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No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil

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Abstract

Soil aggregation plays a crucial role in soil physicochemical and biological processes, thus influencing soil nutrient retention. It is possible to improve soil aggregation by choosing appropriate agricultural practices. The objective of this study was to evaluate the effects of tillage, crops and fertilizer sources on size distribution of water-stable aggregates (WSA) and nutrient concentrations in aggregate fractions. Soil samples were collected from field sites involving sixteen factorial combinations of tillage [conventional tillage (CT) or no-till (NT)], crop rotations [continuous maize (CC) or soybean/maize (SC)] and fertilizer sources (0, 15, 30 and 45 Mg wet weight ha^{-1} of composted cattle manure balanced with inorganic fertilizers). Aggregate fractionation was performed using a wet-sieving method. Four years after the treatments were established, the proportion of large WSA ($WSA_{>2\ mm}$) was greater in the NT system, suggesting that NT increased soil aggregation compared to the CT system. There was no difference in soil aggregation between continuous maize and soybean/maize rotations. The application of 30 and 45 Mg ha^{-1} $year^{-1}$ of composted manure produced more $WSA_{>2\ mm}$ than inorganic fertilizers. The $WSA_{>2\ mm}$ had a higher total C concentration in CT than NT soils, indicating that $WSA_{>2\ mm}$ formed in CT systems contained more soil organic matter (SOM) than those in NT systems. However, the difference disappeared when the data were expressed on a sand-free aggregate basis, indicating a dilution effect due to more sand in $WSA_{>2\ mm}$ from the NT system than the CT system. Total C, N and P concentrations were at least 3 times higher in water-stable microaggregates ($WSA_{0.25–0.053\ mm}$) than water-stable macroaggregates ($WSA_{>0.25\ mm}$). The $WSA_{0.25–0.053\ mm}$ fraction is considered to be a sink for these nutrients, but may also be susceptible to erosion. Transport processes that preferentially remove the $WSA_{0.25–0.053\ mm}$ fraction from agroecosystems could lead to nutrient loading in adjacent ecosystems. It was concluded that adopting no-tillage and applying composted manure increased soil aggregation and nutrient retention in a sandy-loam soil under maize production.

Keywords: Tillage; Manure application; Water-stable aggregates; Nutrient content

1. Introduction

Aggregated soil structure is the most desirable condition for plant growth (Hillel, 2004) because it has a beneficial influence on soil moisture status, nutrient dynamics, and soil tilth (Oades, 1984). It also reduces nutrient losses through soil erosion and surface runoff. According to the hierarchical model of aggregate organization developed by Tisdall and Oades (1982), roots and hyphae are the major binding agents for macroaggregates (>0.25 mm), while humic compounds promote microaggregate (<0.25 mm) formation. Agricultural practices influence the quantity and persistence of binding agents, which may lead to aggregate formation or breakdown. Thus, soil aggregation can be used to eval-

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uate agricultural management practices and select those that optimize crop growth and minimize soil nutrient loss. We are particularly interested in the interactive effects of tillage, crop rotation and fertilizer sources on aggregation.

Tillage disrupts soil aggregates mechanically and fragments roots and mycorrhizal hyphae, which are major binding agents for macroaggregates (Tisdall and Oades, 1982). In a tillage comparison experiment, Frey et al. (1999) reported that the length of fungal hyphae ranged from 19 to 292 m g^{-1} soil and was 1.9 to 2.5 times higher in NT than CT surface soil (0–5 cm). The proportion of fungi in the microbial biomass ranged from 10% to 60% and was greater in NT than CT surface soil (Frey et al., 1999). Also, tillage hastens SOM decomposition and reduces the soil carbon content by increasing the access of microorganisms to SOM upon aggregate destruction (Elliott, 1986; Oades, 1988; Six et al., 1999; Balesdent et al., 2000). Increased decomposition of SOM compounds that may otherwise serve as aggregate binding agents can, in turn, lead to a decline in aggregation (Carter, 1992). Beare et al. (1994) reported that soil (0- to 5-cm layer) from CT plots had fewer $WSA_{>2\ mm}$ (sand-free basis) and lower total C and total N concentrations than soil from adjacent plots under NT for the same length of time (13 years). Wright and Hons (2004) reported that NT management increased soil aggregation, produced higher concentrations of organic C and N (sand-free basis) in macroaggregates and stored more soil organic carbon (SOC) and soil organic nitrogen in the 0- to 15-cm depth than CT. The mulch layer that develops in NT systems likely protects soil aggregates from disruption due to wetting–drying, freezing–thawing and rainfall events. In addition, the greater presence of fungi, which have an important role in macroaggregate formation, and less physical disturbance from plowing and other agricultural activities may increase both aggregation and C storage in long-term NT systems (Hendrix et al., 1998; Six et al., 2000).

