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Biologically active soil organic matter fractions in sustainable cropping systems

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Abstract

We sampled corn (*Zea mays* L.), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) rotations, corn monocultures, and plant successional experiments in Southwest MI over a 2-year period to study the effects of alternative management practices on microbial biomass and particulate organic matter (POM) C and N in the top 20 or 25 cm of soil. Microbial biomass was measured using the chloroform fumigation, incubation method. POM was defined as the organic C and N content of primary soil particles in the 53–2000 μm size class. Microbial C decreased during a drought in 1994, and was greater in treatments receiving compost rather than inorganic fertilizer in 1995, but was only weakly correlated with N mineralization in aerobic laboratory incubations. Microbial biomass accounted for an average of 2.6% of soil C and 4.9% of soil N in all treatments sampled in 1995. Microbial C:N ratio was lower in July and November (6.0) than in April and September (7.3), and lower in successional treatments without tillage (5.2) than in agronomic treatments (6.7). Changes in microbial N were large enough to affect short term N availability, but tended to be transitory. POM increased after compost additions, and was greater in successional plots without tillage than in tilled treatments, but did not increase immediately after the incorporation of plant residues. POM accounted for 19.7% of C and 14.8% of N in 1995. Its C:N ratio was 20.8 in a never tilled successional treatment and 16.0 in all other soils. The C:N ratio was 17.0 on average in the 250–2000 μm size fraction, compared to 15.5 in the 53–250 μm fraction. There was a strong correlation between POM and N mineralization in 70- and 150-day aerobic incubations, but there was greater N mineralization per unit POM in April and November than in September or October in both years of the study. These results suggest that POM could be used to estimate N mineralization if combined with information about recently deposited plant residues.

Keywords: Microbial biomass; Particulate organic matter; POM; Nitrogen availability; Soil organic matter; Cropping systems; Compost; Sustainable agriculture

1. Introduction

The need to develop cropping systems that better synchronize the availability of inorganic N with crop demand is a major challenge facing farmers and agricultural researchers. Sufficient inorganic N must be available during the growing season to facilitate high yields, but an accumulation of excess soil NO_3^- can lead to increased N-loss and environmental contami-

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nation, particularly when precipitation exceeds evapotranspiration.

The use of inorganic N fertilizer provides a partial solution to the problem of synchrony in that the amount and timing of fertilizer applications can be controlled. However, logistical and economic constraints often limit farmers to a single application, and even when split applications are possible, losses are inevitable. Jokela and Randall (1997) applied ^{15}N labeled fertilizers at the time of planting and at the V8-stage in continuous corn in the Northern US Corn belt and recorded 13–27% losses from the plant–soil system (depending on application rate), regardless of the time of application. Similar losses have been reported across a range of crops and conditions (Russelle et al., 1981; Kitur et al., 1984; Meisinger et al., 1985; Timmons and Baker, 1992; Reddy and Reddy, 1993).

Fertilizer N is often applied at unnecessarily high rates, leading to increased N loss. Keeney (1987) and Meisinger (1984) note that fertilizer recommendations are often made on the basis of insufficient information about the supply of N from plant and soil resources. Hallberg (1986) and Libra et al. (1987a,b) estimate that 50–80 kg N ha^{-1} arable land is leached into groundwater each year in the Big Springs watershed in Iowa, and attribute much of this flux to a failure to account for N mineralized from legumes and animal wastes in estimating crop needs. Existing recommendation systems are often ignored or misused. In a study of irrigated corn production in Nebraska, Schepers et al. (1986) observed that farmers overestimated their yield by an average of 32 bu per acre, resulting in an average over-fertilization of 50 kg N ha^{-1}. Although Hallberg (1987) notes that farmers are becoming increasingly aware of the issue of groundwater contamination, there is usually much more incentive to prevent under- than over-fertilization.

Biologically based cropping systems use a combination of organic amendments and biological N_2 fixation to increase the N supplying capacity of the soil. Such systems have the potential to provide better synchronization with crop demand than conventionally fertilized systems, if only because inorganic N is released more gradually over the growing season. Mineralization is affected by temperature and moisture availability, so the supply of inorganic N can be expected to decrease under conditions not favorable to plant growth. However, management practices that increase mineralization during periods of high demand may also increase mineralization when demand is low and the potential for loss is high. For example, Dou et al. (1995) found that the incorporation of hairy vetch (*Vicia villosa* Roth) as a green manure before corn production resulted in elevated NO_3 levels throughout the season, and a higher NO_3 level at the last fall sample date than was observed for fertilized corn following a non-legume fallow. In a similar study, Brown et al. (1993) found that late fall NO_3 levels can increase in both tilled and no-till systems if the decomposition of vetch is delayed by lack of soil moisture.

Crop and cover crop sequences can be used to enhance the synchrony of both biologically and chemically fertilized systems (McGill and Myers, 1987; Pierce and Rice, 1988; Myers et al., 1994). Winter cover crops have been shown to reduce late fall NO_3 levels in a variety of systems (Guillard et al., 1995; Philips and Stopes, 1995; Solberg, 1995), while the incorporation of these residues may either increase or decrease spring NO_3 levels depending on the extent of immobilization (Wegger and Mengal, 1988). Crop sequences also have consequences on N availability, although increased N availability may account for only a small portion of the increased yields commonly associated with rotations that include legumes (Baldock et al., 1981; Hesterman et al., 1987).

We have defined nitrogen mineralization potential (NMP) as the intrinsic ability of the soil to supply inorganic N through mineralization over time. NMP is constantly changing in response to the accumulation and decomposition of organic materials, and can be altered by managing the inputs of organic material, or by changing the conditions under which decomposition occurs. It should be possible to manipulate NMP to improve the synchronization between mineralization and crop demand.

