Compost Applications Increase Water-Stable Aggregates in Conventional and No-Tillage Systems

Joann K. Whalen,* Quancai Hu, and Aiguo Liu

ABSTRACT

Agricultural practices that alter the soil organic matter (SOM) content are expected to cause changes in soil stability and aggregation. The objective of this study was to evaluate short-term (<2 yr) changes in water-stable aggregates (WSA) in a silt-loam soil under different management regimes. The interactive effects of tillage (no-till and conventional tillage), crop rotations (continuous corn, corn-soybean rotation) and composted cattle manure applications [0, 15, 30, and 45 Mg (wet weight) ha^{-1}] on WSA were assessed in a factorial (tillage $\times$ crop rotation) split plot (compost) experiment. The proportion of WSA >4 mm was greater in compost-amended than unamended soils within 1 yr, and the mean weight diameter (MWD) of aggregates increased with increasing compost application rates. By the second year of the study, no-till soils under continuous corn and the soybean phase of the corn-soybean rotation had more WSA >4 mm and a greater MWD than any crop rotation in conventionally tilled soils. Increasing the C input to soil increased the MWD of aggregates. The MWD of aggregates was related to the C content of soils under no-till, but not conventional tillage, suggesting more physical stabilization of organic matter (OM) in no-till than conventional tillage agroecosystems. Our findings indicate rapid improvements in aggregation of a silt-loam in the first 2 yr after compost application and the adoption of no-tillage practices.

Stable aggregates that persist when soils are wetted or subjected to mechanical stress may indicate a soil's susceptibility to erosion, crust formation, and compaction (Le Bissonnais and Arrouays, 1997). Aggregation is influenced by agricultural practices such as tillage, cropping systems, and the types of fertilizers applied. Tillage disrupts aggregates mechanically, changes the soil climate (temperature, moisture, aeration) and accelerates OM decomposition (Balesdent et al., 2000), reducing the proportion of stable aggregates >0.25 mm (Carter, 1992; Cambardella and Elliott, 1993; Puget et al., 1995; Six et al. 1999). The annual input of residues in continuously cropped soils can increase the quantity of WSA relative to soils with a fallow phase in the crop rotation (Campbell et al., 1993; Monreal et al., 1995; Unger et al. 1998). However, crop residues vary in their ability to promote aggregation, and cultivated soils under corn production have been shown to contain aggregates with a greater MWD than soils under soybean production (Martens, 2000). Fertilizer applications increase the proportion of WSA in agricultural soils in two ways. First, fertilizers can increase crop production, leading to higher inputs of crop residues and more WSA than in unfertilized soils (Campbell et al., 2001). Second, soils amended with organic fertilizers such as legume green manure or animal manure tend to have a higher input of OM and more WSA than soils that receive other types of fertilizer (Angers and N'Dayegamiye, 1991; Sun et al., 1995; Haynes and Naidu, 1998; Aoyama et al., 1999).

Although the separate effects of tillage, cropping systems, and fertilizers on aggregation have been documented, there is limited information on the ways that these factors interact to affect aggregation. Bissonnette et al. (2001) examined the interactive effects of eight management systems that included continuous barley and a 3-yr barley–forage rotation, moldboard and chisel plowing in the fall, and fertilization with liquid dairy manure or mineral fertilizers. Chisel-plowed soils under the barley–forage rotation that received liquid dairy manure had among the highest annual C input, which led to a higher soil C content and a greater MWD of aggregates in this system than other management systems. Bissonnette et al. (2001) concluded that management systems that increased the soil C content also improved soil stability.

Improvements in aggregation can occur within 2 to 3 yr of establishing conservation practices such as reduced tillage, crop rotations that include perennial forages, and organic fertilizer additions (e.g., manure, wood-derived residues) in the cold, humid soils of Eastern Canada (Angers and Carter, 1996; Bissonnette et al., 2001). Most of the evidence for these effects comes from studies on fine-textured (clayey or silty-clay) soils. There is limited information on whether medium-textured (silty or silt-loam) soils producing annual row crops respond as rapidly to conservation practices.

