

Water-Stable Aggregates and Organic Matter Fractions in Conventional- and No-Tillage Soils

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ABSTRACT

No-tillage (NT) practices can improve soil aggregation and change the distribution and retention of soil organic matter (SOM) compared with conventional tillage (CT), but the relationships between aggregates and SOM fractions are poorly known. The effects of long-term (13-yr) CT and NT management on water-stable aggregates (WSA) and aggregate-associated SOM were investigated on a Hiwassee sandy clay loam (clayey, kaolinitic, thermic Rhodic Kanhapludult). Samples were collected at two depths in replicated CT and NT plots and separated into five aggregate size classes by wet sieving. The stability of intact WSA was measured turbidimetrically. The C and N content of total, particulate (POM), and mineral-associated organic matter was determined for each size class. Whole-soil organic C was 18% higher in NT (30.7 Mg C ha⁻¹) than in CT (26.1 Mg C ha⁻¹). In CT, macroaggregates (>250 μ m) were fewer and less stable than those of NT. The POM C made up \approx 36% of whole soil C regardless of tillage, but the quantity of POM was nearly 20% higher in NT than in CT. The POM comprised a higher percentage of total aggregate N in surface soils of NT than in CT and values increased with increases in aggregate size. In NT, concentrations of total and mineral-associated C and N were higher in the 106- to 250- μ m WSA than in the other size classes but, in CT, the concentrations were similar among size classes. An alternative view of aggregate organization is discussed in which microaggregates are formed in association with POM at the center of macroaggregates, helping to explain relationships between SOM storage and aggregate size distributions under different management practices.

CULTIVATION of soils results in the disruption of soil aggregates and the loss of SOM compared with native sod and pasture soils (van Veen and Paul, 1981; Tisdall and Oades, 1982; Elliott, 1986; Kay, 1990). Under CT practices, plowing, harrowing, and rotary tillage result in mixing of the soil profile and the fragmentation and burial of crop residues. These effects tend to moderate the fluctuations of temperature and water in buried residues and increase their proximity to mineral nutrients, thereby enhancing residue decomposition and organic matter transformations (Blevins et al., 1984; Beare et al., 1992). With NT management, the soil is not plowed and crop residues accumulate on the soil surface as a mulch. Several studies have shown that if residues are not removed, NT management can improve soil aggregation and reduce losses of SOM that result from cultivation (Havlin et al., 1990; Carter, 1992; Weill et al., 1989). However, other studies report few changes in soil aggregation (Hamblin, 1980) and no effects on SOM content other than changes in the depth distribution of SOM with plowing (Angers et al., 1992; Carter and Rennie, 1982).

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Kaolinitic soils of the southeast USA are characterized by high dispersibility, a factor that may increase the susceptibility of cultivated soils to aggregate disruption, surface crusting, reduced infiltration, and erosion (Miller and Baharuddin, 1986; Sumner, 1992). In warm humid climatic regimes, these factors can contribute to rapid losses of SOM and a decline in the productivity of agricultural soils (Giddens, 1957; Bruce et al., 1990b; Sanchez et al., 1989).

Many studies have investigated relationships between whole SOM and WSA (e.g., Chaney and Swift, 1984; Kemper and Koch, 1966; Angers et al., 1992), but relatively few have attempted to isolate and characterize the SOM associated with WSA (Dormaar, 1983; Baldock et al., 1987; Monrozier et al., 1991). Knowledge of aggregate-associated SOM may be important to understanding how changes in aggregation under different tillage and residue management practices contribute to the accumulation and loss of SOM (Elliott, 1986; Gupta and Germida, 1988). These relationships are largely unknown for soils of the southeastern USA. Furthermore, understanding these relationships is crucial for evaluating the applicability of the hierarchical model of aggregate organization (Tisdall and Oades, 1982) to a broader range of soils and management conditions.

Both physical and chemical methods have been used to fractionate and characterize SOM. Although the limitations of these individual techniques are well known (Elliott and Cambardella, 1991; Duxbury et al., 1989), various combinations of physical and chemical separation techniques have been used to successfully characterize the chemical composition of primary organo-mineral particle-size fractions (Turchenek and Oades, 1979; Anderson et al., 1981; Tiessen and Stewart, 1983). Cambardella and Elliott (1992) recently described a simple method combining chemical dispersion with particle-size separation to isolate and subsequently characterize particulate and mineral-associated organic matter of native sod and agricultural soils from the Great Plains. Their results suggest that whole soil POM accounts for much of the SOM lost with cultivation of native sod and that NT practices can significantly reduce these losses.

In this study, we combined wet-sieving techniques for the isolation of WSA with the chemical dispersion and physical separation methods of Cambardella and Elliott (1992) to investigate relationships between soil aggregation and the location and composition of aggregate-associated SOM in CT and NT soils. Our objectives were to describe the effects of long-term CT and NT management of a double-cropped soil on (i) the size

Abbreviations: NT, no-tillage; SOM, soil organic matter; CT, conventional-tillage; WSA, water-stable aggregates; POM, particulate organic matter; HSB, Horseshoe Bend Experimental Area; FLPOM, floating particulate organic matter; ASI, aggregate stability index; ANOVA, analysis of variance.

distribution and stability of WSA and (ii) the quantity and composition of aggregate-associated organic matter.

MATERIALS AND METHODS

Site Description and Soils

Soils were sampled from the long-term (13-yr) CT and NT plots at the HSB located in the Piedmont of the southern Appalachian Mountains near Athens, GA (33° 54'N, 83° 24'W). The mean annual precipitation of the area is 1270 mm and potential evaporation is 1564 mm. The soil at this site is a well-drained sandy clay loam (66% sand, 21% clay) in the Hiwassee series. Some general properties of the soils are given in Table 1. The experimental plots (0.1 ha) were established in 1978 with replicated ($n = 4$) tillage treatments assigned in a completely randomized design. The CT plots were moldboard plowed, disked, and rotary tilled (0–15 cm) twice annually to incorporate crop residues and prepare the seed bed. In most years, plots were double cropped to grain sorghum [*Sorghum bicolor* (L.) Moench] and winter rye (*Secale cereale* L.). Summer crops were direct drilled, and winter crops were broadcast seeded. Weeds were controlled with a single annual application of glyphosate [isopropylamine salt of *N*-(phosphono-methyl)glycine, 6 L ha⁻¹] prior to summer planting. The plots have generally received 100 kg N ha⁻¹ (as NH₄NO₃), 10 kg P ha⁻¹, and 20 kg K ha⁻¹ at summer planting. Further details on the treatment histories at this site can be found in Stinner et al. (1984) and Beare et al. (1992).