In a related paper, (Willson et al., 2001) we measured NMP based on the accumulation of inorganic N in 150- and 310-day aerobic incubations of soil from agricultural and extended fallow treatments at the Kellogg Biological Station in Hickory Corners, MI. We found that NMP was highest in the spring and lowest in fall, greater in untilled perennial systems than in tilled annual systems, increased with the addition of compost, and was greater in rotations including wheat and legume cover crops than in corn-soybean rotations without cover crops. These findings confirm that NMP varies predictably with the addition and decomposition of organic materials, and is sensitive to short-term changes in agricultural management.

In this paper, we use data from the same field experiments to examine the relationship between NMP and the C and N content of microbial biomass and particulate organic matter (POM). Both of these pools are closely associated with N mineralization: microbial biomass because N mineralization is a microbially-mediated process (Paul and Voroney, 1984; Smith and Paul, 1989), and POM, also referred to as macroorganic matter, because it contains much of the partially decomposed plant material that fuels mineralization (Cambardella and Elliott, 1992; Gregorich et al., 1994; Hassink, 1995). The objective of this paper is to determine how alternative management practices alter the size and composition of these fractions and to determine whether these fractions can be managed, or used to predict changes in NMP. The measurements described in this paper are relatively simple, and could potentially be used as a basis for fertilizer recommendations.

2. Materials and methods

Soil samples were obtained from experimental treatments at the Living Field Laboratory (LFL) and the Long Term Ecological Research (LTER) experiment at Kellogg Biological Station in Hickory Corners, MI (42°24′N, 85°23′W). These experiments are located adjacent to one another on a mixture of Kalamazoo loam and Oshtemo sandy loam soils (both Typic Hapludalfs). The Ap horizon of both soils reaches a depth of 20–30 cm and has an average content of 10 g organic C kg^{-1} soil and an average bulk density of 1.3 Mg m^{-3} to a depth of 20 cm. (Robertson et al., 1997). The only exception is the LTER never-tilled succession treatment (see below), which is located on a remnant of the pre-agricultural soil profile, with an average organic C content of 1.7 g kg^{-1} soil in the top 20 cm. The climate is temperate, with warm humid summers and cool moist winters. Precipitation on site has averaged 880 mm per year (1988–1997), and is evenly distributed throughout the year.

Composite soil samples, consisting of 12–15 2 cm diameter cores, were obtained to a depth of 25 cm in April, June, August, October and November 1994 and to a depth of 20 cm in April, July, September and November 1995 and April 1996. The samples were cooled immediately, sieved through a 4 mm screen and stored at 4°C during processing (typically 1–3 week). Because of the change in depth, and because different treatments were sampled, the 1994 and 1995–1996 datasets are analyzed separately.

The KBS LTER site was established in 1989 to facilitate cross-disciplinary research on the ecological interactions inherent in row-crop agriculture and related ecosystems in the Midwestern US. Treatments examined in this study include four corn-based rotations and three successional treatments. The agronomic treatments included conventionally fertilized, corn-soybean rotations with and without tillage (conventional tillage (CT) and no-till (NT)), and corn–soybean–wheat rotations with hairy vetch or red clover (*Trifolium pratense* L.) as green manure and either reduced fertilization (low-input (LI)) or no chemical inputs of any kind (zero input (ZI)). The successional treatments include a mowed, but never-tilled, successional meadow (NTS), a historically tilled, old-field succession (HTS), and an annually tilled successional treatment (ATS). All four corn-based treatments were sampled in 1994, while CT and the three successional treatments were sampled in 1995 and April 1996. The agronomic treatments were planted to soybean in June 1994 and wheat in October 1994 after having been in corn with or without hairy vetch in 1993. The CT and NT treatments had not been planted to wheat prior to 1994. Management protocols for the LTER main site experiment can be found on the Internet (http://lter.kbs.msu.edu/Agronomics/protocol.htm)

The LFL was established in 1993 to provide additional information about the effects of alternative management strategies in sustainable agriculture. The LFL has a factorial design that allows the separation of important management alternatives such as rotation versus monoculture, inorganic versus organic fertilizer (compost), broadcast versus banded versus non-chemical weed control, and the presence or absence of cover crops. Each crop in the corn–corn–soybean–wheat rotation is grown each year. This prevents the confounding of crop sequence effects with year-to-year variations and facilitates the comparison of rotation versus continuous corn (Jones et al., 1998).

We sampled 1st year corn, soybean and wheat in 1994, from the Integrated Compost (Compost) and Integrated Fertilizer (Fertilizer) management types with and without cover crops. In 1995–1996 we sampled the complete corn–corn–soybean–wheat rotation along with continuous corn in the Fertilizer management type but only first year corn, continuous corn, and wheat in the Compost management type. The Fertilizer and Compost management types differ only in N source; ammonium nitrate fertilizer or dairy manure–leaf compost. Both utilize reduced tillage (chisel plow) and a combination of banded herbicides and mechanical cultivation for weed control. Cover crops include red clover frost seeded into wheat, and interseeded into first year corn, annual ryegrass (*Lolium multiflorum* Lam.) interseeded into second year corn and a combination of red clover and annual ryegrass interseeded into continuous corn.