Crops can influence aggregation because their roots, especially fine roots, and organic substances released from the roots may contribute to aggregate formation. In addition, crops with a high water demand during growth period are expected to affect soil aggregation because water uptake by roots causes differential dehydration, shrinkage, and numerous small cracks (Hillel, 2004). Moreover, the C/N ratio and biochemical properties of crop residues that affect residue decomposition and SOM dynamics also influence soil aggregation (Martens, 2000). For example, growing barley (*Hordeum vulgare* L.) and alfalfa (*Medicago sativa* L.) for 2 years increased $WSA_{6–2\ mm}$ by 15%, compared to soils under maize (*Zea mays* L.) production (Angers and Mehuys, 1988). Cropping systems that include crop rotations are often beneficial for soil aggregation. Barley–forage rotation increased mean weight diameter (MWD) by 6.7% in mouldboard plowing system and 33.3% in chisel plowing system, compared to the barley monoculture (Bissonnette et al., 2001). Wright and Hons (2004) reported that a wheat–soybean (*Triticum aestivum* L.–*Glycine max* (L.) Merrill) rotation stored 36.7% more SOC and 40% more SON in the 5- to 15-cm layer under CT than a continuous monoculture soybean after 20 years.

Fertilizer applications often increase soil aggregation through their influence on crop production since more crop residues are returned to fertilized than unfertilized soils (Gregorich et al., 1996; Campbell et al., 2001). Manuring increases the C input to soil and consequently enhances SOC concentration (Jarecki and Lal, 2003). Follett (2001) estimated that application of manure in the U.S. would result in SOC sequestration at the rate of 200 to 500 kg C ha^{-1} $year^{-1}$. Composted manure applications up to 45 Mg ha^{-1} $year^{-1}$ for 2 years increased SOM and led to more $WSA_{>2\ mm}$ in CT and NT systems (Whalen et al., 2003).

It is clear that tillage, cropping systems and fertilizers all influence soil aggregation and soil nutrient dynamics. These factors need to be investigated together because crop production systems involve the simultaneous selection of tillage, crop rotation and fertilizer sources. There is limited information on the ways that management practices interact to affect aggregate stability and nutrient retention. Bissonnette et al. (2001) examined the interactive effects of management practices involving two crop sequences, two tillage systems and two nutrient sources on soil aggregation in a silty clay Humic Gleysol. They concluded that practices such as the application of liquid dairy manure, which increased the SOM content, also improved soil stability. However, the SOM content in the soil profile may be lower in NT systems than CT systems when solid animal manure is applied. For example, Paré et al. (1999) reported that SOC in the 0- to 15-cm layer of a silty-clay loam was lower in NT (56.6 g SOC kg^{-1}) than CT (61.5 g SOC kg^{-1}) soils after 3 years of applying stockpiled manure at a rate of 4.5 Mg ha^{-1} $year^{-1}$ (dry weight basis). Incorporation of solid manure by plowing in a CT system could increase the SOC level substantially. Whether soil aggregation is greater in NT or CT systems when the same rate of solid manure is applied to each system is not known.

The objectives of this study were: (i) to evaluate the interactive effects of tillage, crop rotation and fertilizer sources on the WSA size distribution in a sandy-loam soil; (ii) to determine total C, N and P concentrations in WSA size fractions.

2. Materials and methods

Soils in this study were collected from a field experiment located on the Macdonald Research Farm, Ste. Anne de Bellevue, Quebec, Canada (45° 28′ N, 73° 45′ W, elevation 35.7 m). Annual temperature at the nearby Dorval climate station averages 6.1 °C, with mean annual precipitation of 967 mm. The soil is a Typic Endoaquent with 15.4 g total C kg^{-1}, 1.24 g total N kg^{-1}, 0.92 total P kg^{-1} and pH 6.1 in the 0- to 15-cm sandy loam layer (containing, on average, 700 g sand kg^{-1}, 140 g silt kg^{-1} and 16 g clay kg^{-1}). Further details of the research site, and the effect of tillage, crop systems and fertilizer sources on soil fertility and soil physical properties have been reported (Carefoot and Whalen, 2003; Whalen et al., 2003).

2.1. Experimental design

Detailed information on the experiment layout, tillage methods, crop rotations and fertilizer sources have been reported by Jiao et al. (2004). Briefly, it was a factorial split-plot experiment consisting of two tillage systems (conventional and no-tillage) and three crop rotations (continuous maize, soybean/maize or maize/soybean; only one crop per year) as main plots (20 × 24 m), and four fertilizer treatments as split plots (20 × 6 m). The fertilizer treatments included inorganic fertilizer alone, composted cattle manure alone, and mixtures of inorganic fertilizer and compost that supplied 200 kg N ha^{-1} and 45 kg total P ha^{-1} in each plot (Table 1). The six factorial treatments, each containing four split-plot treatments, were arranged in a randomized complete block design with 4 blocks, for a total of 96 plots. The field experiment was established in May 2000, and samples for this study were collected four years later.

The conventionally tilled plots were tilled with a tandem disk (10 cm depth) each spring prior to seeding and with a mouldboard plough (20 cm depth) each fall after harvest, but there was no disturbance through tillage of the no-till plots. Composted cattle manure was applied on the soil surface and either incorporated with an offset disc harrow (CT treatment) or left on the surface (NT treatment) before seeding.