Samples were taken from the replicate NT and CT plots on 2 May 1991, ≈ 2 wk prior to harvesting the winter cover crop. No residues were removed. Six replicate soil cores were collected randomly from each plot with a thin-walled steel cylindrical corer fitted with a removable plastic insert (5.8-cm i.d.). The intact cores were sectioned into 0- to 5- and 5- to 15-cm increments and composited by depth. Soils were stored field moist (3 °C) in crush-resistant air-tight containers prior to analysis (<2 wk). All samples were presieved (10-mm diam.) prior to wet sieving to remove stones and crop stubble and to define the initial dimensions of the aggregates for analysis. In presieving, soils were gently teased apart by hand and the peds were broken along fissures of least resistance to pass the presieve openings.

Aggregate Distributions

The distributions of WSA were measured using a modified Yoder (1936) wet-sieving apparatus that was designed to handle larger masses of soil on stacked sieves (21.6-cm diam.) and to allow for complete recovery of all particle fractions from individual samples (Beare and Bruce, 1993). Five aggregate size classes were collected from duplicate analyses of each field-moist soil, including aggregates >2000, 250 to 2000, 106 to 250, 53 to 106, and <53 μm in diameter. Samples were tension wetted on the sieves by placing a moist filter paper

disk between the top sieve (2000 μm) and the tension plate. Soils were evenly distributed over the sieve surface (<0.60 g soil dry-weight equivalent cm⁻²) and wetted at constant head (3.0 cm of H₂O) for 15 min prior to wet sieving. Only sieves with mesh openings ≥ 250 μm in diameter were oscillated in the water columns (300 s, 0.52 cycles s⁻¹, 2-cm stroke length).

Following wet sieving, the water columns were drained and particles <250 μm in diameter were collected on a stack of finer sieves. To minimize losses in handling, aggregates were first dried on the sieves in a dehumidifying chamber (10 °C, 24 h), then transferred to beakers, oven dried (105 °C), and weighed. Particles <53 μm in diameter were collected in a bucket and flocculated (24 h) with CaCl₂ (0.1 M); the supernatant was removed and the particles dried. The dry masses of primary particles (greater than the original sieve size) and sand (>53 μm) were determined for each aggregate fraction after dispersion in 0.05 M NaOH.

Aggregate-Associated Organic Matter

Intact WSA were collected from a separate wet sieving of each soil sample. The soils were treated as above with two primary differences. First, following their oscillation, the sieves were lowered to the bottom of the stroke and the FLPOM (density <1.01 g cm⁻³) carefully aspirated from the surface before draining the cylinders. The FLPOM was collected on a 53-μm-diam. sieve, rinsed with deionized water, and dried at 50 °C (48 h), and the weight was recorded. Second, the intact dehumidified aggregates were dried at 35 °C (48 h), weights were recorded, and these aggregates were stored in crush-resistant containers. Subsamples of FLPOM and WSA fractions (0.25–2.0 g) were dried at 105 °C (24 h) to allow correction to a final dry weight.

Aggregate-associated POM was determined following the methods described by Cambardella and Elliott (1992) for bulk soils. Subsamples of intact aggregates (5–20 g) were combined with threefold volumes (15–60 mL) of 5 g L⁻¹ sodium hexametaphosphate and shaken for 12 h on a reciprocal shaker. The dispersed organic matter plus sand was collected on a 53-μm-mesh sieve, washed four times with deionized water, and dried at 50 °C (48 h), and the weights were recorded.

The FLPOM, aggregate-associated POM, and subsamples of whole aggregates were ground to a fine powder in a mill (Spex Industries, Edison, NJ). Their total C and N contents were determined by Dumas combustion on a Carlo Erba C/N Analyzer (Carlo Erba Instruments, Milano, Italy). Residual hexametaphosphate does not influence the recoveries of C and N by Dumas combustion.

Aggregate Stability Indices

The stability of intact WSA was measured by a turbidimetric clay dispersion method adapted from Williams et al. (1966). Subsamples of approximately 1.5, 1.0, 1.0, and 0.35 g of the >2000-, 250- to 2000-, 106- to 250-, and 53- to 106-μm

Table 1. Some physical and chemical properties of conventional-tillage (CT) and no-tillage (NT) soils at the Horseshoe Bend Experimental Area.

Depth	Organic C†		Organic N†		Bulk density		CEC‡		pH§	
	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT
cm	g kg ⁻¹									
0–5	24.6	13.5	2.12	1.20	1.20	1.38	8.72	5.32	7.05	6.78
5–15	10.5	11.1	0.87	1.01	1.52	1.51	5.31	5.67	6.80	6.98
	Mg m ⁻³									
	cmol _c kg ⁻¹									

† Determined by Dumas combustion on a Carlo Erba C/N analyzer.

‡ Cation-exchange capacity calculated from the concentration of KCl-extractable NH₄ after saturation with NH₄OAc.

§ Measured by glass electrode in a 1:1 soil/water (w/v) solution.

aggregate size classes, respectively, were weighed into glass tubes (16 by 125 mm) and held overnight in a humidifying chamber (30°C). The samples were then slowly wetted with deionized water, bringing the tubes to full volume (≈ 17 mL), and capped to exclude air bubbles. The tubes were shaken end over end (20 rpm, 0.5-m rotation diam.) for 30 min and allowed to settle for 10 min. The surface 5 mL was transferred to a 50-mL tube and diluted 1:10 in deionized water containing sodium hexametaphosphate (0.357 g L^{-1}). After 1 h of settling, a 2-mL sample was collected from a calculated depth and transferred to a spectrophotometer tube and the impedance of clay-sized particles (by Stokes' Law) to light transmittance (at 620 nm) was measured spectrophotometrically. The maximum potential clay dispersion was measured in each aggregate fraction after complete dispersion in sodium hexametaphosphate (3.57 g L^{-1}). The dispersed samples were settled for 10 min; the surface 5 mL were transferred to a 50-mL tube and diluted 1:10 with deionized water. After 1 h of settling, a 2-mL sample was collected from a calculated depth and transferred to a spectrophotometer tube and the transmittance was recorded. The ASI was calculated as

$$1 - [(100 - T_{30}) / (100 - T_d)]$$

where T_{30} is the percentage transmittance after 30 min of shaking and T_d is the percentage transmittance after complete dispersion. Values range from 0 to 1, with lower values indicating greater susceptibility to clay dispersion and lower aggregate stability.

Statistical Analyses

The data were analyzed statistically using ANOVA, with nesting of plot within tillage. In cases where the results were complicated by multiple interactions, the differences between tillages were compared by a two-tailed *t*-test. The analyses were accomplished using SuperANOVA and StatView SE+Graphics (Abacus Concepts, 1987, 1989).

