to first year corn (kg N ha^{-1})		Continuous corn	
		Cover	No cover	Cover	No cover	Cover	No cover
Fertilizer							
	Day 10	20.8	21.3	27.0	20.6	24.8	18.6
	Day 30	48.5	46.0	55.5	42.8	46.5	42.8
	Day 70	81.2	80.5	86.4	78.1	82.5	68.1
	Day 150	124.0	121.0	127.0	113.0	130.0	102.0
Compost							
	Day 10	24.8	22.6	45.0	59.7	27.9	28.8
	Day 30	52.4	57.1	66.3	60.2	65.2	33.6
	Day 70	108.0	86.3	123.0	142.0	103.0	101.0
	Day 150	161.0	137.0	203.0	180.0	143.0	146.0

Treatments previously cropped to wheat had the greatest NMP ($P = 0.05$). Fertilizer nutrient management*sampling interval was highly significant ($P = 0.01$). Compost nutrient management values indicate that there was greater cumulative N at day 10, 30, 50 and 150 for all crop combinations than under fertilizer nutrient management.
[a] Compost nutrient management had significantly greater cumulative N mineralized (also referred to as NMP) than fertilizer nutrient management ($P = 0.05$).

Table 4
The affect of nutrient management on regression parameters for soils sampled in April 1998

Single pool first order[a] $N_t = N_i + N_o(1 - e^{-t/MRT})$ nutrient management[b]	Regression parameters in unamended soil			
	N_i (mg N kg^{-1} soil)	N_o (mg N kg^{-1} soil)	k^c (d^{-1})	MRT (d)
Compost	8.0	70	0.0048	208
Fertilizer	6.1	44	0.0067	149

[a] N_t is inorganic N at time t. N_i is the inorganic N at time zero. N_o is an estimate of the mineralizable organic N fraction. MRT is the steady-state MRT of the mineralizable organic N fraction.

[b] The curve fit of N mineralized during a 150 d incubation of unamended soil sampled in April 1998 prior to planting (0–25 cm) from the compost nutrient management was highly significant relative to that of the fertilizer nutrient management ($P = 0.01$) based on the sums of squares of the residuals test.

[c] k is the decomposition rate = 1/MRT (d^{-1}).

release of inorganic N after 30 d. Wheat residues that had previously weathered in the field for ~8 months provided a similar quantity of N to that of corn residues 40 mg N kg^{-1} but contained half the C (1333 mg C kg^{-1}). The C:N ratio of wheat straw was 33.

3.2. Carbon dynamics and pool sizes

Nutrient management had no significant affect on the amount of cumulative CO_2-C evolved. Ten percent of total organic soil C was lost as CO_2 during a 317 d incubation of soils sampled in 1994 and 8% from soil sampled in 1998 (data not shown). The percent of total organic soil C lost to CO_2 remained constant from 1994 to 1998. Carbon inputs increased due to the shift out of alfalfa production into corn-based systems and the application of compost. The amount of residues returned over the 4 years rotation and after for years of continuous corn in both nutrient management was not significantly different (Table 6). Composted additions contributed 7 Mg C ha^{-1} to the soil (Table 6). Four years of compost applications increased total soil C by more than 14% relative to that of N fertilizer managements (Table 7).

One year after the treatments were implemented, best management practices did not yet have a significant effect on curve fitting of the rate of CO_2 evolved per unit time. Curve fitting of the rate of CO_2 evolved per unit time was affected by nutrient management in 1998 (Table 8). The rate curves indicate that compost management increased the amount of CO_2 evolved per day after day 200. Therefore, compost additions were increasing slow and possibly resistant pools of C (Table 8). Active pool C dropped in 1998 (0.16 g C kg^{-1} soil) under compost management and 4% (0.43 g C kg^{-1} soil) in the N fertilizer system. The MRT of active pool C increased with N fertilizer use to an estimated 268 d in the field. Compost contributed little C to the active pool. The small portion of C present in the active pool had a rapid turnover rate, a 14 d estimated field MRT.