The purpose of this study was to determine short-term (<2 yr) changes in WSA of a silt-loam soil as influenced by tillage practices, cropping systems, and fertilizer sources.

MATERIALS AND METHODS

The study site was located on the Macdonald Research Farm, Ste. Anne de Bellevue, Quebec. Mean monthly temperature ranged from −10.3°C in January to 18.0°C in July, with mean annual precipitation of 940 mm (Environment Canada, 1998). The soil, fine-silty, mixed, frigid Typic Endoaquents of the St. Amable series (Humic Gleysols), contained a silt-loam layer (mean thickness 28 cm) underlain by sand (mean thickness 6 cm) and clay starting at depths below 34 cm, on average. The top 15 cm of the silt-loam layer contained 300 g kg^{-1} of sand, 540 g kg^{-1} of silt, and 160 g kg^{-1} of clay with 15.4 g C

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Abbreviations: SOM, soil organic matter; WSA, water-stable aggregates; MWD, mean weight diameter; OM, organic matter.

kg^{-1}, 1.24 g N kg^{-1}, and pH 6.1. From 1991 to 2000, when this study began, the site was conventionally tilled for grain corn (*Zea mays* L.) production, and the nutrients required were generally supplied in urea and triple-superphosphate fertilizers.

Experimental Design

The site was disked on 2 May 2000 with a tandem disk before plot establishment, and laid out in a factorial (tillage × crop rotation) design. There were two tillage treatments (no-till or conventional tillage) and three crop rotations (silage corn–soybean, soybean–silage corn or continuous silage corn), for a total of six factorial treatments. The factorial main plots were 20 by 24 m and were arranged in a randomized complete block design with four blocks for a total of 24 main plots. A 3-m-wide unplanted alley separated the main plots within a block and an 8-m wide unplanted alley separated the blocks. After plot establishment, no additional tillage operations were done on the no-till plots, but conventionally tilled plots were tilled with a tandem disk each spring before seeding and with a moldboard plough each fall after harvest.

Each 20 by 24-m main plot was split into four strips (20 by 6-m), and four fertilizer treatments were assigned randomly within each main plot to apply the same amount of N (200 kg N ha^{-1}) and P (45 kg P ha^{-1}), but from different fertilizer sources (inorganic fertilizers, compost). The inorganic fertilizers used were ammonium nitrate and triple-superphosphate. The compost applied in the spring of 2000 and 2001 was composted cattle manure obtained from Les Composts du Quebec (Saint Henri, QC). It contained, on a dry weight basis, an average of 401 g C kg^{-1}, 20.7 g N kg^{-1} (Carlo Erba Flash EA NC Soils Analyzer, Milan, Italy), 2.3 g P kg^{-1} (H_2SO_4/H_2O_2 digestion, Parkinson and Allen, 1975) and 0.66 kg H_2O kg^{-1} (105°C for 48 h). Compost was applied at rates of 0, 15, 30, and 45 Mg ha^{-1} (wet weight basis), which were equivalent to 0, 33, 66, and 100% of silage corn P removal (45 kg P ha^{-1}), according to Conseil des productions végétales du Québec (2000) guidelines. Compost was incorporated before seeding the conventional tillage plots but left on the surface of no-till plots. The balance of P required came from triple-superphosphate banded at seeding.

All plots were seeded with a John Deere 7100 Max Emerge seeder. Silage corn (*Zea mays* L. cv. Cargill 2610) treated with Maxim and Captan was planted on 30 May 2000 and 17 May 2001, at a rate of 75 000 seeds ha^{-1}. Soybeans (*Glycine max* L. Merr. cv. Cargill A0868TR) treated with Soy Select were planted on 1 June 2000 and 18 May 2001 at a rate of 400 000 seeds ha^{-1}. Plots under corn production received 40 kg N ha^{-1} from NH_4NO_3 banded at seeding. Additional NH_4NO_3 was sidedressed at the 4- to 5-leaf stage (about one month after seeding) based on the assumption that 25% of the N in compost would be available for corn uptake during the growing season. We estimated that 15 Mg ha^{-1} (wet weight) of compost 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 soybeans.

