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DIVISION S-3—SOIL BIOLOGY & BIOCHEMISTRY

Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools

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ABSTRACT

Specific impacts of organic management practices on soil organic matter characteristics have not been documented. This study tested how organic management practices influence soil fertility by investigating whether 10 yr of organic or conventional management generated differences in biologically active soil organic matter (SOM) pools at the Rodale Institute Research Center's long-term Farming Systems Trial experiment (FST). The experiment included an organically managed rotation that was animal based, an organic treatment that was cash-grain based, and a conventional cash-grain-based rotation. The biologically active SOM matter pools of the three FST treatment soils were compared through characterization of soil CO_2 evolution, available inorganic N pools and N mineralization rates, water-dispersible organic carbon (WDOC), and particulate organic matter (light fraction). Soils receiving the organic treatments accumulated biologically active C. Accumulated organic matter in the manure-amended soil was the most labile whereas the cover-cropped soil accumulated the most organic matter overall. In the cover-cropped soil, higher total C and N, particulate SOM, and reduced WDOC contents indicated that its SOM was more stable than SOM in the other two treatment soils. The conventionally managed soil had the lowest biological activity (N supply and soil respiration rates) and did not accumulate SOM during the 10-yr experiment. Assays that characterize particulate organic matter emerged as the best indices of biologically active SOM because they documented important quality (i.e., biological lability) and quantity aspects of SOM character in the Rodale FST soils.

SOIL ORGANIC MATTER is linked to desirable soil physical, chemical, and biological properties and is closely associated with soil productivity (Stevenson, 1982; Tate, 1987). Despite this, there are few explicit organic matter management recommendations. Making recommendations about organic matter management is difficult because accepted measures of SOM quality do not exist. Biologically active SOM is believed to be the key to soil productivity when fertility is biologically mediated. Altered management practices can affect active SOM characteristics and soil quality (nutrient supply and retention characteristics) before net organic matter contents change (Woods and Schuman, 1986; Wander et al., 1993, unpublished data). Hence, farmers switching to organic management practices are encouraged to focus their efforts on active SOM pools (Weil, 1992). Changes in biologically active SOM may be linked to the so-called transition effect. When farmers convert from conventional to organic management practices, they frequently observe a period of suppressed yields followed by rebounding crop productivity (U.S. Department of Agriculture, 1980; Brusko, 1989; Liebhardt et al., 1989). Some farmers attribute this transition, or recovery in crop productivity, to management practices that build soil organic matter quality and enhance the life of the soil. Such a shift in SOM characteristics is not well documented in the scientific literature. How organic management practices alter biologically active SOM has not yet been established.

Active SOM refers to a heterogeneous mix of living and dead organic materials that are readily circulated through biological pools. It is a major soil nutrient reservoir. Balance between decay and renewal processes in this pool controls nutrient availability and SOM status, i.e., determines whether organic matter is aggrading or degrading overall. Characteristics of the active fraction have been described primarily through the use of C and N isotopes employed as tracers (Jenkinson, 1971; Paul and van Veen, 1978; Gasser, 1979; Jansson and Persson, 1982). Isotopic analyses have generated consistent descriptions of soil C and N dynamics that have led to SOM classification based on isotope turnover rates (Jenkinson et al., 1987; Parton et al., 1987; Jenkinson and Parry, 1989; Paustian et al., 1992). Consequently, the active SOM fraction has been used as a functional description of organic materials with turnover times of 1 to 2 yr (Ladd et al., 1981; Parton et al., 1987). Although the active fraction has not been fully described in terms of its composition, nor has it been successfully isolated, it has been correlated with several procedurally defined soil fractions (Castellanos and Pratt, 1981; Paul and Voroney, 1983; Janzen, 1987; Sikora and McCoy, 1990). Because organic, sustainable, and low-chemical-input systems rely increasingly on soil nutrient cycling mechanisms, it is critical to understand the relationships between active SOM, total SOM, and nutrient retention and supply characteristics. To effectively manage soil organic matter, indices sensitive to changes in the functionally important active SOM fraction must be identified.

The Rodale Institute Research Center's FST experiment has undergone a typical conversion scenario: the productivity of land converted from conventional to organic management was suppressed for a few years, after

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Abbreviations: SOM, soil organic matter; FST, Rodale Institute Research Center's long-term Farming Systems Trial experiment; WDOC, water-dispersible organic carbon; ANOVA, analysis of variance; ANCOVA, analysis of covariance; RCF, relative centrifugal force; LF, light fraction; HF, heavy fraction.

which corn yields rebounded to equal or exceed those in conventionally managed plots (Liebhardt et al., 1989). During the conversion period in these soils, total SOM content was not a successfully used soil quality monitoring tool. Rebounding productivity may be associated with subtle beneficial changes in SOM and organic-matter-dependent soil properties (Weil, 1992; Wander et al., 1993, unpublished data). This work characterized the effects of management on the active SOM fraction through investigation of several correlative soil parameters that are dependent on biologically active SOM.

The overall objective of this work was to investigate the popular concept that organic management practices enhance biologically active SOM. This hypothesis was addressed by characterization of: soil biological activity (soil respiration), soil N supply capacity (available inorganic and mineralized N), water-dispersible organic matter pools, and particulate SOM pools in organically and conventionally managed soils.