Microbial biomass was determined using the chloroform fumigation, incubation method described by Harris et al. (1997), including the partial control subtraction equation for microbial C (Eq. (1) developed empirically by Horwath et al. (1996)

$$\mathrm{MBC} = 1.73\,\mathrm{Cf} - 0.53\,\mathrm{Cc} \tag{1}$$

and the corresponding microbial N Eq. (2) of Harris et al. (1997)

$$\mathrm{MBN} = \mathrm{MBC}\left(0.56\left(\frac{(\mathrm{Nf} - q\,\mathrm{Nc})}{\mathrm{Cf} - p\,\mathrm{Cc}}\right) + 0.095\right) \tag{2}$$

where Cf and Nf refer to the net CO_2–C and NH_4–N, respectively, produced in fumigated soil over a 10-day incubation at 25°C, Cc and Nc refer to the net C and N mineralization in a non-fumigated control under the same conditions and p and q are the proportion of the non-microbial C and N in the control incubation that is consumed in the fumigated sample. The value of q and p is assumed to be equal for the purpose of this analysis, and is derived using Eq. (3) from Horwath et al. (1996).

$$p = q = 0.29\left(\frac{\mathrm{Cf}}{\mathrm{Cc}}\right) + 0.23 \tag{3}$$

All CO_2–C measurements were made by titration of NaOH traps, and NO_3–N and NH_4–N measurements were made on 1 M KCl extracts using a Lachat automated colorometric analyzer (Lachat Instruments Inc., Milwaukee, WI).

We have defined POM as the total C and N content of sand-sized (53–2000 μm) soil separates. Air dried soil was dispersed in 5% sodium polyphosphate solution, shaken for 8 h, and passed through nested sieves of 2000, 250, and 53 μm using a flow of distilled water to ensure separation. The material remaining on the 250 and 53 μm sieves was analyzed for total C and N using a Carlo Erba N A 1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy) and defined as the coarse (250–2000 um) and fine (53–250 um) POM fractions, respectively.

Treatment and date effects on microbial biomass and POM were analyzed using Proc Mixed of SAS (SAS Institute, 1997), given a randomized complete block design with four blocks at the LTER site, and a split–split plot, randomized complete block design with four blocks at the LFL site. In the LFL design, each management type (Compost or Fertilizer) was applied to a main plot, which was split into subplots for each crop in the rotation plus continuous corn. These subplots were then split for the presence or absence of cover crop (cover or no-cover). Unfortunately, the location of the cover treatment was not randomized, so cover crop effects could be confounded by positional effects. Correlations between the microbial biomass and POM fractions, and between these fractions and the N mineralization data of Willson et al. (2001) were analyzed using SAS procedures (SAS Institute, 1988).

3. Results

3.1. Microbial biomass

There were no significant differences in microbial biomass C due to management in the 1994 dataset, but there was a pronounced decrease in biomass in the June sample relative to other sample dates (Fig. 1). The relatively low June biomass C coincided with a prolonged drought: the LTER weather station recorded 1.4 cm of precipitation between 1 May and 6 June. The greatest decrease in biomass C from April to June (963 kg ha^{-1} or 70%) occurred in the LTER NT treatment. Additional data taken at the time of sampling (not shown) shows that this treatment retained more soil moisture to 25 cm than the other agronomic treatments, but also had the highest proportion of micro-

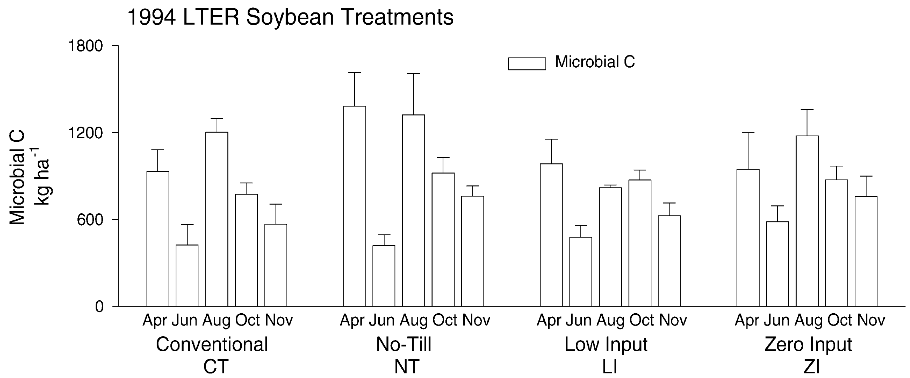

Fig. 1. Microbial biomass C in the top 25 cm in the 1995 LTER Soybean treatments. Error bars represent the standard error of the mean for each treatment. Units are based on an assumed bulk density of 1.3 Mg m^{-3}.

bial biomass near the surface, where it is more likely to encounter temperature and moisture stress.

The lack of a significant difference in microbial C between the compost (833 kg ha^{-1}) and fertilizer (754 kg ha^{-1}) treatments at the LFL is surprising given the large amounts of compost applied. The 1994 wheat plots received 3150 kg C ha^{-1} in October 1993, the corn plots received 9000 kg C ha^{-1} in May 1994, and the soybean plots received 6500 kg C ha^{-1} in October 1994. (All plots also received 500 kg C ha^{-1} of compost in April 1993.). These additions are larger than the above ground net primary productivity in these treatments, and contain 2–7 times as much total N as was applied in the corresponding fertilizer treatment.

The effect of compost on microbial C was more pronounced in the 1995–1996 dataset (Fig. 2). There was an average of 853 kg C ha^{-1} for the Compost plots and 648 kg C ha^{-1} in the Fertilizer plots for the first year corn, continuous corn and wheat treatments. The difference was greatest in the first year corn plots (886 kg C ha^{-1} for Compost, 566 kg C ha^{-1} for Fertilizer) even though these plots received the least compost over the life of the experiment (4950 kg C ha^{-1}, compared to 6960 kg C ha^{-1} for wheat and 10800 kg C ha^{-1} for continuous corn). Microbial C tended to increase in the warmer months. It was significantly greater in July or September 1995 than in April 1995 or April 1996 in this dataset.