Water-Stable Aggregates

Soil samples were collected in the fall of 2000 and 2001 after harvest but before fall tillage. Surface residues were pushed aside, and two 38 cm × 38 cm × 15 cm (deep) pits were dug near the center of each plot, between crop rows. The mean gravimetric water content (± SE) at the time soils were collected was 0.18 ± 0.02 kg kg^{-1} in 2000 and 0.18 ± 0.02 kg kg^{-1} in 2001. The intact soil block removed from each pit was oven dried (60°C for 48 h) to reduce microbial activity and stored at 4°C for up to two months before analysis. The distribution of WSA was determined by wet-sieving following the procedure of Angers and Mehuys (1993). We carefully removed intact clods of unsieved, oven-dried soil from the middle of each soil block along the fracture lines that appeared during storage. Between 60 and 80 g of these intact soil clods were placed in a 120-cm^3 specimen cup and slowly prewetted to a gravimetric water content of 0.20 kg kg^{-1} by capillary action. Each cup was sealed and the soils were allowed to equilibrate overnight (≈16 h). Moistened soil was gently passed through an 8-mm sieve to break apart the clods and then 40 g (oven-dry basis) was spread evenly on the largest of a stack of sieves with openings of 4.0, 2.0, 1.0, and 0.25 mm. The sieves were placed in a wet sieving apparatus with a stroke length of 3.7 cm, based on the design of Kemper and Rosenau (1986), and sieved in distilled water for 10 min at a frequency of 29 cycles min^{-1}. The aggregates remaining on each sieve were washed onto a preweighed coffee filter, oven dried at 105°C for 24 h, and weighed. The aggregates were then suspended in 50 mL of 0.5% sodium hexametaphosphate in a 250-mL Erlenmeyer flask, shaken for 45 min to disperse sand particles >0.25 mm and the suspension poured through a sieve with the same mesh size as the one from which the aggregates were collected. The sand remaining on each sieve was washed onto a preweighed coffee filter, oven dried at 105°C for 24 h and weighed. The mass of stable, sand-free aggregates was the difference between the mass of total aggregates (nondispersed) and the mass of sand collected on each sieve. The proportion of WSA in each size fraction (WSA_i) was calculated from Eq. [1]:

$$WSA_i = (Total_i - Sand_i)/ \{[Soil/(1 + Moisture)] - \Sigma Sand_i\}, \quad [1]$$

where i is the ith size fraction (>4 mm, 4- to 2-mm, 2- to 1-mm, and 1- to 0.25-mm aggregate size fractions); Total is the oven-dry mass of total, nondispersed aggregates collected on each sieve; Sand is the oven-dry mass of sand collected on each sieve; Soil is the oven-dry mass of the remoistened, sieved (<8 mm) soil; and Moisture is the gravimetric moisture content of the remoistened, sieved (<8 mm) soil. The proportion of WSA <0.25 mm was calculated from Eq. [2]:

$$WSA_{<0.25\ mm} = 1 - \Sigma\ WSA_i. \quad [2]$$

The MWD of aggregates collected from each experimental treatment was calculated from Eq. [3]:

$$MWD = \Sigma\ X_i\ WSA_i, \quad [3]$$

where i is the ith size fraction (>4 mm, 4- to 2-mm, 2- to 1-mm, 1- to 0.25-mm, and <0.25-mm aggregate size fractions), and X is the mean diameter of each size fraction, based on the mean intersieve size.

Crop Yields and Soil Carbon Content

Corn yields were determined by harvesting the grain and stover of 20 plants randomly selected from the center of each split plot. Soybean grain yield was determined by combining a swath 3 m wide by 20 m long in the center of each split plot. Grain and stover samples were then oven dried (60°C for 48 h) to calculate yield on a dry-matter basis. Two soil samples (0- to 15-cm depth) were collected from each split plot in the fall after harvest, before fall tillage, with a tractor-mounted soil auger (7.5-cm diam.), and combined to make a composite sample. The total C content of oven-dried (60°C for 48 h), finely ground (<1-mm mesh) soil was determined with a Carlo Erba Flash EA NC Soils Analyzer (Milan, Italy).