All plots were seeded with a row width of 76 cm. Silage maize (*Zea mays* L. 'Cargill 2610') and soybeans (*Glycine max* L. Merr. 'Cargill A0868TR') were planted in late May or early June each year from 2000 to 2003. Each plot under maize production received 200 kg N ha^{-1} in total, with 50 kg N ha^{-1} was from NH_4NO_3 banded at seeding. Additional NH_4NO_3 was sidedressed at the 4- to 5-leaf stage, depending on the amount of composted manure applied (Table 1). We estimated that 15 Mg ha^{-1} (wet weight) of composted manure would provide 50 kg ha^{-1} of plant-available N, 30 Mg ha^{-1} would provide 100 kg N ha^{-1}, and 45 Mg ha^{-1} would provide 150 kg N ha^{-1}. No NH_4NO_3 fertilizer was applied to soybean.

2.2. Water-stable aggregates

Soil samples were taken from the maize phase of CC and SC crop rotation systems (64 plots) of the field experiment in October 2003, after crop harvest. Surface residues (plant debris, unincorporated composted manure) were pushed aside before collecting soil cores. Three soil cores (10-cm-diameter cylinder) were taken to a depth of 10 cm diagonally across the plot at a distance of 19 cm from the crop row. Samples from 3 cores in each plot were combined, passed through a 6-

Table 1
Fertilizer treatments applied to maize and soybean plots at the experimental site, 2000–2003

Fertilizer treatment	Silage maize			Soybean		
	N fertilizer[a] (kg N ha^{-1})	P fertilizer[b] (kg P ha^{-1})	Manure[c] (Mg ha^{-1})	N fertilizer (kg N ha^{-1})	P fertilizer (kg P ha^{-1})	Manure (Mg ha^{-1})
Man0	200	45	0	0	45	0
Man15	150	30	15	0	30	15
Man30	100	15	30	0	15	30
Man45	50	0	45	0	0	45

[a] NH_4NO_3 applied at seeding (50 kg N ha^{-1} to all treatments) and sidedressed at the 4–5 leaf stage.
[b] Triple superphosphate applied at seeding.
[c] Composted cattle manure application (wet weight basis). 1 Mg ha^{-1} of composted manure supplied about 1 kg total P ha^{-1}.

mm sieve in the field, put into a flat-bottom paper bag and air-dried in the laboratory.

Fractionation of water-stable aggregates was performed using a wet-sieving procedure (Angers and Mehuys, 1993). A 100-g subsample of soil from each plot was spread evenly on the top of a nest of sieves with openings of 2, 1.0, 0.25 and 0.053 mm. Soil was prewetted by spraying with 20 ml of distilled-deionized water and left for 10 min to equilibrate. Sieves with moist soil were placed in a wet-sieving apparatus and immersed in distilled-deionized water for 10 min. Then, the soil was sieved for 10 min at a frequency of 29 cycles min^{-1} with a stroke length of 3.7 cm. Floatable plant residues were removed and discarded using a 1-mm mesh scoop during the sieving process since they were not part of soil aggregates or SOM (SSSA, 2001). Soil aggregates retained on each sieve were then transferred into a preweighed glass jar, oven dried at 65 °C for 3 days and weighed. Approximately 5-g subsamples of oven-dried aggregates were used to determine the primary particles (sand, gravel and other coarse fragments) in each size fraction following the procedure of Angers and Mehuys (1993). For example, the primary particles in the $WSA_{>2\ mm}$ fraction included gravel and other coarse fragments that remained on the 2 mm after wet-sieving the soil for 10 min, as described above, whereas primary particles in the $WSA_{0.25–0.053\ mm}$ fraction were sand and fragments that passed through a 0.25 mm sieve but were retained on a 0.053 mm sieve at the end of the 10 min wet-sieving procedure. The percentage of WSA in each size fraction to total WSA in 100-g soil sample was calculated as:

$$\mathrm{WSA}_i = \frac{i\text{th size fraction (g)} - \text{primary particle in the } i\text{th size fraction (g)}}{100\text{(g)} - \text{total primary particle (g)}} \times 100 \tag{1}$$

where $i=1$ to 4, representing the four aggregate size fractions (>2, 2–1, 1–0.25 and 0.25–0.053 mm). The quantity of primary particles in the ith size fraction was the sand, gravel and other fragments collected on sieves of the same size as the aggregate fraction. Total primary particle was the sum of all primary particle weights associated with the four aggregate size fractions.

The percentage of WSA smaller than 0.053 mm ($WSA_{<0.053\ mm}$) was calculated as:

$$\mathrm{WSA}_{<0.053\,\mathrm{mm}} = 100 - \sum \mathrm{WSA}_i \tag{2}$$

where $i=1$ to 4, representing the four aggregate size fractions described in Eq. (1), which are subtracted from 100%.