Microbial C and N were both significantly greater in the never tilled succession (NTS) than in the other LTER treatments in the1995–1996 dataset, but this treatment also had a greater total C content (1.7%) than the others (1.0%). Expressed per unit C, there were no significant differences in microbial C or N. The HTS and NTS treatments had lower microbial C:N ratios (5.0 and 5.4) than any of the other treatments (6.3–7.2) in the 1995–1996 dataset (Table 1). The C:N ratios in the HTS and NTS treatments were relatively stable whereas those in the tilled treatments were significantly lower after tillage in July and after senescence in November than in the other sample dates. These C:N ratios suggest that the microbial community is shifted toward bacterial production when fresh residues are available (July and November), whereas there are relatively more fungi at other sample dates.

3.2. Particulate organic matter

The greatest changes in POM in the 1994 dataset were associated with the large compost inputs before wheat (October 1993), before first year corn (May 1994), and following soybean (October 1994) at the LFL (Fig. 3). Particulate organic matter C increased by 1300 kg ha^{-1} and N increased by 50 kg ha^{-1} in the soybean treatment in November 1994 relative to the April through October samples. This difference is equivalent to 23% of the applied compost C and 26% of the applied compost N. Similarly, there was an increase of 1400 kg ha^{-1} C and 115 kg ha^{-1} N between the April and June samples in the first year corn plots with compost, which represents 17 and 19% of the applied compost C and N in those treatments. The POM content of the compost itself can explain much of this increase. We

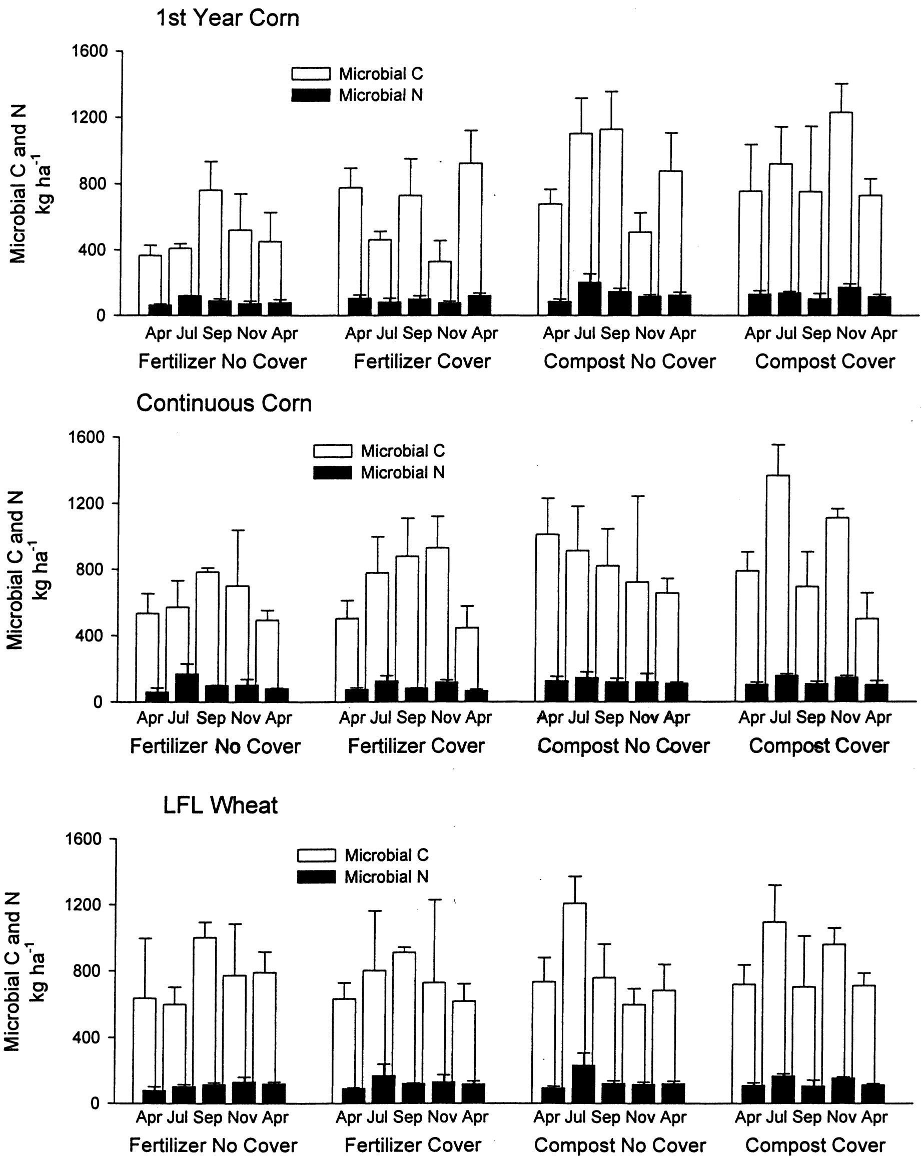

Fig. 2. Microbial biomass C and N content in the top 20 cm in the 1995–1996 LFL Samples. Error bars represent the standard error of the mean for each treatment. Units are based on an assumed bulk density of $1.3\,Mg\,m^{-3}$.

performed a size fractionation procedure on compost from the same source as was applied in 1994, and found that 46% of compost C and 33% of compost N separated in the 250–2000 μm fraction, with an additional 10% of compost C and 8% of compost N separating into the 53–250 μm fraction. Those treatments that did not receive compost in 1994 averaged 4900 kg POM C ha^{-1} and showed only small changes during the season. There were no treatment or date effects on POM C or N in the 1994 LTER dataset.

