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Impact of Tillage and Crop Rotation on Aggregate-Associated Carbon in Two Oxisols

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ABSTRACT

In temperate regions, the adoption of no-tillage (NT) often stimulates the sequestration of soil C and N and improves soil structural stability. The aim of this study was to investigate if NT has similar impacts on the stability of water-stable aggregates and C and N stabilization in two Oxisols (Typic Haplorthox) under different crop rotations. Slaking-resistant aggregates were isolated by wet sieving and analyzed for C and N concentrations at two agricultural experiment sites (Passo Fundo and Londrina) in southern Brazil. At both sites, the total organic C and N in the 0- to 5-cm depth interval, decreased in order native vegetation (NV) > NT > conventional tillage (CT). The mean weight diameter (MWD) of the aggregates was on average 0.5 mm greater under NT compared with CT, and was also greater (approximately 0.2 mm) under more diverse rotations, which included a leguminous green-manure crop, in comparison with continuous wheat (*Triticum aestivum*)–soybean (*Glycine Max* L.). The aggregate-size distribution was dominated (60–90%) by macroaggregates (>250 μm). At both sites, CT decreased the proportion of the largest macroaggregate class (>2000 μm) by approximately 10% in comparison with NT management, and there was a corresponding increase in the proportion of the 53- to 250-μm aggregate class. In the 0- to 5-cm soil layer of both sites, the C and N concentrations were significantly higher in the macroaggregates of the NT than of the CT systems. The lack of differences in C, N content, and C/N ratio across aggregate-size classes indicated that these soils dominated by 1:1 clays and Fe/Al oxides do not express an aggregate hierarchy and that an increase in aggregation does not explain the increase in C and N under NT. In conclusion, CT decreased aggregation similarly in Oxisols as in temperate soils, but this decrease does not explain the loss of C and N because the tight feedback between soil organic matter (SOM) and aggregate stability (i.e., SOM being a major binding agent) observed for temperate soils was not found for Oxisols.

Oxisols are the most common soil type in Brazil. The main soil characteristics of Oxisols are good structural stability due to a clayey texture and a high Fe and Al oxide content (Oades and Waters, 1991). The association of intense weathering conditions and frequent tillage have in many regions intensified soil erosion, resulting in a decrease in SOM, soil permeability, water retention, soil aggregation, soil macro- and microfauna, and increasing the soil compaction and imbalance of nutrients (Lynch and Painting, 1980; Tisdall and Oades, 1980, 1982; Egashira et al., 1983; Lynch, 1984; Lal et al., 1989). In Brazil, NT practices were introduced in the 1970s as a strategy to control soil erosion. Currently, NT is being increasingly adopted in agricultural systems and to date the area under NT management is approximately 22 Mha.

Under NT, the soil fertility and SOM becomes stratified, with the highest concentration of SOM in the topmost soil layer (Six et al., 2000a). The conservation of crop residues on the soil surface also leads to soil moisture conservation and a decrease in the fluctuations of soil temperature (Lal et al., 1978). These soil characteristics generally improve the biological activities in the surface layers of the soil (Cattelan et al., 1997; Hungria et al., 1997).

Conventional tillage destroys the original soil structure, breaking up the macroaggregates into microaggregates and this results in an increase in microporosity and may increase soil bulk density values (Tisdall and Oades, 1980; Carpenedo and Mielniczuk, 1990). Recently, Six et al. (2002) reviewed the literature on bulk density values under NT and CT and found that in tropical and subtropical soils there were rarely differences in this parameter between the two tillage systems. In contrast, bulk density was generally higher in no-tilled than in conventionally tilled temperate soils. These results indicate differences in soil structural responses to implementation of NT practices in temperate versus (sub)-tropical soils. Six et al. (2002) also reviewed changes in soil aggregation under NT, and found a much higher increase in aggregation in the early years of NT adoption in tropical and subtropical regions compared with temperate regions. They suggested that this was a result of the specific soil mineralogical characteristics (i.e., high Fe- and Al-oxide contents and a kaolinite dominated clay mineralogy) of (sub)tropical soils such as Oxisols and Ultisols. However, this suggestion was based on a synthesis of only five publications reporting data for Oxisols. In addition, these five studies reported magnitudes of responses in aggregation to NT that differed greatly. Consequently, little is known about the effect of NT on soil aggregation and its relationship with C stabilization for Oxisols.

In addition, different crops have different effects on soil aggregation and C accumulation: perennial grasses due to their extensive root systems are more efficient in soil aggregation than annual crops cultivated under CT (Tisdall and Oades, 1980, 1982). Legume crops used as green manures in crop rotation systems have an important role in the introduction of N from biological N fixation into the soil–plant system and the maintenance of soil C. Recent reports have emphasized the importance of legume green-manure crops for the accumulation of SOM in crop rotations managed under NT in

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Abbreviations: CT, conventional tillage; MWD, mean weight diameter; NT, no-tillage; NV, native vegetation; SOM, soil organic matter.

southern Brazil (Gonçalves and Ceretta, 1999; Amado et al., 2001; Sisti et al., 2004).