The mean weight diameter (MWD) of WSA in soils collected from each plot was calculated as:

$$\mathrm{MWD} = \sum X_i \mathrm{WSA}_i/100 \tag{3}$$

where $i=1$ to 5 and includes the four aggregate size fractions described in Eq. (1) plus the $WSA_{<0.053\ mm}$ fraction, and X is the mean intersieve size.

2.3. Total C, N and P in whole soil and aggregates

A subsample of the air-dried 6-mm soil and oven-dried aggregates from each size fraction was taken for total C, N and P analysis. After visible plant residues (about 1 mm length) were removed by hand with forceps (Sainju et al., 2003; Cambardella and Elliott, 1993), the subsample was finely ground in a mortar and pestle. Total C and N in whole soil and aggregate-size fractions were determined on a Carlo-Erba C and N analyzer (Milan, Italy). Total C is equivalent to organic C since there are no carbonates in this soil. Total P in whole soil and aggregate-size fractions was digested in hydrogen peroxides/sulfuric acid (Parkinson and Allen, 1975) and quantified colorimetrically with the ammonium molybdate–ascorbic acid method (Murphy and Riley, 1962) on a Lachat Quik-Chem AE flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI).

Unless otherwise stated, total C, N and P concentrations in whole soil and aggregate fractions were expressed on a primary particle-free basis. We think that it is more accurate to describe aggregate characteristics for primary particle-free aggregates[1] than sand-free aggregates[2] because all the sand embedded in an aggregate is part of it, according to the definition of a soil aggregate (SSSA, 2001). Total C, N and P in WSA fractions were thus calculated as (using C as an example):

$$\text{Total C}\left(\mathrm{g\,kg^{-1}}\right) = \frac{\text{Total C}\left(\mathrm{g\,kg^{-1}}\ i\text{th size fraction}\right)}{1 - \text{Proportion of primary particle in } i\text{th size fraction}} \tag{4}$$

where $i=1$ to 5 (see Eq. (3)) and the primary particle stands for the sand, gravel and other fragments that are the same size as the aggregate fraction (see Eq. (1)). We

[1] Aggregates excluding **only** the primary particles (sand, gravel and fragments) that are the same size as the aggregate fraction investigated.

[2] Aggregates excluding **both** the primary particles that are the same size as the aggregate fraction *and* the sand found inside the aggregate.

also determined the sand content in whole soil and the $WSA_{>2\ mm}$ fraction. First, we passed samples through a 2-mm mesh sieve to remove gravel and coarse fragments, and then measured the sand content by the hydrometer method (Ashworth et al., 2001). Total C in whole soil and the $WSA_{>2\ mm}$ fraction were then calculated on a sand-free basis using the method of Elliott (1986).

2.4. Statistical analysis

The statistical analysis was conducted with SAS GLM procedure (SAS Institute, 1999) based on the split-plot experimental design. The effects of tillage, crop rotation and the tillage × crop interaction on WSA distribution and nutrient concentrations were tested by using the main plot error term (Error I). Differences were considered significant at $P<0.05$. The effects of fertilizer treatments and interactions between main plot (tillage, crop) and split-plot (fertilizer) treatments on WSA distribution and nutrient concentrations were determined by using the split-plot error term (Error II) with a Student–Newman–Keuls (SNK) test at 0.05 level. The functional relationship between soil aggregation and soil C concentration was fitted using structural analysis (Webster, 1997).

3. Results and discussion

3.1. Size distribution of water-stable aggregates

The proportion of $WSA_{>2\ mm}$ is the most important fraction to evaluate the effect of management practices on soil aggregation because it exerts a strong influence on the MWD (Eq. (3)), a comprehensive index for evaluating soil aggregation (Angers and Mehuys, 1993). Four years after tillage treatments were imposed, we observed a significant increase in $WSA_{>2\ mm}$ and a significant improvement in soil aggregation as illustrated by MWD in the NT system, compared to the CT system (Fig. 1, Table 2). A similar result was obtained for a sandy-loam soil by Carter (1992), who found that the MWD of wet-sieved aggregates from a 3-year-old direct drill system (MWD = 3.52 mm) was significantly greater than that from soils that were cultivated each year with a mouldboard plow (MWD = 2.46 mm). It appears that reducing tillage intensity by adopting NT practices improved soil aggregation in the sandy loam soil at our study site within 4 years.

The application of composted cattle manure at rate of 30 Mg ha^{-1} $year^{-1}$ or greater significantly increased the proportion of $WSA_{>2\ mm}$, compared to soils that received no manure (Fig. 2). Similarly, N'Dayegamiye and Angers (1990) found that solid cattle manure applications to a silt loam soil at rates of 20 and 40 Mg ha^{-1} every 2 years during a 10-year period increased the proportion of $WSA_{>2\ mm}$ to 27%, while the proportion of $WSA_{>2\ mm}$ was 22.5% in the unmanured control. This indicates that manuring can enhance soil aggregation and therefore improve soil structure in our sandy loam soil when over 30 Mg ha^{-1} $year^{-1}$ is applied, which is consistent with manure application practices in Quebec (CPVQ, 2000). We did not observe a difference in WSA distribution or aggregate MWD between continuous maize and the soybean–maize rotation, but maize was produced in both cropping systems during the year that this study was conducted (Table 2).