MATERIALS AND METHODS

The Farming Systems Trial Experiment

The Rodale FST experiment is located in east-central Pennsylvania near Kutztown. It occupies 6.1 ha of mostly Comly channery silt loam (fine-loamy, mixed, mesic Typic Fragiudalf), with large inclusions of Berks channery silt loam (loamy-skeletal, mixed, mesic Typic Dystrochrept) and Duffield and Murill shaley silt loams (fine-loamy, mixed, mesic Ultic and Typic Hapludalfs, respectively) (Liebhardt et al., 1989). The site had been farmed conventionally prior to the experiment's initiation. Since 1981, it has been managed under three distinct rotations. The experimental treatments included: (i) an organic animal-based rotation that received cattle manure and produced N_2-fixing red clover (*Trifolium pratense* L.) hay as its sources of fertility, (ii) an organic cash-grain rotation (cover cropped) receiving N fertility from leguminous cover crops alone, and (iii) a conventional cash-grain, mineral fertilizer rotation. The complete crop rotation sequences and a summary of management practices are listed in Tables 1 and 2.

In addition to differences in fertility and residue inputs, the rotations varied in their pest control strategies and planting patterns. The organically managed rotations relied on cultivation and heterogeneous crop mixes for their weed and pest control (Litsinger and Moody, 1983; Vandeemer, 1989). The conventional rotation received synthetic amendments (fertilizers, herbicides, and insecticides) as recommended by Pennsylvania State University agronomists. All rotations were moldboard plowed to the same depth (approximately 25 cm). The experiment was a randomized complete block that included eight replications of the three rotation treatment main plots (animal-based, cover-cropped, and conventional); main plots were 18 by 91 m. To allow same-crop comparisons in any one year, each rotation main plot was split into three 6 by 91 m subplots and the main rotation was begun at three different crop-entry points. Grass buffer strips (1.5 m) were maintained between plots to prevent material transfer between plots. This experiment was more fully described by Liebhardt et al. (1989), Janke et al. (1991), and Peters et al. (1992).

Soil Sampling and Statistical Analysis

Soil samples were collected from entry points planted in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in 1990, on five dates during the 1990–1991 cropping season: (10 May, 22 June, 13 Sept., and 4 Nov. 1990 and 26 Feb. 1991). Samples were collected from six of the eight blocks, excluding Blocks 6 and 7. On all dates, soil composites were collected from all plots (n = 36) by drawing 10 evenly spaced cores (4.5-cm diam., 0–10 cm deep). Cores were taken adjacent to plants, one row from plot centers. Soils were transported from the field site in plastic bags kept on ice and were stored at 4°C prior to sieving (≤2 mm). The Rodale Institute Research Center provided archived, air-dry soil samples that had been collected from the same depth (0–10 cm), from the same plots, in a similar manner in 1981.

Table 1. Farming Systems Trial cropping sequence.

Rotation	Entry†	Crops produced each year				
		Year 1‡	Year 2	Year 3	Year 4	Year 5
				1981–1990		
Animal-based	1	Wh/Hay...§	...	.../Corn	Soy	Corn-si
	2	Corn	Soy	Corn-si/Wh...	.../Hay...	...
	3	Corn-si/Wh...	.../Hay...	...	.../Corn	Soy
				1981–1985		
Cover-cropped	1	Oats/C.Crop...	.../Corn	Oats/C.Crop...	.../Corn	Soy
	2	Soy	Oats/C.Crop...	.../Corn/Wh...	.../C.Crop...	.../Corn
	3	Corn	Soy	Oats/C.Crop...	.../Corn	Oats/C.Crop...
				1986–1990		
Cover-cropped	1	Oats/C.Crop...	.../Corn	Bar/Soy¶/Wh...	.../C.Crop...	.../Corn
	2	Bar/Soy/Wh...	.../C.Crop	.../Corn	Bar/Soy/Wh...	Oats/C.Crop...
	3	C.Crop/Corn/Wh.	.../Soy/Wh...	Oats/C.Crop...	.../Corn	Bar/Soy
				Beginning in 1981		
Conventional	1	Corn	Corn	Soy	Corn	Soy
	2	Soy	Corn	Corn	Soy	Corn
	3	Corn	Soy	Corn	Corn	Soy

† Entry designates the crop entry point in the organic animal-based organic cash-grain-based (cover-cropped), and conventional cash-grain-based rotations. After two cycles of the organic animal-based rotation, the crop sequence was altered. The crop sequence was modified every 5 yr in the organic cash-grain-based rotation and the sequence remained unchanged in the conventional cash-grain-based rotation.

‡ Year 1 corresponds to 1981, 1986, and 1991, Year 2 to 1982 and 1987, Year 3 to 1983 and 1988, Year 4 to 1984 and 1989, and Year 5 to 1985 and 1990.

§ Crops followed by "..." are grown throughout the winter or following season and tilled in or harvested during the spring of the crop season marked ".../". Wh = wheat, Hay = red clover (1981–1985) and (1988–1990), and red clover + alfalfa (1986 and 1987). Soy = soybean, Corn-si = corn silage, Bar = barley, C.Crop = red clover (1981–1983) and (1985–1990), and hairy vetch (1984).

¶ Soybean was not seeded in 1988.

Table 2. Comparison of Farming System Trial rotations†.

	Animal-based	Cover cropped	Conventional
Crops grown	Corn grain, corn silage, soybean, wheat, legume hay	Corn grain, soybean, wheat, oat, barley, legume green manure	Corn grain, soybean
Surface condition of soil from Jan. 1986–Dec. 1990	Bare 7%, live plants 73%, dead residue 20% of time	Bare 8%, live plants 69%, dead residue 23% of time	Bare 8%, live plants 42%, dead residue 50% of time
Primary tillage	Moldboard plow: 4 times per 5 yr	Moldboard plow: 5 times per 5 yr, spring or fall	Moldboard plow: every spring
Weed control	Rotary hoe, cultivate corn and soybean	Rotary hoe, cultivate corn	Hebricides applied to corn and soybean
Insect control	Rotation	Rotation	Insecticide is applied to 2-yr corn
Nitrogen fertility	Beef manure applied to corn (poultry manure applied in 1986), residual hay	Legume (red clover-alfalfa) green manure	34 kg ha^{-1} urea starter fertilizer, side dress N 112 kg ha^{-1} NH_4NO_3
Potassium fertility	139 kg ha^{-1} K added as K_2SO_4 in 1989, ≈56 kg ha^{-1} K added per year in manure	139 kg ha^{-1} K added as K_2SO_4 in 1989	139 kg ha^{-1} K added as K_2SO_4 in 1989
Phosphorus fertility	≈45 kg ha^{-1} added annually in manure	none	14.6 kg ha^{-1} added as starter fertilizer each year
Lime	3360 kg ha^{-1} of Ca limestone added in 1989	3360 kg ha^{-1} of Ca limestone added in 1989	8960 kg ha^{-1} Mg limestone added in 1982
Additional features	Frost seeded legumes into small grains	Frost seeded legumes into small grain, relay cropped soybean into small grain	None