RESULTS

The distribution of WSA from surface samples (0–5 cm) was significantly influenced by tillage practice (Fig. 1). Macroaggregates $>2000 \mu\text{m}$ in diameter made up the largest percentage of the whole soil, and these aggregates were nearly 1.5 times greater ($P < 0.05$) in NT than in CT. The smaller WSA size classes, especially the 250- to 2000-, 106- to 250-, and $<53\text{-}\mu\text{m}$ aggregates, made up a greater proportion of the surface soil in CT than in NT. There were no significant differences in the distributions of WSA from deeper samples (5–15 cm) of both NT and CT.

The stability of intact WSA, as measured by the ASI, was significantly ($P < 0.05$) affected by tillage practice, soil depth, and aggregate size class (Fig. 1). The ASI was significantly higher for all size classes $>106 \mu\text{m}$ in diameter from surface samples of NT than of CT. There

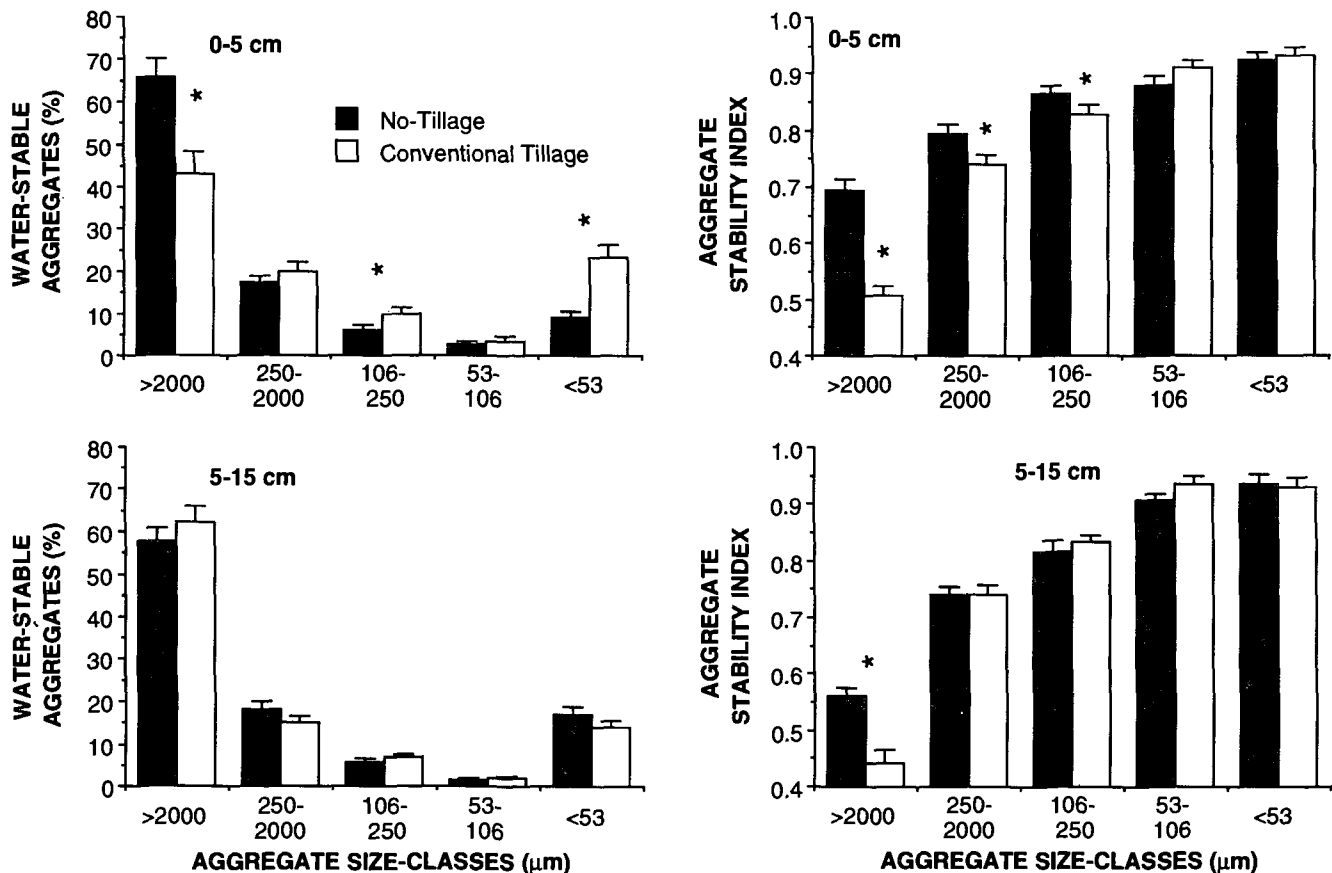


Fig. 1. Distributions and stabilities of intact water-stable aggregates from conventional- and no-tillage soils at 0- to 5- and 5- to 15-cm depths. Bars are means ± 1 standard error; $n = 4$. Asterisks indicate significant differences ($P < 0.05$, two-tailed *t*-test) between tillage treatments within size class and depth.

were no significant differences between tillages in the 53- to 106- and <53- μm size classes, and these aggregates were the least susceptible to disruption. In general, the stability of aggregates increased with decreasing size; however, the difference in the ASI of NT and CT was much greater in macroaggregate (>250- μm) than in microaggregate (<250- μm) size classes. There was a significant interaction of tillage and depth on ASI ($F_{1,2} = 75.2$; $P = 0.001$) that reflected the greater reduction in ASI with depth in NT than in CT.

The concentrations of C and N in aggregate size classes were strongly influenced by the different proportions of sand in each size class. Therefore, to describe interaggregate differences in C and N concentrations, as well as the effects of tillage and soil depth, all values were normalized to a sand-free basis (Fig. 2). In the surface soils, sand-free concentrations of C and N were significantly affected by tillage, aggregate size, and their interaction ($P < 0.01$). Except for the <53- μm aggregates, total sand-free C ($F_{1,6} = 207$; $P = 0.0001$) and N ($F_{1,6} = 198$; $P = 0.0001$) were significantly higher in all WSA of NT (0–5 cm) than of CT. There were no significant effects of tillage on aggregate C and N at the 5- to 15-cm depth.

In the surface soils of NT, sand-free C and N were highest in the 106- to 250- μm aggregates, which were

1.58 and 1.56 times greater than the concentrations in the largest WSA (>2000 μm) and 5.36 and 4.38 times that of the <53- μm fraction. In CT, only the C and N content of the <53- μm WSA differed significantly from concentrations in other size classes. Although some differences in C and N content of WSA from 5- to 15-cm soils were significant and similar in pattern to the surface soil, the absolute differences between size classes were relatively small. Within size classes, the reduction in sand-free C and N content with depth was much greater in NT than in CT.