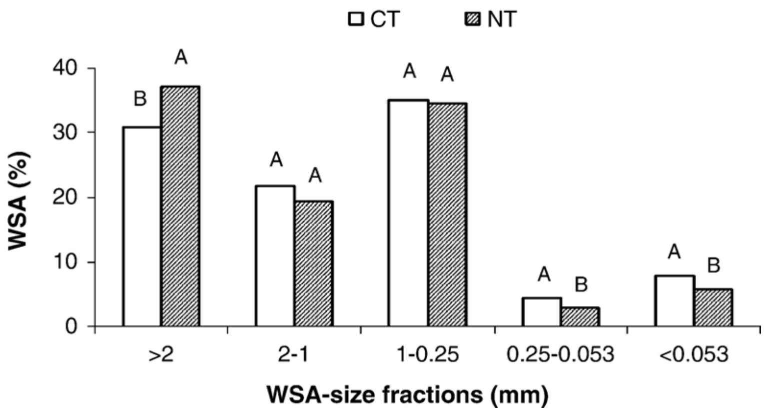

Fig. 1. Tillage effects on the percentage of water-stable aggregates (WSA) in a sandy-loam soil. Values were pooled among crop and fertilizer treatments ($n = 32$ for each tillage treatment). Bars with different letters in each size fraction were significantly different at $P<0.05$ (contrast analysis).

Table 2
Water-stable aggregate (WSA) distribution (percentage of each size fraction) and mean weight diameter (MWD) as affected by tillage, crops and fertilizers

Treatment[a]	WSA-size fraction (mm)					MWD (mm)
	>2	2–1	1–0.25	0.25–0.053	<0.053	
NT–CC–Man0	32.0	21.3	34.4	4.48	7.80	1.82
NT–CC–Man15	34.0	23.1	31.5	2.88	8.53	1.91
NT–CC–Man30	34.5	22.8	36.0	1.93	4.75	1.95
NT–CC–Man45	42.7	17.7	33.5	2.83	3.40	2.19
NT–SC–Man0	30.0	15.0	44.0	4.63	6.35	1.71
NT–SC–Man15	33.0	20.5	37.9	2.60	6.03	1.87
NT–SC–Man30	43.1	17.0	31.6	2.23	6.10	2.18
NT–SC–Man45	48.1	18.2	27.8	2.05	3.88	2.37
CT–CC–Man0	26.8	20.0	39.5	5.80	8.03	1.63
CT–CC–Man15	28.8	19.1	39.4	4.58	8.10	1.69
CT–CC–Man30	37.1	18.1	32.1	4.65	8.10	1.96
CT–CC–Man45	36.3	19.9	32.0	3.73	8.08	1.96
CT–SC–Man0	24.4	29.6	32.8	4.13	9.13	1.63
CT–SC–Man15	30.3	22.2	35.1	4.85	7.60	1.77
CT–SC–Man30	26.0	22.5	39.4	4.93	7.25	1.63
CT–SC–Man45	37.1	21.3	30.4	3.85	7.38	2.00
Interactions[b]						
Tillage * crop * manure	NS[c]	NS	0.0499	NS	NS	NS
Contrast analysis[d]						
CT vs. NT	0.0234	NS	NS	0.0027	0.0170	0.0282
Man0 vs. Man45	<0.0001	NS	0.0168	0.0035	0.0397	<0.0001

[a] NT: no-till; CT: conventional tillage; CC: continuous maize; SC: maize–soybean rotation. Description of the Man0, Man15, Man30 and Man45 treatments were provided in Table 1.
[b] No other interactions were significant ($P<0.05$).
[c] NS: not significant ($P>0.05$).
[d] Contrast analysis of the CC vs. SC effects on WSA and MWD were not significant ($P>0.05$).

3.2. Soil aggregation and total nutrient concentrations in aggregates

Soil aggregation, expressed as MWD, was related to whole soil C concentrations. Under CT and NT systems, the MWD increased as the whole soil C concentration increased. This indicates that composted manure applications to either CT or NT systems, at rates that increase soil C, are likely to improve soil aggregation. However, more aggregation was usually observed in NT than CT systems at the same level of whole soil C concentrations (Fig. 3). Specifically, NT had significantly higher MWD than CT ($P=0.0282$, Table 2) when the total C concentration in the whole soil was similar ($P>0.05$, Table 3). In contrast, most of the literature reports that NT improved soil aggregation