† Table modified from Peters et al. (1992).
‡ Assume that the soil surface is bare for 1 mo following plowing and planting a new crop. When a legume crop is established in the fall, the winter period is considered to be under live cover even though the plants are dormant.

Pooled ANOVA was used to analyze farming system effects on biologically active SOM pools. The experiment was treated as a randomized complete block, split into two crop entry points, and five dates: six blocks × three farming systems × two crop types × five dates. Analysis of covariance of the archived 1981 and November 1990 samples used a six block × three farming systems × two entry point randomized complete block design. All ANOVA (1990–1991 data) and ANCOVA (1981 vs. 1990) analyses were performed using the PC-based computer program SYSTAT 5.1 (Wilkinson, 1990). Fisher protected least significant differences were used to compare treatment means at the 0.05 significance level.

Total Soil Carbon and Nitrogen

Soil was dried (60°C), sieved (≤2 mm), and disk milled to powder consistency. Total soil C and N were then determined on 20-mg samples by combustion analysis using a Carlo Erba CN Analyzer (Carlo Erba, Milano, Italy). Treatment effects on C and N contents were assessed on a mass basis using coarse-fragment-free soil rather than on a volume basis to avoid confounding by variable coarse-fragment contents. The FST soils are texturally heterogeneous and the average coarse-fragment contents (rock particles >2 mm) of the three treatment soils were: animal-based (28.1%), cover-cropped, (27.9%), and conventional (21.2%). These values are based on nine treatment composites (three farming systems split into three entry points); differences between treatments were not statistically significant at the 0.05 level. The bulk densities of individual samples were affected by differences in their rock content, suggesting that coarse-fragment corrections for bulk density estimates needed to be made on a per-sample basis. Our sampling methods prevented such an approach. The average uncorrected soil bulk densities were 1.05,1.04, and 1.07 g cm^{-3} in the animal-based, cover-cropped, and conventional soils, respectively.

Active Fraction Measures

Soil respiration rates of homogenized soils were assayed to compare in situ soil biological activity (Anderson, 1982). Following sieving, which generally stimulates soil respiration rates, 10 g (dry-wt basis) of field-moist soil was placed into 117-cm^3 incubation vials; 25 g of clean silica sand was added to ensure adequate aeration. Soil–sand mixtures were brought to 60% water-holding capacity based on the mass of water remaining after saturated soil freely drained for 24 h. Vials were then sealed with rubber septa and covered with two layers of Parafilm (American National Can Co., Greenwich, CT). Incubations were initiated as soon as possible following field sampling events; all were begun within 5 d of soil collection. Carbon dioxide in the vial headspace was subsampled throughout a 2-wk period using a Varian Model 3700 gas chromatograph (Varian, Sunnyvale, CA) equipped with a Chromosorb 102 column and a thermal conductivity detector. Headspace gas samples were stored in serum vials on the first sampling date. Because serum vials were not gas tight, reported CO_2 values were multiplied by a correction factor (1.4) based on the loss of similarly stored gas standards. During all other incubations, gas sample injections were made directly from incubation vials. Sample incubation vials were opened and sparged following each sampling to prevent O_2 depletion of headspace gases. Random sampling of resealed vials confirmed that their gas composition matched ambient air.

Soil N supply characteristics were assessed through characterization of available inorganic and mineralizable N pools. Available inorganic N (NH_4^+ + NO_3^-) was determined by extraction of 7 g of freshly sieved field-moist soil (≈5.3 g oven-dry wt) in 60-mL centrifuge tubes with 33 mL of 2 *M* KCl. After shaking 1 h on a reciprocal shaker, the extracts were removed and filtered through rinsed Whatman no. 50 filter paper. The amounts of NH_4^+ and NO_3^- were quantified colorimetrically using a Lachat auto analyzer (Lachat Instruments, Milwaukee, WI). Mineralized N in the incubated soils

used for the soil respiration study was extracted and analyzed in the same manner as was available inorganic N. Net mineralized N ($NH_4^+ + NO_3^-$) was determined by subtracting initial available N concentrations from the total mineral N concentrations that were present in extracts of postincubation soils.

Water-dispersible organic C in the FST soils was used as a measure of low molecular weight C that is removable by relatively mild techniques. The method used was modified from Traina et al. (1989). Sieved, field-moist soil was Na^+ saturated with 1 *M* NaCl (10:1 v/w). Deionized H_2O (200 mL) was then added to disperse the soil. This solution was separated by centrifugation (12 000 RCF, 0.5 h) and discarded. The first rinse solutions were completely clear. The soil pellet was rinsed (shaken) in deionized H_2O for 1 h, and the supernatant was separated by centrifugation (12 000 RCF, 0.5 h). This rinse procedure was repeated three times and the extracts were combined. The C content of bulk WDOC extracts were quantified using a Dohrmann Model CR 80 Carbon Analyzer (Rosemount Analytical, Santa Clara, CA). Extracts from the first and second sampling dates were concentrated using a rotary evaporator prior to C analysis and an autosampler was used to introduce the samples. The WDOC samples from all other dates were not preconcentrated and were manually injected.