Among the four LTER treatments sampled in 1995, NTS had the highest amount of POM C, and the widest C:N ratio (Fig. 4). It had about the same amount of POM N as the HTS treatment. The HTS treatment had significantly greater POM C and N than either of the tilled treatments (ATS or CT), but the difference

Table 1
Date and treatment effects on microbial C:N ratios in the 1995–1996 dataset

Treatment	Month					Average
	April 1995	July	September	November	April 1996	
LTER						
NTS[a]	6.4 b[b]	5.2	4.8 c	3.8 b	4.5 b	5.0 b
HTS	5.4 b	5.4	6.0 b	5.3 ab	4.9 ab	5.4 b
ATS	7.0 ab	5.6	7.7 a	6.4 ab	5.0 ab	6.3 ab
CT	8.5 a	5.6	7.4 a	6.8 a	7.6 a	7.2 a
LFL						
Compost	7.4	6.6	6.5 b	6.0	5.9 a	6.5
Fertilizer	7.9	5.7	7.9 a	6.0	7.3 a	6.9
All data	7.4 A[c]	5.9 B	7.0 A	5.9 B	6.3 B	6.6

[a] Abbreviations: NTS = never tilled succession, HTS = historically tilled succession, ATS = annually tilled succession, CT = conventionally tilled wheat.
[b] Values with the same letter are not significantly different ($\alpha = 0.05$).
[c] Capital letters indicate comparisons between dates.

was much greater in the coarse fraction (48% more C and 53% more N) than in the fine fraction (15 and 18%, respectively). The difference in POM C between the NTS and HTS treatments is primarily in the fine fraction. The coarse fraction may be more sensitive to recent changes in management, such as the conversion from tilled agriculture to succession without tillage, whereas the fine fraction probably accumulates C and N more slowly, making it more indicative of long-term management.

The NTS treatment had significantly wider C:N ratios for both coarse (23.4) and fine (19.0) POM than the other LTER treatments. The NT soybean treatment and the other successional treatments (HTS and ATS) also had higher coarse fraction C:N ratios (17.9, 17.2, 18.5) than the tilled agronomic treatments (16.3 for CT soybean, 16.9 for CT wheat, 15.7 for LI, and 16.8 for ZI). The two low-input treatments, LI and ZI had the lowest fine fraction C:N ratios (15.9, 15.6) and the lowest total POM C:N ratios (15.8, 16.1) at the LTER. It would appear that the C:N ratio of plant residues play a role in generating the observed treatment differences. The ATS and NTS treatments are dominated by relatively low diversity of grass species whereas vegetation in the HTS treatment is more diverse and has a higher proportion of legumes.

The LFL treatments (Fig. 5) continued to show significant effects of compost on POM in 1995–1996. The compost treatments contained an average of 24% more POM C and N than the fertilizer treatments. The coarse fraction accounts for 2/3 of this difference. All of the treatments in the 1995–1996 dataset show a sharp decrease in POM in November relative to the other sample dates. While POM is expected to reach a minimum in the fall, it is possible that some of this decrease was caused by the necessity of removing snow from the surface of certain treatments before sampling, which may have removed some of the surface soil.

The C:N ratios or POM at the LFL were extremely consistent throughout the study. While there were no significant differences between treatments or dates, the C:N ratio of the fine fraction (15.28) was significantly lower than that of the coarse fraction (16.52) and was less variable (S.D. = 0.82 for fine POM compared to S.D. = 1.73 for the coarse fraction). These differences are consistent with the idea that newer POM fragments may be larger, and have a higher C:N ratio, than older, finer, POM fragments.

Table 2 shows the coefficient, *r*, for the correlations between the organic matter pools discussed in this paper and the N mineralization measurements performed in Willson et al. (2001). The strongest correlations are those between POM C (coarse and total) and the accumulation of inorganic N after 150 days of incubation. POM N is also a good predictor of NMP, but microbial biomass is not. The 10- and 30-day N mineralization measurements are poorly correlated with all other indices, due to the influence of immobilization early in the incubation. The relationship between POM C and 150 day N mineralization changes over the sea-