The concentrations of POM C and N in sand-free aggregates were significantly affected by tillage, depth, and size class ($P < 0.05$). In surface soils, sand-free concentrations of POM C ($F_{1,6} = 279$; $P = 0.0001$) and N ($F_{1,6} = 409$; $P = 0.0001$) ranged from 1.2 to 2.3 times greater in NT than in CT, irrespective of size class (Fig. 3). Unlike total aggregate C and N, the concentrations of POM C and N did not differ significantly between WSA >106 μm in diameter in either NT or CT. However, the POM content of 53- to 106- μm aggregates was only about one-third of that found in the larger size classes. Some differences between WSA were also found in the 5- to 15-cm soils. In 5- to 15-cm samples of CT, only the POM C and N content of the 53- to 106- μm WSA differed from the larger aggregates,

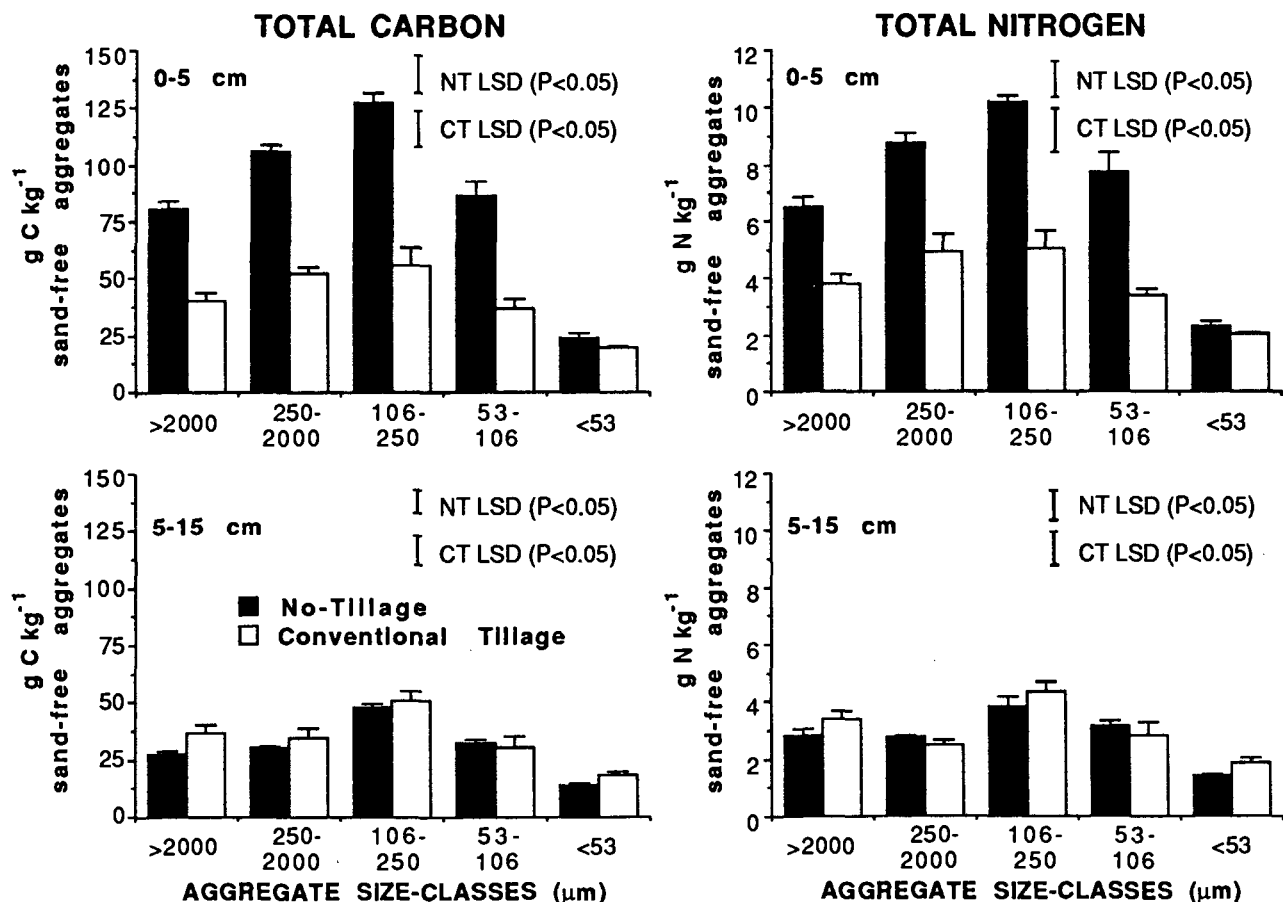


Fig. 2. Total C and N (g kg^{-1} ; normalized to a sand-free basis) in water-stable aggregates from 0- to 5- and 5- to 15-cm depths of no-tillage and conventional-tillage soils. Bars are means ± 1 standard error; $n = 4$.

while, in NT, the highest concentrations were in the 106- to 250- μm size class.

The mineral-associated organic matter of WSA was calculated as the difference between total aggregate C or N and POM C or N, respectively. With POM removed, the remaining mineral-associated organic matter showed even greater differences between tillages and size classes than did total aggregate C and N (Fig. 4). In surface soils, there was as much as a fourfold difference in mineral-associated C and N of WSA from NT, being highest in the 106- to 250- and 53- to 106- μm WSA and significantly lower in the smallest (<53- μm) and largest (>250- μm) aggregates. Mineral-associated organic matter in WSA of CT (0–5 cm) differed by less than a factor of two. There were no consistent effects of tillage in the 5- to 15-cm samples; however, the concentrations of mineral-associated C and N were higher in 106- to 250- μm WSA of CT than in any other size class. Except for the <53- μm WSA, which have no POM by definition, mineral-associated C and N ranged from 1.21 to 2.21 and 1.15 to 1.86 times greater in surface samples of NT than of CT.

In surface samples of both tillage treatments, POM increased as a percentage of the total aggregate C ($F_{3,18} = 75.2$; $P < 0.0001$) and N ($F_{3,18} = 55.2$; $P < 0.0001$) with increasing aggregate size (Table 2). A

similar pattern was observed at the 5- to 15-cm depth in CT, but in NT, POM in the >2000- and 106- to 250- μm size classes contributed the highest percentage of total aggregate C and N. In NT as compared with CT, POM N composed a higher percentage of total aggregate N in all size-classes except the 53- to 106- μm WSA ($F_{1,6} = 21.5$; $P = 0.0036$). For >2000- μm WSA, POM C was a significantly higher percentage of total aggregate C in CT than in NT, but there were no differences in the other size-classes. The most notable difference in the 5- to 15-cm soils was that POM C and N composed a much higher percentage of total aggregate C and N in the 106- to 250- μm WSA of NT than of CT.