Particulate SOM was assayed by collection of the LF (i.e., organic matter with densities <1.6 g cm^{-3}). The LF is a procedurally defined SOM fraction principally comprised of particulate, noncolloidally bound organic matter (Greenland and Ford, 1964). It has been recognized to be an important biological substrate and has been recommended as a fertility index (Greenland and Ford, 1964; Janzen, 1987). The LF was collected by dispersion of 25 g of freshly sieved, field-moist soil in sodium polytungstate solution (1.6 g cm^{-3} density), followed by centrifugation (10 000 RCF, 0.5 h) and collection of the supernatant. The procedure was modified from Turnchenek and Oades (1979) and Strickland and Sollins (1987). After three such separations, the composite supernatant (containing the LF) was filtered through 0.2-μm polycarbonate membrane filters. Light fraction materials retained on the filters were rinsed with a 0.5 *M* $CaCl_2$ and 0.5 *M* $MgCl_2$ solution followed by a final rinse in deionized H_2O. This was done to prevent any remnant biological toxicity due to Na^+ saturation of the ion-exchange sites in the LF. The membrane filters and the LF samples were freeze dried and the LF was recovered from the dried papers and weighed. The HF of the soil, comprised of the remaining mineral matter and the organic matter bound to it, was recovered by rinsing the LF-free residual soil once with a solution of 0.5 *M* $CaCl_2$ and 0.5 *M* $MgCl_2$, and twice with deionized H_2O. The HF soils were oven dried at 100°C. On the last sampling date, the LF was extracted from treatment crop–entry point composites (n = 6, three treatments × two crops) because insufficient sodium polytungstate was available for complete extraction of all samples.

Total C and N of the LF and HF pools were determined using a Carlo Erba C & N analyzer. The biological labilities of HF and LF pools were assayed using incubations of the HF and the HF amended with LF. The LF amendment rate was proportional to the initial amount of LF material removed from each sample. This allowed comparison of microbial utilization of stabilized organic matter in the HF and, comparatively much smaller, LF pools. The incubations were conducted in the same way as the soil respiration studies. Harsh salt treatment of the soils during the LF extraction procedure destroyed soil structure and presumably lysed cells and removed extractable nutrient salts. To ensure that only the biological availability of C substrates controlled microbial metabolism and accordingly CO_2 evolution, all incubation vials received 1 mL of a general soil inoculum. Inoculum was obtained by shaking 1 kg of fresh soil (composited from all three rotation treatments) for 1 h in H_2O on a reciprocal shaker. The resulting soil suspensions were allowed to settle for a few minutes and the opaque solution was collected as the inoculum source. In addition, incubation vials also received 1 mL of nutrient solution [1 g K_2PO_4, 0.25 g KCl, 0.25 g $MgSO_4$, and 23 mg $(NH_4)_2SO_4$ L^{-1}] and 1 mL L^{-1} of micronutrient solution (Houghton and Cain, 1972).

RESULTS

Total Soil Carbon and Nitrogen

In 1990 the soil C and N contents of each plot were a function of the initial SOM content and of the applied rotation. There was a slightly uneven spatial distribution of SOM (inferred from C and N contents) in soils under the three treatments at the initiation of the experiment; however, differences in C distribution were not statistically significant (Tables 3 and 4). Archived soils from the cover-cropped plots had significantly less N than those from the conventional treatment plots. The blocking pattern did not effectively remove spatial variability. Earlier reports of SOM contents did not note significant treatment effects (Fraser, 1984; Peters et al., 1992).

After 10 yr there were small but significant changes in total soil organic C and N in the FST soils (Tables 3 and 4). Total C was greatest in the cover-cropped, intermediate in the animal-based, and the least in the conventional treatment soils. In 1990 there was no significant difference in cover-cropped and conventional soil N contents. The N content of the animal-based soil was significantly greater than the conventional soil. Analysis of covariance was used to statistically assess treatment effects. Analysis of covariance simultaneously examines the variances and covariance among primary variables (1990 C and N contents and the FST treatment) and their covariates (1981 C and N contents) (Gomez and Gomez, 1984). The relationship between inherited SOM (1981 C and N) and 1990 C and N was used to adjust inherited SOM to a common level; this adjustment separated the variation in C and N due to management (see Table 4 results following the treatment and residual 1990 variables).

Table 3. Total soil C and N: October 1981 and November 1990.

Farming system	1981†		1990	
	C	N	C	N
		g kg^{-1}		
Animal-based	22.7 a‡	3.31a,b	23.4 a,b§	3.50a§
Cover-cropped	23.6 a	2.87b	24.5 a	3.42a,b
Conventional	22.3 a	3.41a	21.3 b	3.25b

† Soils were collected in 1990 from 0–10-cm depths from Blocks 1–5 and 8 in crop entry point plots producing corn and soybean. Corresponding archived 1981 soil samples were obtained from the Rodale Institute Research Center.

‡ Treatment means within columns followed by different letters are significantly different based on Fisher-protected LSDs ($P < 0.05$).

§ Statistics for C and N 1990 were performed on residual values generated by regression of C or N 1990 and C or N 1981; this was done to remove initial spatial variation in soil organic matter distribution.

Table 4. Total soil C and N statistics: Change 1981-1990.