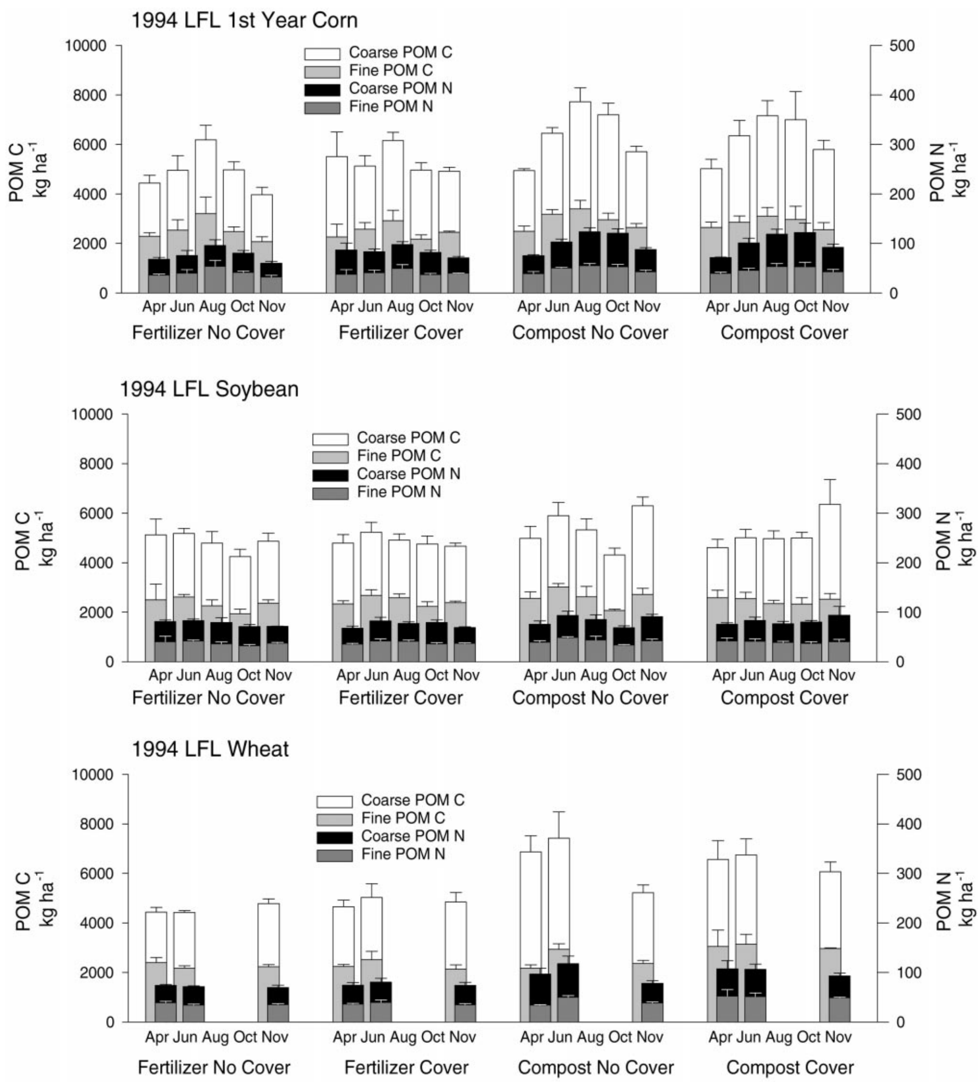

Fig. 3. Two size classes of POM in the top 25 cm of the 1994 LFL treatments. Error bars represent the standard error of the mean for each treatment. Units are based on an assumed bulk density of 1.3 Mg m^{-3}.

son as the availability of residue N changes (data not shown). Nitrogen mineralization per unit POM was lowest in October and September when most plants are near peak biomass and highest in November and April when most plants have senesced. This is similar to the overall pattern found for NMP in Willson et al. (2001), and suggests that POM and fresh plant residues are the two most important sources of mineralizable N in these soils.

4. Discussion

4.1. Organic matter fractions in relation to plant needs

Table 3 relates the N contents of the microbial biomass and POM fractions in the LFL first year corn, no cover and LTER NTS treatments to their above ground plant biomass, yield, and residue N. The 'min-

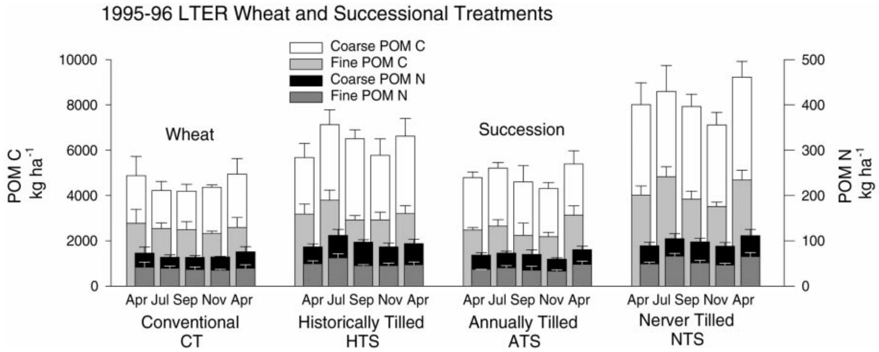

Fig. 4. Two size classes of POM in the top 20 cm of the 1995–1996 LTER wheat and successional treatments. Error bars represent standard error of the mean for each treatment. Units are based on an assumed bulk density of $1.3\,\mathrm{Mg\,m^{-3}}$.

imum N required' is an estimate of the quantity of inorganic N that must be made available during the growing season to supply plant needs. It is based on an overall uptake efficiency of 50% of available inorganic N (50% of fertilizer plus mineralized N is captured in plant tissue). This is near the upper end of the range of recovery efficiencies reported in fertilization studies (e.g. Keeney, 1982; Jokela and Randall, 1997).

Microbial biomass accounts for only 4% of Soil N in the fertilized first year corn treatment and 8% in the compost amended and a native succession soils. The data presented in Fig. 3 shows that microbial N changed substantially between dates in each treatment, with a maximum increase of $120\,\mathrm{kg\,N\,ha^{-1}}$ between April and July in the first year corn, Compost plots, more than doubling the initial N content. Given that the inorganic N pool never exceeded 45 ppm ($117\,\mathrm{kg\,N\,ha^{-1}}$) in the top 20 cm during this study, microbial immobilization could be very important in modifying inorganic N availability. The change in microbial N from April to July was smaller following the incorporation of red clover in the first year corn, cover plots in 1995 than following the incorporation of a higher C:N ratio 'weedy fallow' in the no cover plots.

Table 2
Correlations (r) between biologically active organic matter fractions and cumulative mineralization measurements across all treatments and dates

Organic matter fraction	Inorganic N accumulation			
	10 days	30 days	70 days	150 days
POM C				
Total	0.12 NS	0.39***	0.58***	0.64***
250–1000 μm	0.17*	0.41***	0.59***	0.64***
53–250 μm	0.03 NS	0.30***	0.47***	0.54***
POM N				
Total	0.16*	0.44***	0.57***	0.59***
250–1000 μm	0.19*	0.45***	0.57***	0.57***
53–250 μm	0.08 NS	0.36***	0.47***	0.51***
Microbial biomass				
C	−0.13 NS	0.12 NS	0.21**	0.28***
N	−0.17*	−0.12 NS	0.14 NS	0.41***

* Significance at 0.05 probability level.
** Significance at 0.01 probability level.
*** Significance at 0.001 probability level.