The differences between NT and CT in aggregate-associated POM C and N were also reflected in the C/N ratios of POM and mineral-associated organic matter (Table 3). In surface samples, the C/N ratio of POM was consistently and significantly higher in WSA of CT than of NT ($F_{1,6} = 172$; $P = 0.0001$), but there were no consistent differences in the 5- to 15-cm soils ($F_{1,6} = 3.3$; $P = 0.120$). Alternatively, the C/N ratios of mineral-associated organic matter were higher in WSA of NT than of CT ($F_{1,6} = 29.0$; $P = 0.0017$). In general, there were much greater differences between size classes in the C/N ratios of mineral-associated organic matter

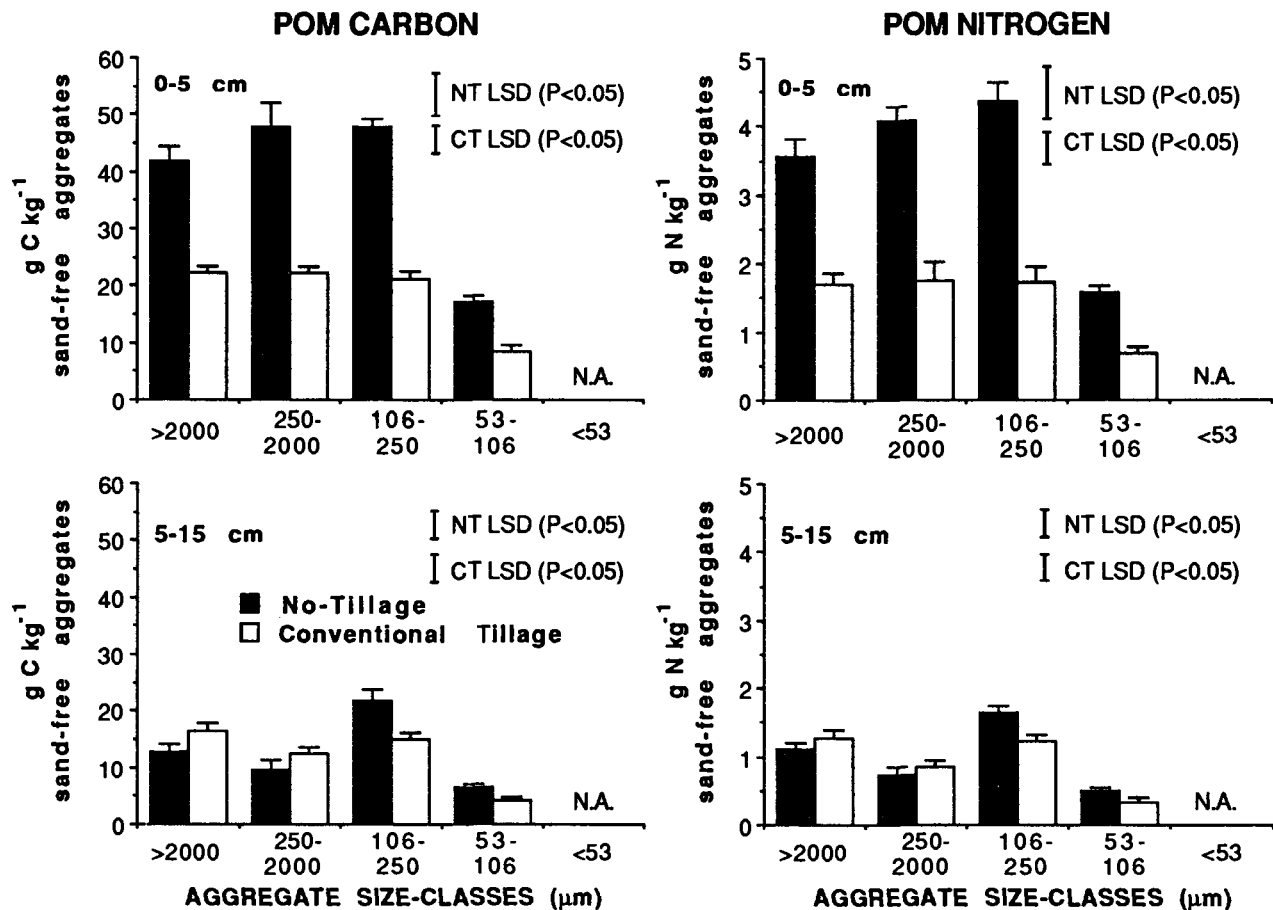


Fig. 3. Particulate organic matter (POM) C and N (g kg^{-1} ; normalized to a sand-free basis) in water-stable aggregates from 0- to 5- and 5- to 15-cm depths of no-tillage and conventional-tillage soils. Bars are means \pm 1 standard error; $n = 4$.