Active pool C following alfalfa constituted 5% of total soil C (0.50 g C kg^{-1} soil) and had an estimated MRT of 108 d in the field (Table 8). Fifty-two percent of total soil C was in the resistant fraction in 1994. Values for the resistant fraction did not vary from those of 1994 under N fertilizer management. Application of compost augmented the slow (40%) and resistant C (30%) fractions. Slow pool C was equal to 43% of total soil C and had a field MRT of 12 y in 1994 (Table 8). The greatest gain of C across nutrient managements (more than 30% from 1994 to 1998) occurred in the slow pool. Estimates of C pool sizes suggest that the increase in SOC associated with compost applications is

Table 5
Cumulative ($NH_4^+ + NO_3^-$)-N mineralized from residue amended and unamended soil

Nutrient management		Cumulative ($NH_4^+ + NO_3^-$)-N mineralized				
		Wheat planted to first year corn (kg N ha^{-1})		Continuous corn (kg N ha^{-1})		
		Wheat straw	No residue	Corn[a] residue	Clover residue	No residue
Fertilizer						
	Day 10	10.7	20.6	−1.60	142.0	18.6
	Day 30	18.3	22.2	−5.20	55.4	24.2
	Day 70	80.9	35.3	43.3	112.0	25.3
	Day 150	60.9	34.9	90.8	53.9	34.5
Compost						
	Day 10	10.6	59.7	−10.6	62.0	28.8
	Day 30	28.3	0.56	17.6	37.9	4.76
	Day 70	81.9	81.4	28.6	79.7	67.3
	Day 150	97.8	38.4	34.1	25.9	45.2

[a] Negative values contained less ($NH_4^+ + NO_3^-$)-N than the initial day 0 soil sample (0–25 cm) taken in April 1998 prior to application of residues.

Table 6
Carbon inputs from crop residues and compost (1993–1998)

Cropping system[a]	Carbon inputs	
	Fertilizer (Mg C ha^{-1})	Compost (Mg C ha^{-1})
Continuous corn		
Total C inputs 1993–1998[b]	31.8	38.8
Rotation[c]		
Total C inputs 1993–1998	24.6	31.6

[a] Crop biomass values are the average above ground biomass measured in 1993 and 1998 plus estimated below ground biomass. Below ground estimates were calculated with the following formulas: root-C for corn = crop residue C × 0.53, root-C for soybean–crop residue C × 0.47 (Paul et al., 1999) and the root-C for wheat residue was based on measured above ground biomass, a shoot/root ration of 1.13 and a root C content 30% (Buyanovsky and Wagner, 1997).
[b] Total C inputs = crops biomass and compost in the compost nutrient management.
[c] Wheat straw was harvested. Wheat biomass is equivalent to estimated below ground biomass.

mostly slow and some resistant pool C. Rate curves for CO_2-C evolved per unit time level off after 150 d (Fig. 1).

4. Discussion

4.1. Organic and inorganic nitrogen pools

Residual N from previous alfalfa contributed to elevated NMP measurements in 1994. The first 2 years corn is grown after alfalfa there is a measurable decrease in N response (Bundy et al., 1999). The shift away from an alfalfa based system to a corn and corn-based rotation resulted in lowered N inputs from crop residues and greater potential for N immobilization. The contribution of alfalfa to soil C is minimal. Higher initial active pool C in 1994 was likely due to termination of alfalfa production in 1992. Much of the above ground net primary production of alfalfa is harvested and removed. Most row crops such as corn and to some extent soybean return a significant amount of biomass to the soil as crop residue. The amount of CO_2 evolved from an alfalfa treatment on the adjacent Long-Term Ecological Research site was not significantly different from treatments in a corn-soybean-wheat rotation (Paul et al., 1999).

Thus, although alfalfa supplies mineral N it does not contribute to soil C storage. Decomposition of residues during long-term N incubations in the laboratory provided information concerning the mineralization pattern of the previous season's residues. Immobilization of N occurred in many of the treatments. Soil samples were taken in April. Previous research at the LFL indicated that N immobilization was greatest in samples taken in April prior to tillage (T.C. Willson, PhD Thesis, Michigan State University, 1998). Winter wheat residues not removed as grain or straw had 2 months to decompose before temperatures dropped below 5 °C. Corn residues were left standing on the LFL and had little time to decompose prior to the drop in temperature. Corn root residues have been shown to immobilize N for as much as 24 w (Risasi et al., 1999). Immobilization of N in the LFL was greatest following second year corn and in continuous corn fertilized with compost. The rate of compost application was doubled in second year corn to compensate for decreased inorganic N. Decreased N availability has resulted in reduced corn yields indicating that the compost continuous corn treatment without clover and second year corn rotation without clover require additional N inputs to maintain yields (Fortuna et al., 2003). Wheat plantings reduced N immobolization. We have shown that the immobilization of N by corn residues is at least a partial explanation for increased N uptake of corn after wheat. Prior research on the LFL has shown that the presence of corn roots, but not wheat roots, increased soil inorganic N during crop growth in the field (Sanchez et al., 2002).