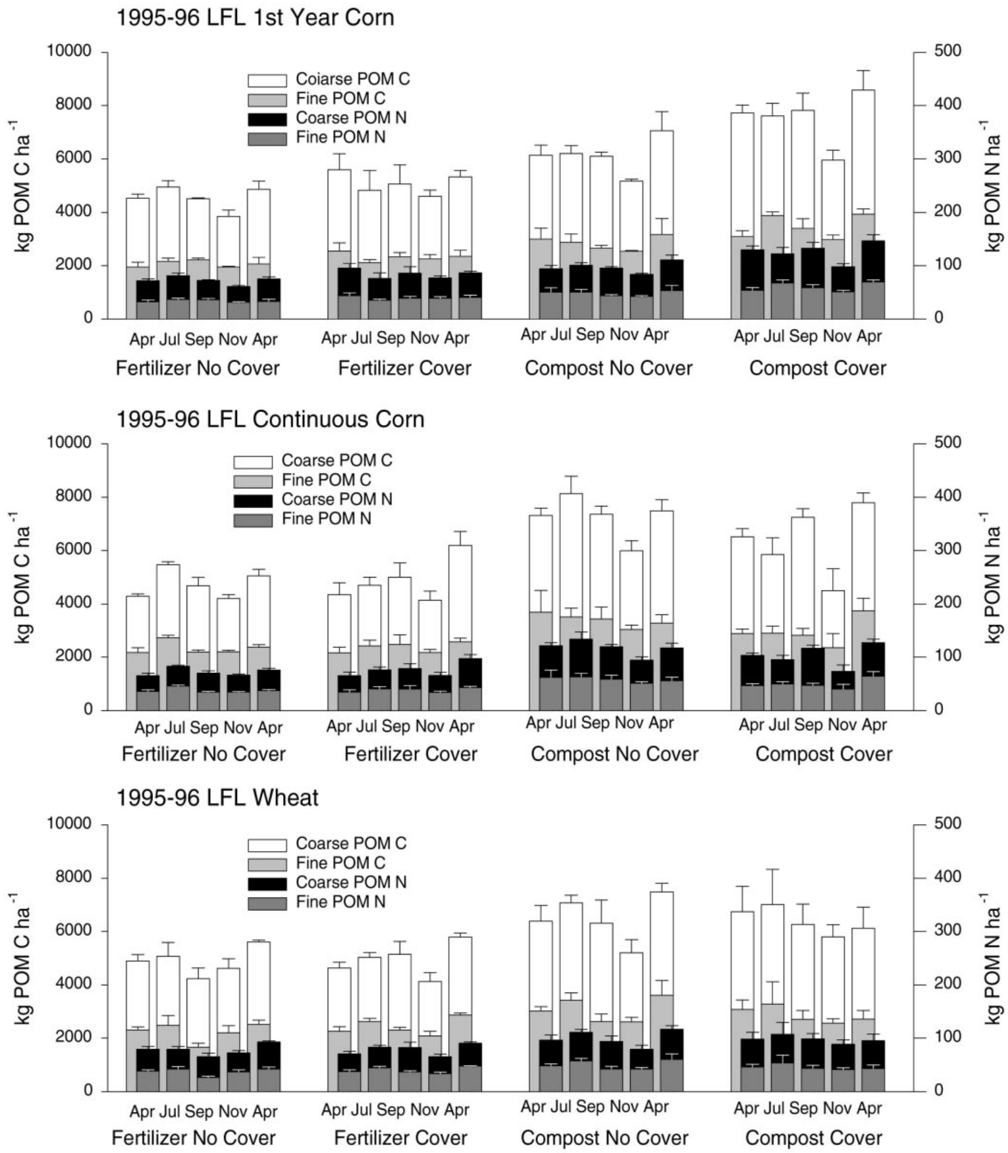

Fig. 5. Two size classes of POM in the top 20 cm of the 1995–1996 LFL treatments. Error bars represent standard error of the mean for each treatment. Units are based on an assumed bulk density of $1.3\,Mg\,m^{-3}$.

Low C:N ratio cover crops may decrease the extent of early season immobilization, thereby freeing more inorganic N for plant uptake. A microbial turnover rate of 2–3 generations per year (Harris and Paul, 1994) would result in an average of 250–370 kg N ha^{-1} cycled through the microbial biomass in the LFL agronomic treatments, which is similar to the minimum requirement of 240–500 kg N ha^{-1} needed to produce the observed crop biomass.