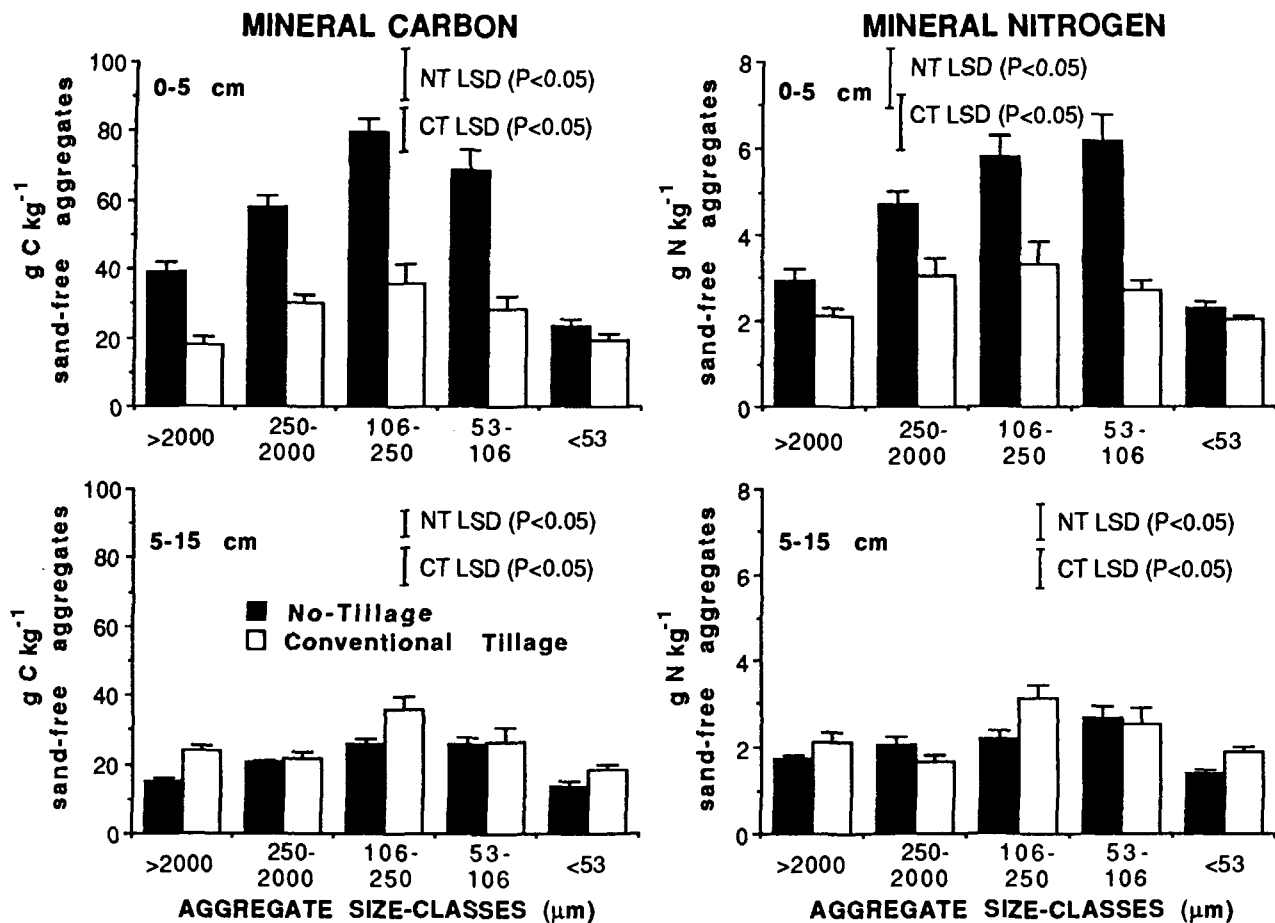


Fig. 4. Mineral-associated C and N (g kg^{-1} ; normalized to a sand-free basis) in water-stable aggregates from 0- to 5- and 5- to 15-cm depths of no-tillage and conventional-tillage soils. Bars are means \pm 1 standard error; $n = 4$.

than of POM. In CT, the C/N ratios of mineral-associated organic matter were relatively similar for the different size classes, although the ratios were lower in the very largest and smallest size classes at both depths. In NT, the C/N ratios of mineral-associated organic matter were widest in the 106- to 250- μm size class and generally narrowed with increases and decreases in aggregate size at both depths. The primary difference with depth in NT was that the largest aggregates (>2000 μm) from 0- to 5-cm soil depth had much wider C/N ratios than the same size class at 5- to 15-cm depth.

The distribution of aggregate-associated C and N was calculated by multiplying the quantity of whole soil representing each aggregate size class by the element concentrations, making corrections for differences in bulk density at each sample depth. These results showed that most of the whole-soil C and N in NT was associated with the largest macroaggregates (>2000 μm), being equally distributed between 0- to 5- and 5- to 15-cm soils (Table 4). In CT, however, there was significantly ($P < 0.05$) less C and N in WSA >250 μm in diameter compared with NT and much of the aggregate-associated C and N was localized in the >2000- μm WSA of 5- to 15-cm samples. As a percentage of whole-soil (0-15 cm) C and N, POM C and N were concentrated in the >2000- μm macroaggregates of the surface samples in NT and in the same size class of WSA from the deeper soils of CT. The somewhat coarser FLPOM that was

collected during the wet sieving of soils comprised <1.5% of whole-soil SOM and <4% of the POM.

The results of the correlation analyses for selected properties of aggregates are presented in Table 5. Sand-free concentrations of total, particulate, and mineral-associated C and N were not significantly correlated to ASI. However, mineral-associated C and N as a percentage of total C and N, respectively, were positively correlated with the ASI. The C/N ratio of POM was negatively correlated to mineral-associated SOM, especially mineral-associated N, but there was no significant correlation to the C/N ratio of mineral-associated SOM.

DISCUSSION

Thirteen years of CT and NT management at HSB have resulted in an 18% greater standing stock of soil organic C in the plow layer (0-15 cm) of NT (30.7 Mg C ha^{-1}) than of CT (26.1 Mg C ha^{-1}). Because the average annual inputs of aboveground crop plus weed residues to NT (6.6 Mg C ha^{-1}) and CT (6.7 Mg C ha^{-1}) were very similar, the differences in SOM content can best be attributed to differences in the assimilation and decomposition of SOM under the two tillage regimes. The results of this study show important differences in WSA distributions and aggregate-associated organic matter of NT and CT soils that may help to explain their differences in organic matter retention.

Table 2. Particulate organic matter (POM) as a percentage of total aggregate C and N in water-stable aggregates of conventional-tillage (CT) and no-tillage (NT) soils at the Horseshoe Bend Experimental Area.

Aggregate size class	POM C		POM N	
	NT	CT	NT	CT
μm	%†			
	0-5-cm depth			
>2000	51.8	65.2	55.3	44.5
250-2000	45.2	42.7	46.4	37.2
106-250	37.6	38.2	42.9	35.3
53-106	20.5	23.7	20.8	20.6
<53	NA‡	NA	NA	NA
LSD(0.05)§	4.6		4.9	
	5-15-cm depth			
>2000	45.6	41.0	38.8	38.5
250-2000	31.9	37.2	27.0	33.9
106-250	45.5	30.3	43.1	28.3
53-106	20.0	14.7	15.6	12.7
<53	NA	NA	NA	NA
LSD(0.05)§	5.6		5.6	

† Values are POM C and N as a percentage of total aggregate C and N content, respectively.

‡ Not applicable.

§ Fisher's least significant difference values for comparing means within depth.

Although it is well known that SOM contributes in important ways to soil physical properties (Tisdall and Oades, 1982), aggregate stability is often weakly correlated to total SOM (Chaney and Swift, 1984). Changes in aggregate distributions and stabilities often occur before significant declines in total SOM are detected following cultivation of native sod or pasture soils (Baldock et al., 1987; Haynes and Swift, 1990; Angers et al., 1992). In this study, we observed a reduction in the largest macroaggregates (>2000 μm) from surface soils of CT and a redistribution of particles into smaller size classes compared with NT, but there were no differences in the

Table 3. Carbon/nitrogen ratios of total, particulate, and mineral-associated organic matter in water-stable aggregates of conventional-tillage (CT) and no-tillage (NT) soils at the Horseshoe Bend Experimental Area.

Aggregate size class	Total organic matter		Particulate organic matter		Mineral-associated organic matter	
	NT	CT	NT	CT	NT	CT
μm	0-5-cm depth					
>2000	12.4	10.5	11.7	13.3	13.5	8.3
250-2000	12.8	11.7	11.7	12.7	12.8	10.1
106-250	12.6	11.4	11.0	12.3	13.8	10.9
53-106	10.9	10.6	11.0	12.3	11.2	10.4
<53	10.2	9.7	NA†	NA	10.2	9.7
LSD(0.05)‡	0.6		0.8		1.0	
	5-15-cm depth					
>2000	11.5	11.7	11.6	12.9	8.8	10.6
250-2000	11.0	11.4	13.0	14.9	10.3	12.9
106-250	13.3	13.4	13.3	12.4	12.0	11.3
53-106	10.0	10.9	13.1	12.5	9.7	10.5
<53	9.9	9.7	NA	NA	9.9	9.7
LSD(0.05)‡	1.0		0.9		1.2	

† Not applicable.