Independent variable†	Dependent variable	Analysis	C		N	
			F	*P*	*F*	*P*
Treatment	C or N 1981	ANOVA	0.50	0.620	7.23	0.011
Block	C or N 1981	ANOVA	1.00	0.463	1.04	0.445
Treatment	C or N 1990	ANOVA	2.87	0.103	3.74	0.044
Block	C or N 1990	ANOVA	2.04	0.158	1.72	0.179
C or N 1981‡	C or N 1990	Regression	31.23	0.0001	22.73	0.0001
Trt. × C or N 1981	C or N 1990	Regression	0.17	0.845	2.24	0.214
Treatment	Residual 1990	ANOVA	4.07	0.207	8.14	0.001
C or N 1981	Residual 1990	ANOVA	34.48	0.0001	18.21	0.009

† The effect of parameters (independent variables) listed in the left column on the dependent variable (soil C or N) was determined by statistical analyses using Systat (Wilkinson, 1990). The parameter (C or N) is followed by the year.

‡ To remove inherited C and N variability, soil organic matter (SOM) (C or N) 1981 was regressed with SOM 1990 and the residual error was saved. Treatment effects on SOM content were then determined by ANOVA of rotation treatment and C and N 1981 on the residual error.

Farming System Impacts on Active Soil Organic Matter

Rotation treatments significantly influenced soil N supply characteristics considered throughout the 1990–1991 season (Table 5). Averages of available and net mineralized N (based on means from all five sampling dates) were greatest in soils from the animal-based rotation, intermediate in the cover-cropped soils, and least in those under conventional management (Table 5, Fig. 1a and 1b). Sampling date (temporal effects and field management events) had a greater impact on seasonal N supply patterns than did rotation history (i.e., farming system effects). Available and mineralized N were the only measured parameters in which the relative ranking of farming systems shifted among dates (data not shown). This made statistically backed comparisons of overall farming system effects technically invalid.

Farming system treatments also significantly influenced soil respiration rates (Table 5). Again, the animal-based treatment appeared to be the most biologically active. Soil respiration rates were consistently greatest in soils from this treatment, intermediate in cover-cropped soils, and the least in the soils under conventional management (Table 5, Fig. 1c).

Animal-based and conventional treatments had significantly greater WDOC pools overall than did the cover-cropped soil (Table 5, Fig. 2). The quantity of dispersible C varied significantly over the 1990/91 season. The animal-based system always had the largest dispersible C pool, followed by the conventional soil, and the cover-cropped soil had a significantly smaller WDOC pool than did the other two.

Density Fractions

The densimetric separation procedure lowered soil respiration rates to one-sixth of the rates observed in incubations of whole soils (Fig. 1 and 3). Addition of LF materials to the litter-free HF significantly increased total respiration rates over the rates evolved from the HF alone (Fig. 3).

Table 5. Average active soil organic matter fraction statistics.

Independent variable	Dependent variable	Analysis	*F*	*P*
Treatment	Available N	ANOVA†	3.4	0.036
Treatment	Mineralized N	ANOVA	5.0	0.031
Treatment	CO_2 evolution	ANOVA	17.5	0.001
Treatment	Water-dispersible organic C	ANOVA	12.4	0.0002

† ANOVA of data from all five sampling dates, $n = 180$, except CO_2 evolution, where $n = 174$.

Cropping system treatments altered the quality and quantity of the organic matter in the LF and HF pools (Table 6). On average, respiration rates from the cover-cropped treatment's unamended HF were greater than were rates from the conventional HF (Fig. 3a). The ranking of CO_2 evolution rates from incubated HF soil was the same as the relative rank of HF C and N contents: in all cases, cover-cropped > animal-based > conventional. Total soil C and N contents had the same relative ranking. Heavy-fraction total C and N contents of the three rotation soils were not significantly different at the 0.05 level. High HF C/N ratios were associated with high respiration rates. The HF C/N ratios were greater in the cover-cropped soil than in the other two soils.

Addition of particulate organic matter (LF) to HF soil changed the relative order of respiration rates: animal-based > cover-cropped > conventional (Fig. 3b). Animal-based treatment respiration rates were significantly greater than conventional soil rates. The C/N ratios of LF materials have the inverse ranking: conventional > cover-cropped > animal-based (Fig. 3d). The conventional LF C/N ratio was significantly greater than the animal-based LF ratio. Lower C/N ratios of organic residues are associated with greater respiration rates and hence biological lability (Levi-Minzi et al., 1990).

There was significantly more C and N in the LF isolated from the cover-cropped soil than from the conventional soil (Fig. 4a and 4b). The masses of C and N in the animal-based treatment LF pool were intermediate. Light fraction additions to the animal-based treatment HF (which were based on the proportion removed from the whole soil) stimulated respiration to a greater degree than did LF addition to the cover-cropped HF, despite the fact that a smaller amount of material was added to the animal-based HF. The quality of readily decomposible organic matter can be interpreted through its ability to function as an energy source and its ability to drive microbial activity (Jansson and Persson, 1982). The greater resource quality of the animal-based LF was further clarified by normalizing the respiration induced by LF application with the quantity of LF C applied