POM represents 20% of soil N in the first year corn, Compost treatment, and 12 and 13% in the fertilizer and NTS treatments, respectively. As discussed previously, there were large increases in POM N associated with the large compost additions in 1994, and

Table 3
Selected N pools in 1995–1996 relative to one another and to soil N

	LFL first year corn without cover ($kg\,N\,ha^{-1}$)		LTER	LFL first year corn without cover (% of soil N)		LTER
	Fertilizer	Compost	NTS	Fertilizer	Compost	NTS
SOM[a]	2340	2470	2990	100	100	100
Microbial biomass	95	136	239	4.1	5.5	8.0
Fine POM (53–250 μm)	135	239	225	5.8	9.7	7.5
Coarse POM (250–2000 μm)	154	265	170	6.6	10.7	5.7
Total POM (53–2000 μm)	289	504	395	12.4	20.4	13.2
Above ground biomass[b]	248	209	68	10.6	8.5	2.3
Yield removed	137	125		5.9	5.0	
Residue returned (1995)	111	85	68	4.7	3.4	2.3
Fertilizer/compost	134	67		5.7	2.7	
Residue input (from 1994)	51	46	79	2.2	1.8	2.6
Minimum N required [c]	496	418	136	21.2	16.9	4.5

[a] Soil parameters are averaged across sample dates.
[b] Plant parameters were measured at time of peak biomass (late summer) except yield (late fall).
[c] The minimum amount of inorganic N required for uptake, assuming 50% efficiency.

there was a temporary decrease in most treatments in November 1995. Date to date changes were relatively small, otherwise, indicating that the decomposition of POM is balanced by the formation of new POM for much of the season. The decrease in POM N in November 1995 was equivalent to 100 $kg\,N\,ha^{-1}$ on average and a maximum of 214 $kg\,N\,ha^{-1}$ in the first year corn treatment with compost and cover. It has been estimated that the steady-state turnover time for POM is 20–40 years. This would imply an annual turnover of 7–25 $kg\,N\,ha^{-1}$ in the treatments described in Table 3, which is 6–30% of the total amount of plant and compost N added to the soil in these treatments.

4.2. Organic matter fractions as predictors of N mineralization

Willson et al. (2001) found that NMP was enhanced by the addition of compost, the incorporation of legume residues, and the conversion from annual to perennial vegetation as in the HTS and NTS treatments. NMP was greatest in the late spring (April–June), and lowest in the early fall (September and October), although it often recovered by November.

Like NMP, POM C and N are enhanced by compost additions and are much greater in the NTS and HTS treatments than in either of the tilled treatments. However, the incorporation of residues did not significantly change POM C and N during in this study, whereas the incorporation of legume residues increased spring and fall NMP in Willson et al. (2001), particularly in contrast to the low NMP observed in September and October.

The correlation between POM C and NMP found in this study, and in Hassink (1995), suggests that POM C, which Hassink calls macroorganic matter, may be useful as an aid to fertilizer recommendations, particularly if combined with information about recently incorporated residues. The measurement of POM C should be sufficiently simple to be included in routine testing, and would provide an objective method for modifying fertilizer recommendations in cases where past management has resulted in unusually high or low N supplying capacity. POM measurements that combine size and density fractionation (Meijboom et al., 1995; Cadisch et al., 1996; Barios et al., 1996) and the anaerobic incubation of Waring and Bremner (1964) have also proven to be excellent indicators of N mineralization, but would be more expensive to implement in routine testing.

Microbial biomass was a less reliable indicator of changes in substrate availability than either POM or NMP. Microbial biomass not enhanced by cover crops, increased with compost only in the 1995–1996 season and experienced a decline in June 1994 that was not related to substrate availability.

4.3. Seasonal changes in microbial biomass

There was a trend toward greater microbial biomass in the warmer months (July–October) than the cooler months (April and November). This is consistent with the data at other moist temperate sites (Kaiser and Heinemeyer, 1993; Kirchner et al., 1993; Joergensen et al., 1994; Paul and Harris, 1997). The opposite pattern was found for cool-season production systems in semi-arid environments (Van Gestel et al., 1992; Bremer and van Kessel, 1992; Collins et al., 1992; Franzluebbers et al., 1994). Maxwell and Coleman (1995) also report lower microbial biomass in the summer in a moist riparian habitat, but in that study summer microbial biomass seems to have been limited by microfaunal predation. While substrate availability is usually assumed to be the most important determinant of microbial biomass, it is clear from these studies that other factors have a greater influence on patterns of seasonal change.

We detected significant differences in microbial C:N in the 1995–1996 dataset, with lower C:N ratios after tillage and plant senescence (July and November 1995) in the tilled treatments and lower C:N ratios at all dates in the untilled successional treatments. The C:N ratio of the microbial biomass should reflect the species composition, particularly the ratio of bacteria:fungi (Jenkinson, 1976; Shen et al., 1984; Sparling and Zhu, 1993). The C:N ratios of Fungi range from 4.5:1 to 15:1 while the C:N ratios of bacteria tend to be between 3:1 and 5:1 (Paul and Clark, 1996). If one assumes a C:N ratio of 10 for fungi and 4 for bacteria, the bacteria:fungi ratio of the July and November samples overall would be approximately 2:1 whereas the ratio in April and September would be 1:1 and the ratio in the NTS treatment would be approximately 6:1 across all dates. Direct microscopy of LTER treatments in 1991 and 1993 and of the LFL in 1994 resulted in bacteria:fungi ratios ranging from 0.3:1 to 5:1 (Paul and Harris, 1997). The high relative abundance of bacteria at this site contradicts the assumption of Anderson and Domsch (1975) that agricultural soils are dominated by fungi.

4.4. Management implications

In these coarse textured soils, NMP, microbial biomass and POM all have the capacity to change in response to inputs of organic material from plants and external sources. While changes in microbial biomass N may be important in modifying N availability to plants at various times of the year (e.g. after tillage and after plant senescence), the size of the microbial biomass at any point in time is not a good indicator of the N supplying capacity of the soil. Apparently, microbial biomass functions as a catalyst for microbial degradation rather than as a long term source or sink of mineralizable N in these soils. POM proved to be a much more reliable indicator of NMP across treatments, but it did not detect differences in NMP associated with the use of recently incorporated plant residues. This suggests that POM measurements could be used to estimate N mineralization if combined with information about the previous year's crop and cover crop production. Additional testing will be required to determine whether the observed relationships between POM and NMP are valid across regions and soil types.

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