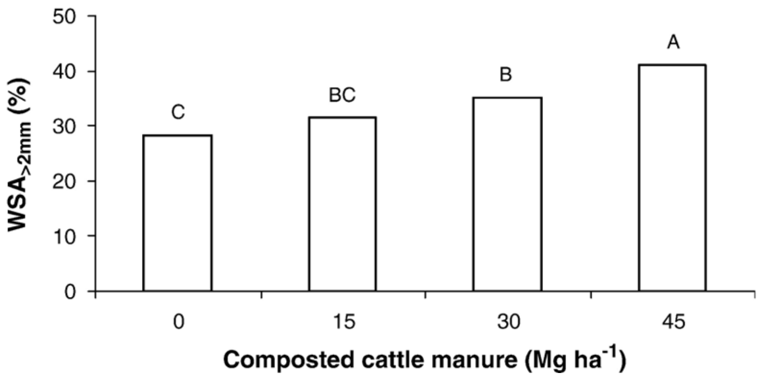

Fig. 2. Fertilizer effects on the percentage of water-stable aggregates >2-mm ($WSA_{>2\ mm}$) in a sandy-loam soil. Values were pooled among crop and tillage treatments ($n=16$ for each fertilizer treatment). Bars with different letters were significantly different at $P<0.05$ (SNK test).

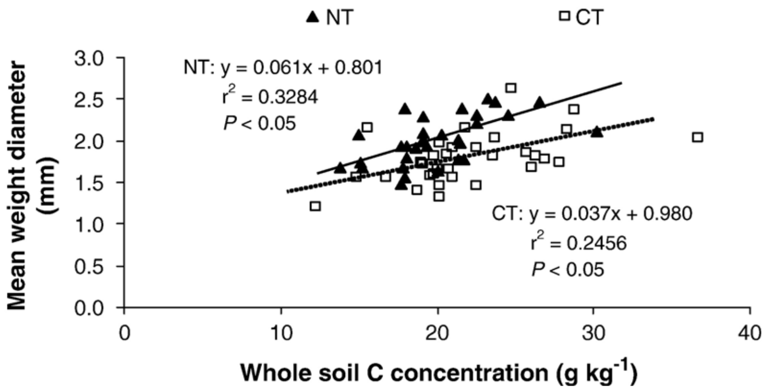

Fig. 3. Functional relationship between soil aggregation (MWD) and the whole soil C concentrations in no-till (NT) and conventional tillage (CT) systems. Lines represent the average relation by structural analysis. Correlations were significant at $P<0.05$.

and was always accompanied by more SOC than in CT systems (Paustian et al., 1997; Bissonnette et al., 2001).

The $WSA_{>2\ mm}$ from soils under CT contained more total C than those from NT systems when the results were expressed on a primary particle-free basis, but not on a sand-free basis (Fig. 4, Table 3). In contrast, Beare et al. (1994) reported that sand-free-macroaggregate C is greater in the 0–5 cm layer of NT than CT systems. In this study, there tended to be more sand embedded in $WSA_{>2\ mm}$ from NT than CT soils, which suggests a dilution effect (Table 3). It may also be that tillage mixes composted manure into the soil, contributing to a higher

Table 3

Sand content and total C concentration in whole soil and large water-stable aggregates ($WSA_{>2\ mm}$) as affected by tillage, crops and fertilizers

Treatment[a]	Whole soil			$WSA_{>2\ mm}$		
	Sand	Total C		Sand	Total C	
	(%)	(g kg^{-1})[b]	(g kg^{-1} sand-free)[c]	(%)	(g kg^{-1})[b]	(g kg^{-1} sand-free)[c]
NT–CC–Man0	70.0	17.7	67.2	68.7	20.1	72.0
NT–CC–Man15	69.3	20.3	70.3	66.9	25.1	78.6
NT–CC–Man30	75.4	18.6	83.7	73.1	19.5	77.5
NT–CC–Man45	73.1	19.7	76.8	71.0	22.8	80.7
NT–SC–Man0	73.5	17.2	67.5	70.1	18.5	63.1
NT–SC–Man15	77.1	20.3	92.5	73.4	20.7	81.4
NT–SC–Man30	70.4	23.9	88.7	67.9	23.6	78.6
NT–SC–Man45	70.4	21.6	75.7	69.1	23.3	79.7
CT–CC–Man0	69.1	18.3	64.4	63.7	23.1	63.5
CT–CC–Man15	66.3	21.9	72.7	64.0	26.6	76.3
CT–CC–Man30	67.7	24.9	80.7	64.5	28.3	80.1
CT–CC–Man45	68.9	27.6	89.7	66.7	28.4	85.6
CT–SC–Man0	64.7	18.9	54.5	60.2	22.8	57.5
CT–SC–Man15	64.0	19.6	54.9	60.0	21.4	54.4
CT–SC–Man30	60.4	19.9	51.9	56.8	22.3	52.6
CT–SC–Man45	62.7	25.1	69.9	58.8	24.7	62.7
Interactions[d]						
Crop * manure	0.0394	NS[e]	NS	NS	NS	NS
Contrast analysis[f]						
CT vs. NT	NS	NS	NS	NS	0.0221	NS
Man0 vs. Man45	NS	<0.0001	0.0026	NS	0.0091	0.0026

[a] Treatments were described in Table 2.
[b] Total C concentration expressed on a g C kg^{-1} soil or g C kg^{-1} primary particle-free aggregate fraction basis.
[c] Total C concentration expressed on a g C kg^{-1} sand-free soil or g C kg^{-1} sand-free aggregate fraction basis.
[d] No other interactions were significant ($P<0.05$).
[e] NS: not significant ($P>0.05$).
[f] Contrast analysis of the CC vs. SC effects on sand content and total C concentration were not significant ($P>0.05$).