Field inorganic N was limited in all compost treatments with the exception of 1st y corn following wheat fallow and clover cover crop in 1998 (Fortuna et al., 2003). This may be due to additional C contained in compost that consists of oak leaf-alfalfa based feed silage. Compost treatments had higher NMP and lowered field inorganic N in 1998 after 5 y of compost treatment. This is attributed to the increase in MRT of N in SOM resulting from the addition of N in humic compounds formed during the composting process. Other organic amendments such as leguminous green manures and cattle manure have been shown to decrease the MRT of N (85 d) relative to systems utilizing N fertilizer (150 d) (Harris, PhD Thesis, Michigan State University, 1993). Nitrogen turnover on the LFL was best described by a single-pool, first order exponential model. Other researchers have obtained a better fit using a double exponential model (Harris, PhD Thesis, Michigan State University, 1993). The difference in fit may be a result of the quantity, quality, and types of compounds present in organic amendments. Highly variable mixtures of organic amendments may require a model with greater complexity.

Table 7
Changes in total SOC with time and nutrient management system

Year[a]		Nutrient management 1998[b]	
	SOC (g kg^{-1})		SOC (g kg^{-1})
1994	9.50*	Fertilizer	11.5a
1998	12.5	Compost	13.4b

SOC sample depth 0–25 cm in 1998. Sample depths were combined 0–10 and 10–25 cm in 1994.
[a] Increases in total organic C from 1998 to 1994 were highly significant ($P = 0.01$).
[b] Increases in total organic C were highly significant ($P = 0.01$) where compost was applied in place of N fertilizer.

Table 8
Estimates of active, slow and resistant C pool size and MRT

Treatment	Active C pool			Slow C pool			Resistant C pool, total C (%)
	Total C (%)	Lab MRT[a] (d)	Field MRT (d)	Total C (%)	Lab MRT (y)	Field MRT (y)	
1994[b]	5	54	108	43	6	12	52
1998 nutrient management[c]							
Fertilizer	4	134	268	52	13	26	44
Compost	1	7	14	50	9	18	49
Carbon content	Active C pool[d] (g C kg^{-1} soil)	Slow C pool[e] (g C kg^{-1} soil)	Resistant C pool (g C kg^{-1} soil)				
1994	0.50	4.0	4.9				
1998 nutrient management							
Fertilizer	0.43a	6.0 A	5.1				
Compost	0.16b	6.7B	7.0				

[a] Laboratory MRT were converted to field MRT using a Q_{10} of 2.
[b] Curve fitting of the CO_2 evolved per unit time; $C(t)$ was fit with a two-pool first order constrained model using the SAS NLIN procedure (SAS Inst., 1997). The curve fit of 1994 CO_2-C evolved per unit time was highly significant relative to that of 1998 ($P = 0.01$) based on the sums of squares of the residuals test.
[c] The curve fit of CO_2-C evolved from the compost nutrient management in 1998 was highly significant relative to that of the fertilizer nutrient management in 1998 ($P = 0.01$) based on the sums of squares of the residuals test.
[d] The active C pool in the compost nutrient management was lower and significantly different ($P = 0.05$) from the N fertilizer nutrient management in 1998.
[e] The slow C pool in the compost nutrient management was greater and significantly different ($P = 0.05$) from the N fertilizer nutrient management in 1998.

The wheat-fallow and added cropping diversity provided by the rotation and clover cover crop increased field inorganic N and in some instances improved corn yields in both nutrient managements. Clover wheat-fallow has consistently increased soil inorganic N on the LFL (T.C. Willson, PhD Thesis, Michigan State University, 1998). Sanchez et al. (2002) found that soil from first year corn following wheat especially with clover in the rotation had much higher inorganic N content than soils in a non-corn control or wheat. Subsequent incubation showed that the mineralizable N pool was depleted during corn growth.

Growers should take into account the timing and quantity of inorganic N released from residues and residual organic amendment applications when sampling for soil nitrates at preplant vs. presidedress and in adjusting N fertilizer recommendations. Corn residues increased the N fertilizer recommendation for the subsequent corn crop while winter wheat and clover cover crops resulted in lowered N recommendation. An evaluation of soil NO_3^- testing and corn N response across the North Central Region of the United States indicated that sampling for soil nitrates at preplant following small grain and soybean was most effective in determining the critical soil NO_3^- level (Bundy et al., 1999). The critical soil NO_3^- level is the soil NO_3^- concentration above which no crop yield response to additional N is expected. Mineralization of organic N from corn residues, manure, and SOM in fine textured soils occurred later in the growing season. Therefore, presidedress sampling of NO_3^- was recommended. Information concerning mineralization of organic N from a variety of sources including: row crop, cover crop residues and compost on the LFL should be used in conjunction with other information in our data base to adjust N recommendations and the timing of soil nitrate testing for optimum yield response and decreased nitrate leaching.