Statistical Analysis

The percentages of WSA in different size fractions were log transformed before evaluation by ANOVA in a general linear model (SAS Institute, 1999). The significance of the factorial main effect (tillage × crop rotation), the split plot effect (compost), and their interactions on WSA were determined, and mean comparisons of significant ($P < 0.05$) effects were done with a Student-Newman-Keuls test at the 95% confidence level. Linear regressions relating the MWD of aggregates with compost application rates, estimated C inputs, and the soil C content were fit with the SAS/INSIGHT function of SAS software (SAS Institute, 1999).

RESULTS AND DISCUSSION

In 2000, the proportion of WSA >4 mm was greater in soils receiving compost than soils that did not receive compost and there were fewer WSA <0.25 mm in compost-amended than unamended soils (Fig. 1). We observed the same trend in 2001, although it was not statistically significant at the lowest compost rate (Fig. 1). In addition, there were fewer WSA between 0.25 and 1 mm in compost-amended than unamended soils in 2001 (Fig. 1). The MWD of aggregates increased linearly with increasing rates of compost application in both years (Fig. 2). Long-term applications (>10 yr) of animal manure increased the soil organic C level and favor the formation of WSA >0.25 mm under field conditions (Angers and N'Dayegamiye, 1991; Aoyama et al., 1999), but less is known about how compost applications affect aggregation in the short term. Our results indicate a greater proportion of WSA >4 mm in compost-amended than unamended soils within five months of the first compost application, which persisted after the second annual application of compost.

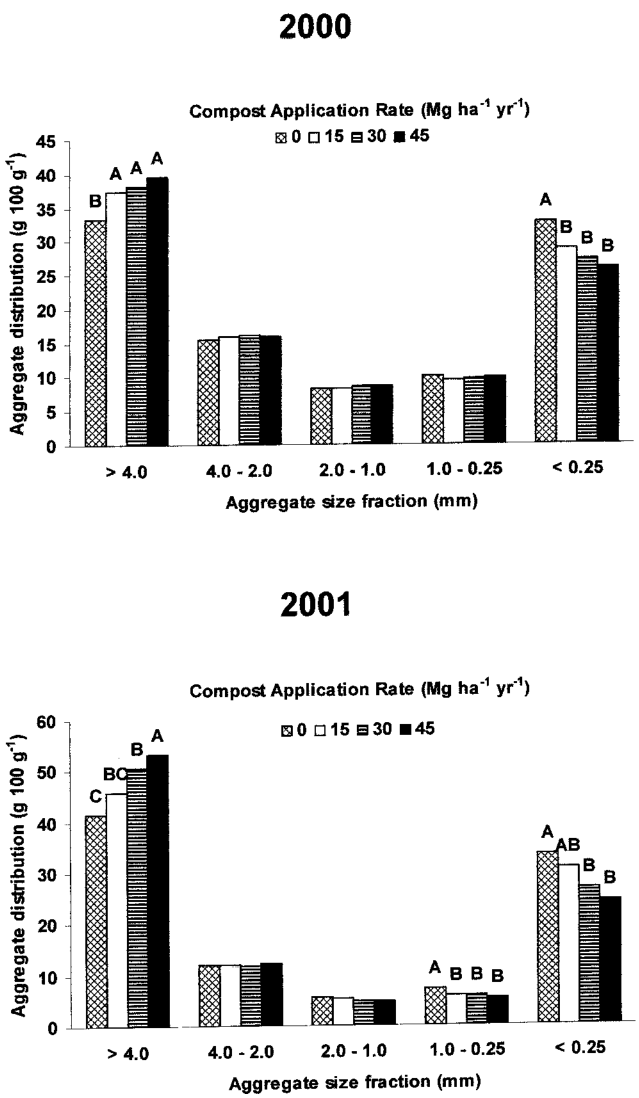

Fig. 1. Effect of compost applications on the distribution of water-stable aggregates in 2000 and 2001. Bars within an aggregate fraction with different letters are significantly different ($P < 0.05$, Student-Newman-Keuls). The absence of letters on bars within an aggregate fraction indicates no significant difference between compost treatments.