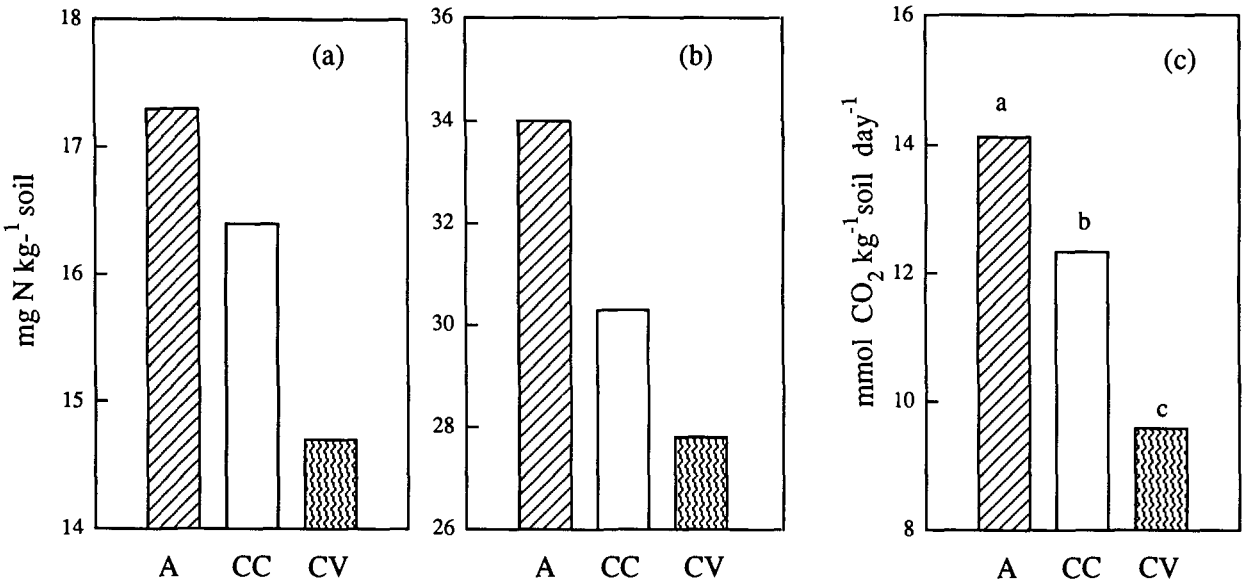

Fig. 1. Average soil N supply and respiration rates in 1990: (a) available inorganic N, (b) mineralized N, and (c) whole-soil respiration rates in the animal-manure-based (A), cover-cropped (CC), and conventional (CV) rotation treatment soils. Different letters indicate treatments were significantly different based on Fisher's protected LSD ($P < 0.05$). Mean separation based on pooled ANOVA is not indicated in (a) and (b) because soil N supply (available and mineralized N) parameters had significant date × treatment interactions; however, the appropriately calculated LSDs would distinguish between the animal-based and conventional treatments.

(Fig. 4c). The amount of CO_2 evolved per gram of LF applied was greater in the animal-based soil than in the other soils. The lability of the LF from the two cash-grain-based rotations, cover-cropped and conventional, were the same.

DISCUSSION

Changes in Soil Organic Matter

Between 1981 and 1991, an average 6760, 5120, and 6450 kg ha^{-1} of dry organic residues were returned annually to the surface of the animal-based, cover-cropped, and conventional treatment soils, respectively. Despite the equal or greater amounts of C added to the animal-based soil, it had not accumulated significant amounts of total C or N. Greater C and N turnover rates of the animal-based treatment soil were suggested by its comparatively rapid soil respiration rates and its relatively high N supply capacity. Moreover, the low C/N ratio of particulate SOM (i.e., LF) isolated from the animal-based soil, and the relatively greater stimulation of respiration by LF amendment of HF, indicated that the LF from the manure-amended soil was more biologically

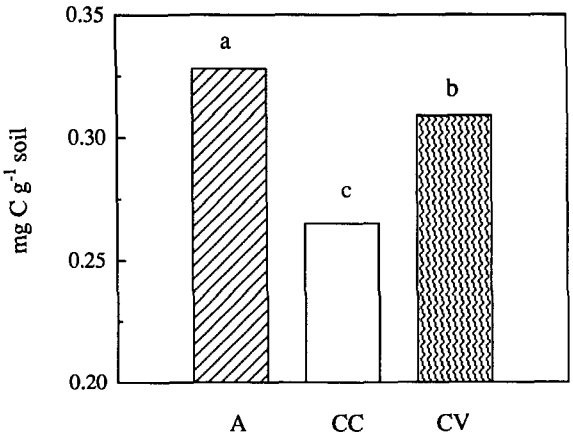

Fig. 2. Average water-dispersible organic C contents in 1990. Different letters indicate that seasonal averages of animal-manure-based (A), cover-cropped (CC), and conventional (CV) rotation treatment soils were significantly different based on Fisher's protected LSD ($P = 0.023$).

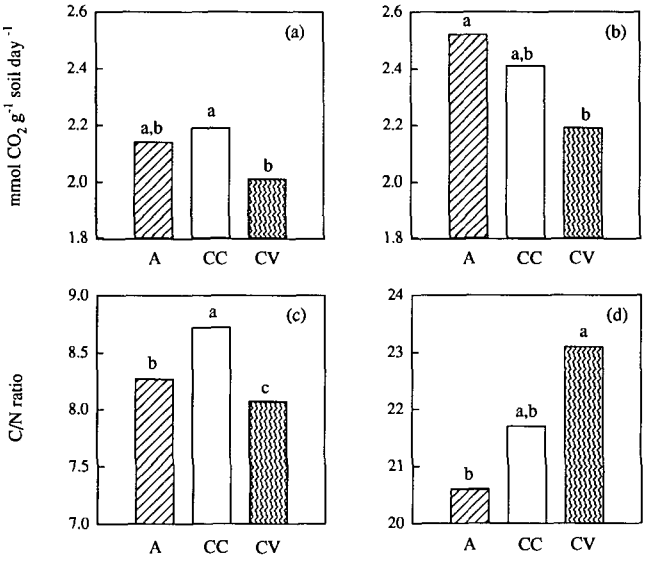

Fig. 3. Average (a) heavy fraction (HF, >1.6 g cm^{-3}) and (b) heavy plus light fraction (LF, ≤1.6 g cm^{-3}) organic matter respiration rates and (c) HF and (d) LF C/N ratios for animal-manure-based (A), cover-cropped (CC), and conventional (CV) rotation treatment soils in 1990. Different letters indicate that seasonal averages were significantly different based on Fisher's protected LSD ($P < 0.05$); HF C/N statistics were performed on log-transformed data.