‡ Fisher's least significant difference values for comparing the means of aggregate size classes and tillage within depth.

distributions of WSA from deeper samples. Whereas several studies have shown increases in macroaggregate stability after three or more years of reduced tillage compared with CT management (Weill et al., 1989; Bruce et al., 1990a; Carter, 1992), reductions in the stability of CT macroaggregates appear to account for most of the differences in WSA distributions between tillages in this study. The disruption of aggregates by tillage may be countered by a transient increase in aggregate stability resulting from the flush of microbial activity that follows cultivation and the burial of crop residues (Molope et al., 1987). This effect may persist at a depth

Table 4. The distribution of total aggregate C and N and particulate organic matter (POM) C and N as a percentage of whole-soil (0-15-cm) C and N in water-stable aggregates of conventional-tillage (CT) and no-tillage (NT) soils at the Horseshoe Bend Experimental Area.

Aggregate size class	Aggregate C			Aggregate N			POM C/whole-soil C			POM N/whole-soil N		
	NT	CT	P < 0.05	NT	CT	P < 0.05	NT	CT	P < 0.05	NT	CT	P < 0.05
μm	g m ⁻²											
	0-5 cm-depth											
FLPOM†	25	18	*	1.7	1.4	*	0.8	0.7		0.6	0.6	
>2000	895	376	*	71.9	35.7	*	15.1	8.1	*	14.6	7.5	*
250-2000	329	244	*	25.6	20.8	*	4.5	3.6	*	4.4	3.5	*
106-250	129	111		10.2	9.7		1.6	1.5		1.6	1.5	
53-106	47	37		4.3	3.5		0.2	0.2		0.2	0.2	
<53	45	77	*	4.4	7.9	*	NA‡	NA		NA	NA	
Total	1469	863	*	118.2	79.0	*	22.2	14.1	*	21.4	13.3	*
	5-15-cm depth											
FLPOM	7	16	*	0.5	1.2	*	0.2	0.6	*	0.2	0.6	*
>2000	867	1047	*	75.5	89.2	*	9.6	16.1	*	9.3	15.3	*
250-2000	239	214		21.7	18.8		2.4	3.0		2.1	2.5	
106-250	136	155		10.2	11.6		1.7	1.6		1.5	1.5	
53-106	22	24		2.2	2.2		0.1	0.1		0.1	0.1	
<53	151	120		13.3	10.4		NA	NA		NA	NA	
Total	1422	1576		113.4	133.4		14.1	21.4	*	13.2	20.0	*
	0-15-cm depth											
Total	2891	2439	*	241.6	212.4	*	36.3	35.5		34.6	33.3	

* Significant differences (two-tailed *t*-test) at the *P* < 0.05 level between tillage treatments within aggregate size classes.

† FLPOM, floating particulate organic matter.

‡ Not applicable.

Table 5. Partial correlation matrix for selected properties of water-stable aggregates from conventional-tillage and no-tillage soils of both sample depths.

	Total‡		POM‡		Mineral-associated‡		Mineral/total§		Mineral-associated C/N	POM C/N
	C	N	C	N	C	N	C	N		
Min./total C§	-0.15	-0.12	-0.54**	-0.48**	0.16	0.22				
Min./total N§	-0.44**	-0.40	-0.78†	-0.74**	-0.13	-0.01	0.90†			
Mineral C/N	0.65***	0.57**	0.61**	0.62**	0.59**	0.41**	0.01	-0.39**		
POM C/N	-0.65**	-0.70**	-0.46	-0.53	-0.69**	-0.73***	-0.12	-0.09	-0.12	
ASI¶	0.22	0.22	-0.09	0.05	0.41	0.42	0.73†	0.56***	0.27	-0.15

** , *** , † Significant at 0.01, 0.001, and 0.0001 probability levels, respectively.

‡ Correlations were based on concentrations normalized to a sand-free basis; POM = particulate organic matter.

§ Mineral-associated C or N as a percentage of total aggregate C or N, respectively.

¶ ASI, aggregate stability index.

where the soil is not subjected to the dispersive energy of raindrop impact (Sumner, 1992) and the slaking that results from rapid wetting (Adu and Oades, 1978). These factors may explain the reduction in macroaggregates in 0- to 5- compared with 5- to 15-cm samples of CT.

With the use of tension wetting procedures, the distributions of WSA in NT and CT soils were not as different as expected, particularly at depth. However, the stability indices showed that intact macroaggregates from CT were much less stable than those from NT, reflecting their greater susceptibility to dispersion. Similarly, Elliott (1986) found few differences in the distributions of aggregates from native sod and long-term cultivated soils when wetted gradually (misted), but macroaggregates of the cultivated soils were much more susceptible to slaking. Haynes and Swift (1990) also found decreases in aggregate stability with increasing time under arable cropping compared with long-term pasture soils.

Previous studies that used turbidimetric measures of aggregate stability have shown that the amount of dispersible clay is a function of both clay and organic matter content (Pojasak and Kay, 1990). Others have stressed that various ligands, including organic anions that form complexes with polyvalent metals, can increase the dispersion of clays by reversing the positive charge on clay surfaces (Oades, 1984; Sumner, 1992). Repeated cultivation of soils enhances SOM decomposition, however, changing the composition of the residual organic matter. The result is a more soluble, aromatic organic matter with a higher content of acidic functional groups (e.g., higher fulvic/humic acid ratio) that substantially increases the susceptibility of cultivated soils to clay dispersion (Oades, 1984). The ASI used in this study normalizes the turbidimetric measures of suspended clay for the total dispersible clay and thus allowed us to compare the stabilizing influences of organo-mineral complexes of different size classes and soils independent of clay content. Our results confirm earlier observations that macroaggregates are much less stable than microaggregates (Edwards and Bremner, 1967; Tisdall and Oades, 1982). Although the differences in aggregate stabilities with depth reflect the general distribution of SOM in NT and CT, there were no significant correlations between the concentrations of aggregate-associated SOM and ASI. The only significant correlate to ASI was mineral-associated SOM (C and N) as a percentage of total aggregate SOM, possibly reflecting differences in

the degree of humification. This observation is consistent with the hypothesis that microaggregates are stabilized by more humified or highly processed SOM (Elliott, 1986), which may be an important constituent of mineral-associated SOM.