Aggregation is influenced by the chemical composition of organic residues added to soils. Organic residues that decompose quickly may produce a rapid but temporary increase in aggregation, whereas organic residues that decompose slowly may produce a smaller but long-lasting improvement in aggregation (Sun et al., 1995). During decomposition, some of the OM in animal manure may become associated with WSA >0.25 mm as particulate OM (Aoyama et al., 1999). Animal manure also contains hydrophobic compounds such as lipids that may bind with soil mineral particles and microaggregates to form macroaggregates (Paré et al., 1999), as well as dispersing agents (Na^+, K^+, NH_4^+, and positively charged organic acids) that can disrupt macroaggregates (Whalen and Chang, 2002). The compost applied in this study favored the formation of WSA >4 mm, but additional research is required to determine how long these newly formed aggregates persist under field conditions and how their formation and disruption are affected by the chemical composition and decomposition rate of compost.

The factorial tillage × crop rotation treatment had a significant ($P < 0.05$) effect on water-stable aggregation

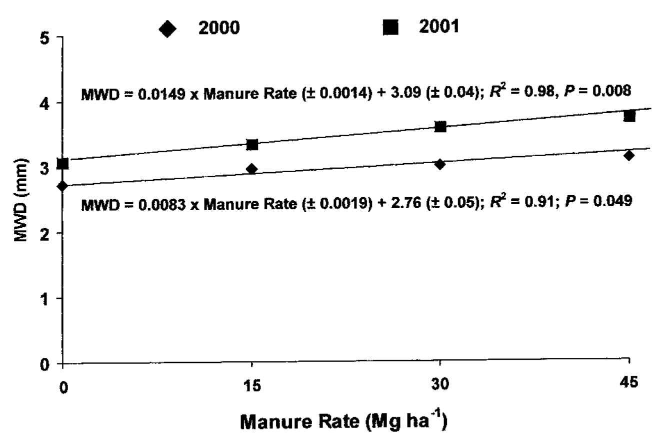

Fig. 2. Relationship between the compost application rate and the mean weight diameter (MWD) of water-stable aggregates in 2000 and 2001. Data were pooled among tillage systems and crop rotations (n = 24 for each compost rate). Values in parenthesis are the SEs of the estimated slopes and intercepts.

Table 1. Percentage of water-stable aggregates and mean weight diameter (MWD) of aggregates in different tillage × crop rotation treatments in 2001. The phase of the crop rotation grown in 2001 is underscored.

Tillage System	Crop Rotation	Water-stable aggregates					MWD
		>4 mm	4–2 mm	2–1 mm	1–0.25 mm	<0.25 mm	
		%					mm
No-till	Corn–<u>Corn</u>	57a†	11b	4.2b	4.4b	23c	3.9a
	Corn–<u>Soybean</u>	55ab	12ab	4.7b	5.0b	23c	3.8a
	Soybean–<u>Corn</u>	51bc	13a	4.7b	5.0b	26bc	3.6ab
Conventional	Corn–<u>Corn</u>	47c	12ab	5.5a	6.7a	29bc	3.3bc
	Corn–<u>Soybean</u>	39d	12ab	5.5a	7.1a	37a	2.9d
	Soybean–<u>Corn</u>	42d	13a	6.2a	7.9a	31b	3.1cd

†Means within a column followed by the same letter are not significantly different ($P < 0.05$, Student-Newman-Keuls).

in 2001, the second year of the study. Between 39 and 57% of the soil was WSA >4 mm, with 23 to 37% in the <0.25-mm aggregate fraction and <28% in the 0.25- to 4-mm aggregate fractions (Table 1). No-till soils under continuous corn and the soybean phase of the corn-soybean rotation in 2001 had more WSA >4 mm, fewer WSA <2 mm, and a greater MWD than any crop rotations in conventionally tilled soils (Table 1). The proportion of WSA >4 mm and MWD of aggregates from no-till soils in the corn phase of the corn-soybean rotation was similar to conventionally tilled soils under continuous corn, but greater than conventionally tilled soils under corn–soybean rotations (Table 1).