Table 6. Average light- (LF) and heavy-fraction (HF) organic matter statistics.

Independent variable	Dependent variable	Analysis	*F*	*P*
Treatment	LF mass C†	ANOVA	79.04	0.0001
Treatment	LF mass N†	ANOVA	9.55	0.008
Treatment	LF C/N ratio†	ANOVA	12.46	0.003
Treatment	HF C/N ratio†	ANOVA	5.03	0.038
Treatment	Respiration rate LF + HF	ANOVA	3.34	0.039
Treatment	Respiration rate HF	ANOVA	4.22	0.017

† Analyses were performed on LF, HF, and treatment composites formed on each date, $n = 30$ (3 treatments × 2 crops × 5 dates). For HF and HF + LF soil respiration rate data, $n = 180$.

labile and therefore of higher quality than were the LF pools of other two treatment soils.

Organic matter aggradation in the cover-cropped treatment soil was shown by its increased total soil C and N, and particulate organic matter contents. The cover-cropped treatment soil had the highest C/N ratio. Increased mineral soil C/N ratios have been associated with enhanced fertility in residue fertilized soils (Spycher et al., 1983) and with accelerated organic matter turnover rates (Kaffka and Koepf, 1989). The low LF turnover rates, inferred from low respiration rates, and small WDOC pool size in the cover-cropped soil suggested that the greater retention of SOM was linked to differences in the extent to which labile SOM was chemically stabilized or physically protected (Ladd et al., 1985).

The similarity between C turnover rates of LF and total soils in the conventional and cover-cropped treatments (corrected on a per-C basis) and other results (Wander et al., 1993, unpublished data), suggest that the chemical composition of their SOM was similar. Both of these treatments introduce only plant-derived residues to the soil. The primary difference between these two cash-grain-based treatment soils was the quantity of SOM present in each. During the 10-yr experiment, the conventionally managed soil did not accumulate SOM and, ultimately, had the smallest particulate SOM pool. Accordingly, it had the lowest levels of biological activity (soil respiration rates) and nutrient supply potential (available and mineralized N). In addition, the WDOC contents were higher in the conventionally managed soil than in the cover-cropped soil. They were also higher in the manure-amended soil. Soil organic matter loss through downward transport may be a factor contributing to differences in the SOM status of the FST soils.

Active SOM characteristics provide indirect evidence that the microbial ecology of the experimental soils varied. In general, soil respiration rates reflect the availability of SOM for microbial growth and maintenance and are a measure of basic microbial turnover rates in soils (Insam et al., 1991). Respiration is an indirect measure of the microbial biomass, when no other factor is limiting; CO_2 evolution rates have been suggested as a proxy measure of the active SOM pool (Paul, 1984). There is a positive correlation between crop yields and the proportion of all C in the microbial biomass (Insam et al., 1991). The proportion can be affected by management practices (Insam, 1990). The relatively elevated soil N supply characteristics and respiration rates present in the two organic treatment soils are consistent with other findings, suggesting that mixed-crop rotations increase the proportion of C in the biomass (Anderson and Domsch, 1989). Carbon dioxide evolution rates per mass C also followed this trend. Despite their greater biological activity, the organically managed soils maintained or accumulated C. If SOM losses (mineralization, CO_2 evolution, leaching, and translocation) were not offset by organic matter inputs, then net organic matter, microbial biomass, and activity would have declined (Jenny, 1980; Woods, 1989). Several aspects of the FST may have led to the faster C turnover rates in the two organically managed soils. Both the animal-based and cover-cropped treatments were rotary hoed and ridge cultivated. However, the animal-based treatment received less primary tillage than the other two rotations: it was moldboard plowed four times in 5 yr while the other two treatments

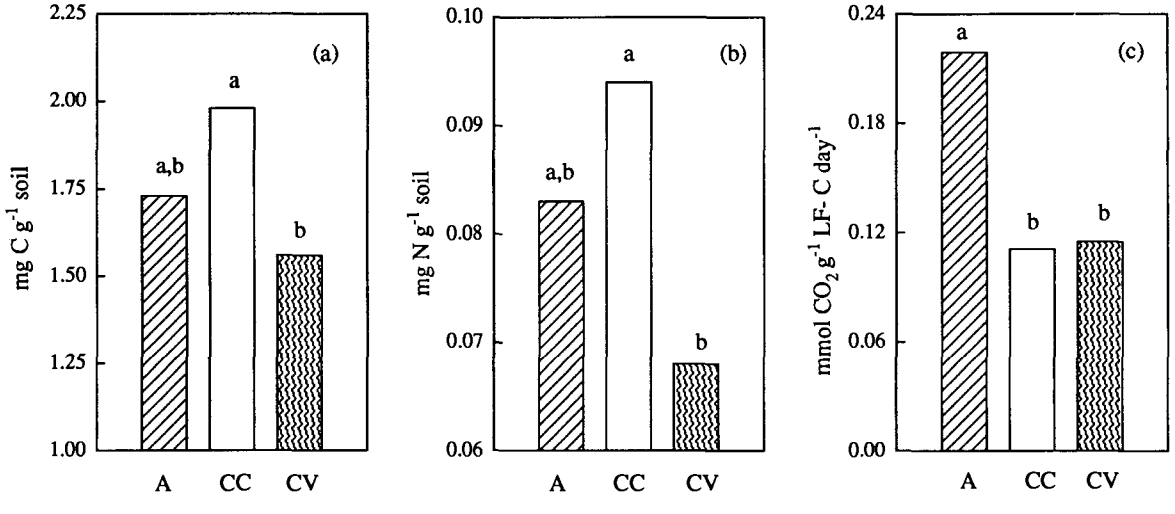

Fig. 4. Average soil light fraction (a) C and (b) N contents and (c) the relative light fraction (LF) stimulation of soil respiration rates (rate of CO_2 evolution increase normalized by the mass of LF C applied) in animal-manure-based (A), cover-cropped (CC), and conventional (CV) rotation treatment soils. Different letters indicate significantly different seasonal averages. Statistics were based on Fisher's protected LSD ($P < 0.05$); N statistics were performed on log-transformed data.