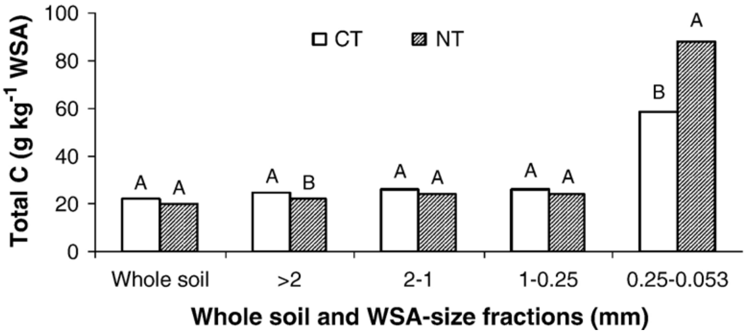

Fig. 4. Tillage effects on the total C concentration in whole soil and water-stable aggregates (WSA) in a sandy-loam soil. Values were pooled among crop and fertilizer treatments ($n=32$ for each tillage treatment). Bars with different letters in whole soil or each size fraction are significantly different at $P<0.05$ (contrast analysis).

C concentration in $WSA_{>2\ mm}$ fractions in CT than NT systems (Table 3). When we collected soil blocks, we excluded plant residues and composted manure on the soil surface, and thus considered only the SOC that was intimately mixed with the soil. The total C concentration of whole soil, pooled among crop and fertilizer treatments, was 22.0 g kg^{-1} in CT soils and 20.0 g kg^{-1} in NT soils (Table 3). It also appeared that fewer $WSA_{>2\ mm}$ were found in CT than NT systems (Fig. 1). We propose that more SOM is needed to produce or maintain $WSA_{>2\ mm}$ in CT systems than NT systems (Fig. 5). These results are consistent with data from an unpublished study conducted at the same site in 2002. In that study, we found that CT soil contained fewer $WSA_{>2\ mm}$ than NT soils ($P=0.0627$) but the total C concentration in $WSA_{>2\ mm}$ was greater in the CT than the NT system ($P=0.0032$). Further research is needed to elucidate the mechanisms responsible for this observation.

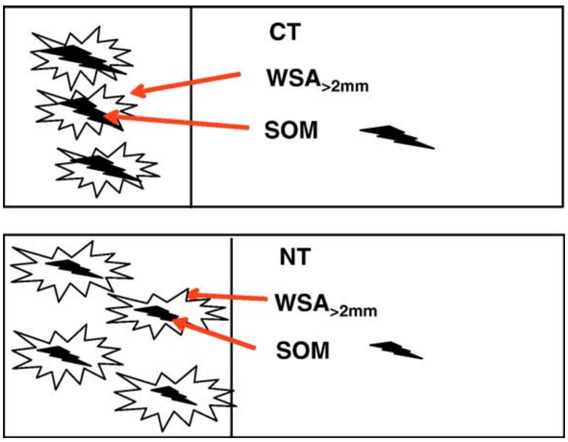

Fig. 5. Hypothetical representation of tillage effects on macroaggregate formation. Conventional tillage (CT) produced fewer water-stable aggregates >2-mm ($WSA_{>2\ mm}$) than no-till (NT). More SOM (represented by total C concentration) is required for $WSA_{>2\ mm}$ formation in CT than NT systems.

Composted manure applications influenced the concentration of total C, N and P in whole soil and aggregate fractions. In most aggregate-size fractions, total C concentrations increased as the manure application rate increased (Fig. 6). This finding is consistent with Whalen et al. (2003) and suggests that significant quantities of C from composted manure were retained in whole soil and aggregate fractions. The total N concentration in whole soil and the $WSA_{2–1\ mm}$ fraction increased with composted manure applications, but there was no difference in the total P concentration that could be attributed to manuring (Table 4). Notably, the $WSA_{0.25–0.053\ mm}$ fraction had a greater total N and total P concentration in NT than CT soils (Table 4). The $WSA_{0.25–0.053\ mm}$ fraction contained up to 3 times more total C, five times more total N and 8 times more total P than the other aggregate fractions (contrast $WSA_{0.25–0.053\ mm}$ vs. $WSA_{>2,\ 2–1,\ 1–0.25\ mm}$: $P<0.0001$) (Fig. 6, Table 4). Therefore, the $WSA_{0.25–0.053\ mm}$ fraction is a sink for these nutrients. The $WSA_{0.25–0.053\ mm}$ fraction is also more susceptible to erosion than larger aggregate-size fractions. Ghadiri and Rose (1991) reported that eroded sediment is finer and richer in organic C, total N and sorbed pesticides than the original soil, which contributes to pollution when such material is transported to waterways. Agricultural practices that increase aggregation, such as no-tillage and manuring, are expected to increase the retention of total C, N and P in soils. However, this should be verified in other crop production systems and climates.