Soils under no-till systems generally exhibit more aggregation and contain more SOM than those under conventional tillage systems because plowing changes the soil conditions and increases decomposition rates (Paustian et al., 1997; Balesdent et al., 2000). In addition, the quantity of C retained in agroecosystems influences the proportion of WSA in soils and the SOM content (Campbell et al., 1993; Paustian et al., 1997). There can be considerable variation in the C input to soil from crop residues. Yields were ≈40% lower in 2001 than 2000 because of a prolonged drought (>30 d without rainfall) in July and August of 2001 (Table 2). In compost-amended soils, a larger proportion of the estimated C input to soils was from compost than crop residues (Table 2). The MWD of aggregates was related linearly to the estimated C input (Fig. 3) of conventional tillage and no-till systems in 2001. The slopes of these regression lines were not different, indicating similar increases in the MWD of aggregates with increasing C inputs (estimated) to conventional tillage and no-till systems (Fig. 3). The intercept of the regression line was larger for the no-till than conventional tillage system (Fig. 3), which is consistent with the greater MWD of aggregates in no-till than conventionally tilled soils observed earlier (Table 1).

The type of crop residues returned to the soil can also affect aggregation. In our study, the >4-mm fraction was more sensitive to variation in crop residue characteristics than other aggregate fractions, and there tended to be a larger proportion of WSA >4 mm under continuous corn than the soybean–corn rotations (Table 1). The estimated C input was higher under soybean production than corn production in both years of the study (Table 2), but it appears that corn residues were superior to soybean residues in forming WSA >4 mm, particularly in conventional tillage systems. Our findings are consistent with those of Martens (2000), who found aggregates with a lower MWD in the soybean phase than the corn phase of a corn-soybean rotation (both phases were grown in the study year). The decline in aggregation following soybean production may have been because of the lower phenolic acid content (humic acid precursors) in soybean than corn residues (Martens, 2000). Our findings suggest that WSA formation may be affected more by residue quality than the quantity returned to soils. Further work is needed to determine why corn residues promote the formation of more WSA >4 mm than soybean residues.

The MWD of aggregates collected from soils under no-till, but not conventional tillage, was related linearly to the soil C content (Fig. 4). The soil C pool contains OM that is physically, chemically, and biochemically stabilized and hence retained in soils (Six et al., 2002). Our results may indicate that there is more physical stabilization of the soil C in no-till than in conventional

Table 2. Dry matter (DM) yield, estimated net primary production (NPP), and estimated annual C input from corn silage and soybeans to soils under different tillage × crop rotation treatments in 2000 and 2001. Yield values are means ± SE.

Tillage System	Crop Rotation	Yield		Estimated NPP†		Estimated C input‡	
		2000	2001	2000	2001	2000	2001
		Mg DM ha^{-1}				kg C ha^{-1} yr^{-1}	
No-till	Corn–Corn	13.8 ± 0.6	6.7 ± 0.3	16.3	7.8	1127	545
	Corn–Soybean	13.4 ± 0.9	1.3 ± 0.1	15.8	3.6	1088	1028
	Soybean–Corn	2.6 ± 0.03	8.7 ± 0.7	7.2	10.3	2072	712
Conventional	Corn–Corn	14.6 ± 0.5	7.3 ± 0.5	17.2	8.6	1186	594
	Corn–Soybean	13.9 ± 0.4	1.5 ± 0.1	16.4	4.1	1134	1187
	Soybean–Corn	2.6 ± 0.06	9.2 ± 0.5	7.1	10.9	2038	753

† NPP was estimated with a harvest index of 1.00 for corn silage and 0.42 for soybeans. The root:shoot ratios used were 0.18 for corn silage and 0.15 for soybeans (Prince et al., 2001).

‡ The estimated C input was based on 45% C in plant tissues (corn roots; soybean stems, leaves and roots) not removed from the field at harvest. An additional 2045, 4090, or 6135 kg C ha^{-1} yr^{-1} was provided from the annual application of 15, 30, or 45 Mg ha^{-1} (wet weight) of compost that contained 401 g C kg^{-1} and 0.66 kg H_2O kg^{-1}.