4.2. Carbon dynamics and pool sizes

The presence of highly resistant components in compost such as oak leaves (*Quercus rubra* L.) can affect the turnover rate of residues resulting in what appears to be a decrease in active pool C. Compost applications may have increased the size and/or diversity of the microbial community. Previous research in the LFL indicated that there was no significant difference in biomass between nutrient managements in 1994–1995 (Willson et al., 2001). However, long-term applications of compost could affect microbial biomass size. Carbon modeling based on first

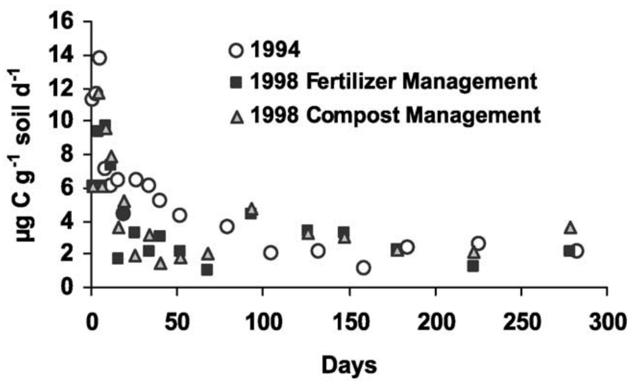

Fig. 1. Change in CO_2-C evolved with time for 1994 vs. 1998 nutrient managements (fertilizer vs. compost) during a 317 d incubation of unamended soil 0-25 cm.

order kinetics disregards the size and activity of the soil biota. Our data indicate that this may lead to errors in modeling long-term C cycling in treatments such as the compost management. Other studies have shown an increase in microbial biomass where legume green manures are incorporated (Harris, PhD Thesis, Michigan State University, 1993).

Slow pool C (field MRT 9–14 y) and its associated N affects the quantity of inorganic N in the soil over multiple growing seasons. Increases in crop residues augmented slow pool C in both nutrient managements. The increase in the rate of CO_2-C evolved g^{-1} soil d^{-1} from day 60 to 150 coincides with the release of C from mainly the slow pool. A similar pattern of increased CO_2 release was found during incubations of soil (0–20 cm depth) from an adjacent agronomic study (Paul et al., 1999). Increased C inputs from compost augmented slow and possibly, resistant pool C. The resistant pool of C does not have a significant seasonal affect on C and N cycling but may improve physical soil properties. The increased resistant pool of C in compost plots could be an artifact from the use of acid hydrolysis. The composting process increased the proportion of lignin, which may not be as old as the humic materials normally found in the resistant fraction (Inbar et al., 1989). The MRT of the resistant fraction is 1500 y older than total organic soil C (Paul et al., 1997).

The potential to sequester C in the LFL has increased over time due to greater crop residue returns in corn-based systems relative to alfalfa and the application of compost. The percent of total C lost as CO_2 was similar to other fine textured agronomic soils (5.8–8.7%) in the corn belt (Collins et al., 2000). The majority of agricultural systems have a neutral affect on GWP no-till management is one of the few agronomic systems that can sequester C (Robertson et al., 2000). Application of humified materials such as compost should have the potential to sequester C and mitigate greenhouse gas emissions.

5. Conclusions

Proper management of nutrients from compost, cover crops and rotations can increase C sequestration and maintain soil fertility. The contribution of alfalfa to soil C is minimal. The potential to sequester C in the LFL has increased over time due to greater crop residue returns in corn-based systems relative to alfalfa and the application of compost. Compost treatments had significantly higher total organic C than the fertilizer management and greater NMP and lowered field inorganic N in 1998 after 5 y of compost treatment. Higher NMP is attributed to the increase in MRT of N in SOM resulting from the addition of N in humic compounds formed during the composting process. The shift away from an alfalfa based system to a corn and corn-based rotation resulted in lowered N inputs from crop residues and greater potential for N immobilization. Best management practices required intensive management in order to synchronize N mineralization from organic sources with that of the phase of maximum vegetative growth for a given crop. We recommend that growers adjust their N fertilizer recommendation to reflect the quantity and timing of N mineralized from organic sources.

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