4. Conclusions

Adopting no-tillage practices and applying at least 30 Mg (wet weight) ha^{-1} $year^{-1}$ of composted cattle manure to maize production systems increased the proportion of large (>2 mm) water-stable macroaggregate

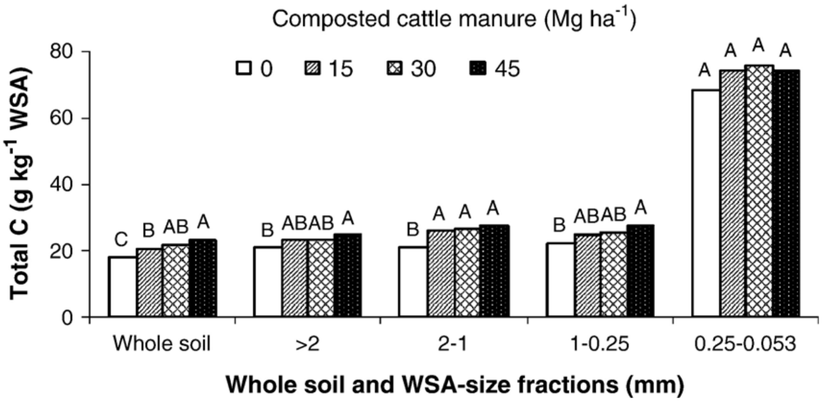

Fig. 6. Effect of manure applications on the total C concentration in different aggregate-size fractions. Values were pooled among crop and tillage treatments ($n = 16$ for each fertilizer treatment). Bars with different letters in each size fraction are significantly different at $P < 0.05$ (SNK test).

within four years. Aggregation was related to the soil C concentration, so that soils with more $WSA_{>2\ mm}$ tended to have a higher soil C concentration. Although NT plots had more large aggregates, as indicated by the aggregate MWD, the soil C concentration tended to be greater in CT than NT plots. The $WSA_{>2\ mm}$ in CT plots also contained more total C than those in NT plots, suggesting that formation and stabilization of such aggregates in CT systems requires more SOM than in NT systems. However, this remains to be verified. Water stable microaggregates ($WSA_{0.25–0.053\ mm}$), a fraction susceptible to erosion, were enriched with total C, N and P compared to other aggregate fractions and whole soil. It will be important to minimize the quantities of $WSA_{0.25–0.053\ mm}$ lost from agroecosystems to prevent pollution of waterways and other ecosystems sensitive to nutrient loading. Further investigation is needed to understand the mechanisms of aggregate formation in CT and NT systems. Our results indicate that no-tillage and composted manure applications improved soil structure and led to greater retention of total C, N and P in a temperate maize production system. This possibility should be investigated in other soil types, crop production systems and climates.

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Table 4
Total N and P concentrations in whole soil and WSA-size fractions as influenced by tillage and fertilizer sources

Factor	Treatment	n	Whole soil	Total N ($g\ kg^{-1}$)[a]		Total P ($g\ kg^{-1}$)[b]	
				WSA-size fraction (mm)		WSA-size fraction (mm)	
				2–1	0.25–0.053	2–1	0.25–0.053
Tillage	CT	32	2.22 a[c]	2.42 a	7.57 a	1.46 a	5.74 a
	NT	32	2.04 a	2.39 a	11.35 b	1.36 b	9.44 b
Fertilizer	Man0	16	1.92 b[d]	2.00 b	8.91 a	1.36 a	7.26 a
	Man15	16	2.09 ab	2.35 a	9.58 a	1.39 a	7.77 a
	Man30	16	2.14 ab	2.61 a	10.25 a	1.45 a	8.24 a
	Man45	16	2.37 a	2.66 a	9.10 a	1.43 a	7.11 a

[a] There was no effect ($P > 0.05$) of tillage or fertilizer sources on the total N concentration in the $WSA_{>2\ mm}$ fraction (mean value: 2.36 g N kg^{-1}) or the $WSA_{1–0.25\ mm}$ fraction (mean: 2.79 g N kg^{-1}).

[b] There was no effect ($P > 0.05$) of tillage or fertilizer sources on the total P concentration in the whole soil (mean value: 1.16 g P kg^{-1}), the $WSA_{>2\ mm}$ fraction (mean: 1.44 g P kg^{-1}) or the $WSA_{1–0.25\ mm}$ fraction (mean: 1.38 g P kg^{-1}).

[c] Values within a column followed by different letters were significantly ($P < 0.05$) affected by tillage.

[d] Values within a column followed by different letters were significantly ($P < 0.05$) affected by fertilizers.

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