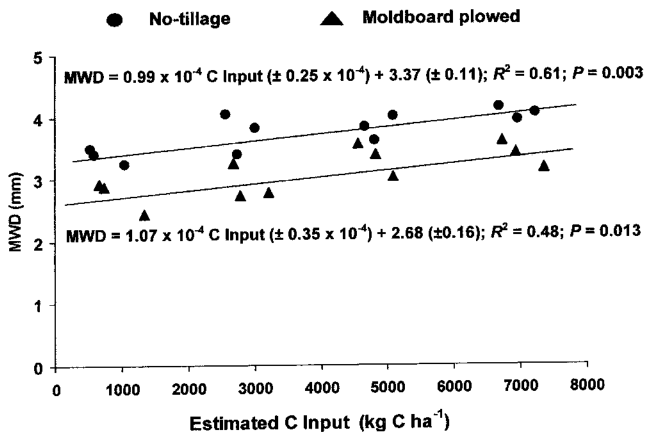

Fig. 3. Relationship between the estimated C input and the mean weight diameter (MWD) of water-stable aggregates in conventional tillage and no-till agroecosystems in 2001. Data points are the mean C input and MWD for each compost treatment within a tillage system × crop rotation (n = 4 for each data point). Values in parenthesis are the SEs of the estimated slopes and intercepts.

tillage systems. Interestingly, the soil C content tended to be greater in soils under conventional tillage than no-till systems, perhaps because all of the organic residues (compost, crop residues) in the agroecosystem were incorporated in the soil. The OM in these residues was not physically stabilized, as seen in Fig. 4, but it may have been chemically and biochemically stabilized. Organic matter can be stabilized chemically through interactions with clay and silt particles (Hassink, 1997; Six et al., 2002) or biochemically as it is decomposed to a more humified material, as occurs during composting. Further research is needed to determine the mechanisms responsible for stabilizing soil C in our conventional tillage and no-till agroecosystems.

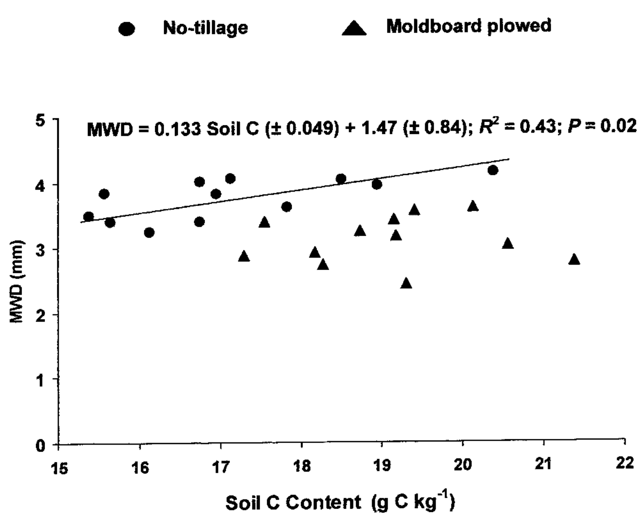

Fig. 4. Relationship between soil C content and the mean weight diameter (MWD) of water-stable aggregates in conventional tillage and no-till agroecosystems in 2001. Data points are the mean soil C content and MWD for each compost treatment within a tillage system × crop rotation (n = 4 for each data point). Values in brackets are the SEs of the estimated slopes and intercepts.

CONCLUSIONS

The proportion of WSA >4 mm was greater in silt-loam soils five months after the first application of compost, and persisted after the second compost application. The MWD of aggregates was related linearly to the compost application rate in both years of the study. In the second year after no-tillage practices were adopted, soils under no-till had more WSA >4 mm and aggregates with a larger MWD than those under conventional tillage, probably because there was less physical disturbance of aggregates and lower decomposition rates in no-till than conventionally tilled soils. The quantity and quality (chemical composition) of crop residues may have affected aggregate size distribution, but research into the transformations of OM from compost is required since more of the estimated C input was from compost than from crop residues in compost-amended soils. The MWD of aggregates increased linearly with the soil C content in no-till, but not conventional tillage systems. Further investigation is needed to determine how OM from recently applied compost and crop residues may be differentially stabilized physically, chemically, and biochemically in conventional tillage and no-tillage agroecosystems. Overall, our results indicate that compost applications and the adoption of no-tillage increased aggregation in a silt-loam soil within 2 yr.

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