were plowed every year. Increased tillage generally stimulates organic matter mineralization, and thereby improves soil nutrient supply; this generally reduces organic matter accumulation. The enhanced microbial metabolism and SOM status in the organic treatments may be connected to the greater presence of live plants in these treatments. The animal-based and cover-cropped treatment soils had live-plant cover a greater proportion of the year (73 and 70%, respectively) than did the conventional soil (42%) (Peters et al., 1992). In these soils the rhizosphere, or active root zone, was extended through time. The size and extent of the root mass, which is a major factor controlling C inputs and turnover, in the FST treatment soils is not known. Pallant (1991) found that in the FST corn-producing plots, the quantity of fine roots was greater in the organically managed soils than in the conventional soil. Roots can stimulate decay of adjacent SOM (Cheng and Coleman, 1990) and can foster SOM protection by increasing soil aggregation (Dormaar and Foster, 1991). Further work investigating the contribution of roots, which definitely contribute to biologically active SOM, to the FST C and N budgets, is needed.

Success of Active Fraction Measures

Several variables investigated in this study successfully documented important differences in SOM characteristics of the FST soils. Soil N supply (available inorganic and mineralized N) and CO_2 evolution assays appeared to measure the same active SOM pool. A close relationship between these parameters has been documented elsewhere (Castellanos and Pratt, 1981). They are better determinants of the biological lability of the active SOM pool than of its overall size (Sorensen, 1983). In some soils, the LF has been closely associated with the active SOM pool and has been successfully used as an assay of nutrient availability (Dalal and Mayer, 1987; Janzen, 1987). Loss of particulate SOM is an important aspect of SOM degradation. Soil particulate organic matter contents declined in newly cropped soil and were lower in conventionally tilled than in no-tilled soils (Oades and Swinger, 1968; Cambardella and Elliott, 1992). Our study suggests that particulate organic matter characteristics may also serve as early indicators of SOM aggradation. Particulate organic matter accumulated as SOM was restored in the cover-cropped soil. Accumulated LF is an important C and nutrient reservoir in soils. The intermediate turnover times associated with LF materials are appropriate for nutrient supply demands in agricultural systems. Jenkinson and Rayner (1977) assigned nonliving active SOM and the soil biomass similar turnover rates (1.65 and 1.69 yr, respectively); however, they assigned resistant plant materials slightly longer turnover times (2.31 yr). The LF (particulate organic matter fraction) best characterizes this more stable yet biologically important SOM pool (Tiessen et al., 1984; Cambardella and Elliott, 1992). On average, in this study, there was roughly three times more N in the particulate SOM fraction than was present in the soil solution as available inorganic N. The LF data indicated that the cover-cropped soil accumulated more slowly metabolized plant material than either of the other treatment soils.

The biological lability (C/N ratio and ability to drive respiration) of the LF produced information similar to that obtained from other active fraction measures (soil respiration and N supply indices). Measures of LF characteristics were less sensitive to temporal (data not shown) and management perturbations than were the other active fraction parameters. Whole soil respiration rates and available and mineralized N were expected to be positively related to WDOC, as they have been shown to be elsewhere (McGill et al., 1986; Norman et al., 1988). In this study, trends in WDOC did not agree with other measures. The small treatment-based difference in SOM conservation or accumulation could be associated with differences in the extent to which active SOM was stabilized or protected (Ladd et al., 1985). Differences in WDOC could indirectly reflect physico-chemical aspects of SOM retention and represent the various soils' abilities to stabilize labile SOM.

CONCLUSION

After 10 yr, the FST experiment established different active SOM characteristics in the soils underlying its three rotation treatments. Net changes in the SOM contents of the FST soils were small; these changes were on the order of a few tenths of a percent (2.27–2.34% C in the animal-based treatment soil). This bulked approximation of soil organic matter content is not an adequate measure of the important changes in SOM characteristics that occurred in soil organic matter at the Rodale site.

Two kinds of organic matter change can be associated with the organic FST rotation treatments: accumulation of biologically active SOM and of more stable, yet still labile, SOM. The biologically active SOM was most closely associated with soil N supply and indirect measures of the soil biomass, whereas the less active labile SOM pool was revealed by measures of the particulate SOM fraction. We conclude the animal-based rotation improved the quality of active organic matter based on apparent rates of SOM turnover and biological activity, which were greater in this soil than in soil receiving strictly plant-derived residues. The cover-cropped treatment principally increased the quantity of SOM. Results from this study suggest that SOM accumulated in the cover-cropped soil was more stable than organic matter in the animal-based soil. Even though respiration rates were greater in the cover-cropped soil than in the conventionally managed soil, and even though it received the least total C (based on inputs of aboveground residues), it was a better net C sink. Its SOM accumulation was linked to the accumulation of particulate SOM. Chemical recalcitrance was discounted as a cause of LF accumulation because mineralization assays indicated that the cover-cropped and conventional LF materials were similar. The higher WDOC contents of the animal-based and

conventional treatment soils indirectly suggested that SOM may have been less well protected (from leaching loss and microbial usage) in these soils than in the cover-cropped soil. It is proposed that SOM was conserved to a greater degree in cover-cropped soil because of greater physical protection of active SOM.

Results suggest that the LF is a functionally important SOM pool. Assays of particulate organic residues effectively characterized both the quality (biological lability) and quantity of active SOM in the FST soils.

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