In the classic model of aggregate formation and organization, microaggregates are bound together by temporary (roots and fungal hyphae) and transient (polysaccharides) binding agents to form macroaggregates (Tisdall and Oades, 1982). Where macroaggregates are relatively stable and resistant to frequent disruption, the additional intermicroaggregate organic matter should increase macroaggregate concentrations of total sand-free C and N compared with that of free microaggregates. In this study, the total sand-free concentrations of aggregate C and N were 1.2 to 2.3 times higher in the surface samples of NT than of CT, but there were no significant differences between tillages in the deeper samples. Similarly, Elliott (1986) and Gupta and Germida (1988) observed that concentrations of C, N, and P were higher in aggregates of native sod than in those of long-term cultivated grasslands. Contrary to expectation, however, our results show that total sand-free concentrations of C and N were highest in the largest microaggregates (106–250 μm) of NT and were significantly lower in both larger and smaller aggregate size classes. For the less stable aggregates of CT, concentrations of macro- and microaggregate SOM were much more uniform than in NT.

Oades (1984) and Elliott and Coleman (1988) discussed an alternative view of aggregate organization in which microaggregates are formed at the center of macroaggregates. Fragmented POM originating as organic debris of roots, fungal hyphae, and fecal matter may become incorporated within macroaggregates by, for example, the feeding and casting activities of earthworms and other soil fauna. During the decomposition of intraaggregate POM, organic matter fragments may become encrusted with microbial mucilages and clay particles, leaving the organic matter increasingly occluded and inaccessible to microbial attack. The microaggregates formed in this way, and subsequently released from macroaggregates by various chemical and mechanical stresses, should be relatively stable and enriched in SOM.

Our results provide support for this alternative model of aggregate organization, and we offer some further interpretations of these relationships. In this study, sand-free concentrations of POM C and N were highest in

aggregates $>106 \mu\text{m}$ in diameter. As a percentage of total aggregate C and N, POM was highest in the largest macroaggregates and generally declined with decreases in aggregate size. We suggest that the very largest microaggregates contain a high proportion of particles formed of POM encrusted with microbial mucilages and clay within the structure of macroaggregates. Consistent with our findings, microaggregates formed in this way would be relatively stable and contain relatively high sand-free concentrations of SOM. As the encrusted organic matter is decomposed, smaller, less organic-matter-enriched microaggregates ($53\text{--}106 \mu\text{m}$) are released. These $53\text{--}106\text{-}\mu\text{m}$ aggregates probably contain significant quantities of previously occluded and thus less highly processed organic matter. This suggestion is supported by the observation that unprotected pools of C in smaller microaggregates ($53\text{--}106 \mu\text{m}$) have much higher rates of mineralization than those of larger size classes (Beare et al., 1994). As this organic matter is further decomposed, smaller microaggregates ($<53 \mu\text{m}$) are released that have relatively low sand-free concentrations of SOM. The remaining clay- and silt-bound organic matter is probably highly humified and sequestered between mineral particles.

Studies of grassland soils have shown that cultivation results in a proportionally greater decline in POM than in mineral-associated organic matter (Tiessen and Stewart, 1983; Cambardella and Elliott, 1992). Despite differences in the quantity and quality of residues to replenish these pools, NT management can reduce the losses of whole-soil C and help to maintain a higher percentage of POM. In contrast to the findings of Cambardella and Elliott (1992), POM C and N were found in this study to be a relatively constant percentage of whole-soil C (36%) and N (34%), regardless of tillage practice. The differences in these findings may be due to differences in the quality and quantity of organic matter inputs during 20 yr of wheat (*Triticum aestivum* L.)–fallow rotation (Cambardella and Elliott, 1992) vs. 13 yr of double-cropped sorghum–rye (this study) in addition to differences in soil type, climatic regimes, and biological properties. Nevertheless, in this study, POM does not appear to be the only source of SOM lost under CT compared with NT practices. Rather, as described below, our results suggest that the association of POM with macroaggregates and their distribution in the soil profile may be more important factors in determining the retention of SOM in these soils.

In general, POM made up a much higher percentage of total aggregate N in surface soils of NT than of CT, and the values increased with increases in aggregate size. The POM C, on the other hand, was a higher percentage of total aggregate C in CT than in NT but only in the largest macroaggregates of surface soils. As a result, there were significant differences between tillage treatments in C/N ratios of both POM and mineral-associated organic matter. In surface samples, the C/N ratios of POM were generally lower in NT than in CT, while the reverse was true for mineral-associated organic matter. More variable differences were observed for deeper samples. In NT, the C/N ratio of mineral-associated organic matter was much higher in aggregates $>106 \mu\text{m}$ in diame-

ter which are those that are thought to contain significant quantities of less humified, more occluded organic matter than in smaller aggregate size classes. These differences in N partitioning and C/N ratios taken together suggest that POM of the largest macroaggregates ($>2000 \mu\text{m}$) may be a relatively greater source of available N in NT, while mineral-associated organic matter represents a greater source of N in $>2000\text{-}\mu\text{m}$ WSA of CT. A significant part of the mineral-associated organic matter in NT is probably protected from microbial attack by its physical isolation within macroaggregates (Beare et al., 1994).

The distribution of total aggregate-associated C and N was considerably different in NT than in CT. In NT, nearly 61 and 62% of the C and N (0–15 cm) were found in aggregates $>2000 \mu\text{m}$ in diameter, and this organic matter was equally distributed between 0- to 5- and 5- to 15-cm depths. In contrast, slightly less of the total aggregate-associated C (58%) and N (59%) was found in the $>2000\text{-}\mu\text{m}$ WSA of CT (0–15 cm) and nearly three-quarters of this organic matter was located in the 5- to 15-cm samples. The distribution of POM C and N among size classes and depths was considerably different from that of total aggregate C and N. In NT, 25% of the soil C (0–15 cm) was found as POM in $>2000\text{-}\mu\text{m}$ WSA and $>60\%$ of that POM was in the surface soils. While macroaggregate ($>2000\text{-}\mu\text{m}$) POM accounted for approximately the same percentage (24%) of whole-soil C in CT, the quantity of POM C (1423 g m^{-2}) in these aggregates was nearly 20% lower than in NT (1762 g m^{-2}) and two-thirds of it was located deeper in the plow layer. Very similar patterns of distribution were found for POM N.

The marked differences in the distributions of POM between depths in NT and CT may be attributed to several factors. In NT, considerable biological activity near the soil surface, including the activities of fungi (Doran, 1980; Beare et al., 1993, unpublished data), roots (Cheng et al., 1990), and soil fauna (Parmelee et al., 1990), probably helps to incorporate POM within macroaggregates and to increase their structural stability (Oades, 1984; Lee and Foster, 1991). The surface soils of CT are subject to much more variable conditions of temperature and moisture, limiting some biological activity to episodic events. These factors not only contribute to the more frequent disruption of soil aggregates, releasing the aggregate-protected SOM for mineralization (Elliott, 1986; Beare et al., 1994), but also to a lower production of aggregate-stabilizing agents such as soil carbohydrates (Angers et al., 1993; Beare et al., 1993, unpublished data). The significance of these micro- and macrobiotic influences on soil aggregation to the accumulation and loss of SOM deserves further study.

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