The objective of this study was to determine the effect of different crop rotations and tillage on soil C and N accumulation, the formation of water-stable aggregates, and the quantity of aggregate-associated C at two sites in southern Brazil both situated on Oxisols. We postulate that the specific mineralogical characteristics of Oxisols (i.e., high Fe- and Al-oxide contents and a kaolinite dominated clay mineralogy) alter the relationship between aggregate formation, soil C and N stabilization and management observed in temperate soils.

MATERIALS AND METHODS

Location and Experimental Layout

The first study was performed at the Experimental Station of the Embrapa Wheat Research Center in Passo Fundo, Rio Grande do Sul State, located 28°15′ S lat. and 52°24′ W long., 687 m altitude. The experiment was installed in 1986 in an area of NV (a mix of tropical rainforest and semi-deciduous forest). In November of 1985, the soil was plowed and limed with 7 Mg ha^{-1} of dolomitic lime with no further lime additions made since that time.

The second site was at the Experimental Station of the Embrapa Soybean Research Center in Londrina, Paraná State, located 23°23′ S lat. and 51°11′ W long., 566 m altitude. The area was originally forested (tropical rainforest) but has been under conventional agriculture since the 1980s, with two crops a year: soybean in summer and wheat in winter. However, from 1994 until implementation of the current experiment in 1997, management was changed to NT with a sequence of soybean/lupin (*Lupinus sp.*)–maize (*Zea mays*)/oats (*Avena sativa*)–soybean/oats.

At both sites, the soils were Oxisols with clayey texture (typic Haplorthox) (Table 1). Both sites had NV, CT, and NT treatments. However, the NV plots were located in adjacent areas near the field experiment plots. The CT plots at Londrina were disk plowed to a depth of 20 cm before planting. The CT treatment disturbed the soil less at Passo Fundo than at Londrina because only the winter cover crop was disk plowed, whereas the summer crop was direct drilled. In the NT treatments, both the summer and winter crops were direct drilled.

At Passo Fundo, the crop rotations were (Table 1): (R1)–soybean/wheat; (R2A)–soybean/hairy vetch (*Vicia villosa*)–maize/oats–soybean/wheat; (R2B)–maize/oats–soybean/wheat–soybean/vetch, and (R2C)–soybean/wheat–soybean/vetch–maize/oats. The rotations R2A, R2B, and R2C, were of the same 3-yr sequence of crops, but the rotation started at the first, second, and third year of the sequence, such that at any time the three years of the rotation could be sampled simultaneously.

At Londrina, the crop rotations utilized were (Table 1): (R1)–soybean/lupin–maize/oats; (R2)–soybean/wheat–soybean/lupin, and (R3)–soybean/lupin–maize/wheat.

Soil Sampling and Aggregate Separation

In July 2001, soils from each treatment were sampled at two depths (0–5 and 5–20 cm). Samples were taken to evaluate the soil bulk density using Kopek rings (5.1-cm i.d. and 4.6 cm height) inserted into the side of a trench approximately 50 × 50 cm square. For these samples taken at the Londrina site the porosity of the soil was determined by placing the Kopek cylinders on a tension table. When the samples were taken, the litter layer (where present) was removed. Once in the laboratory, the moist soil was passed through an 8-mm sieve by gently breaking apart the soil and the samples then air dried, and stored at room temperature.

The method of aggregate separation was adapted from Elliott (1986). Briefly, aggregates were separated by wet sieving the air-dried soil through a series of three sieves (2000, 250, and 53 μm). The air-dried soil was quickly submerged in deionized water on top of the 2000-μm sieve, resulting in slaking of the soil. Aggregate separation was achieved by manually moving the sieve approximately 3 cm up and down for 50 times during a period of 2 min. After the 2-min cycle, the stable >2000-μm

Table 1. General characteristics of the agricultural experiment field sites.

Crop rotation	Variety	Fertilizer (N, P, K)†	Texture (S, Si, C)‡	MAP§	MAT¶
			g kg^{-1}	mm	°C
		Passo Fundo			
R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.)			(240, 130, 630)	1787	17.5
R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat					
R2B–maize/oat/soybean/wheat/soybean/vetch					
R2C–soybean/wheat/soybean/vetch/maize/oat					
Soybean	BR4 or BR16	(0, 48, 60)			
Maize	XL-530	(30, 45, 55)			
Wheat	BR23 or BR16	(20, 28, 40)			
Oat	UFRGS 7	(0, 0, 0)			
Vetch	Common	(0, 0, 0)			
		Londrina			
R1–soybean/wheat/soybean/lupin/maize/oat			(200, 80, 720)	1622	20.6
R2–maize/oat/soybean/wheat/soybean/lupin					
R3–soybean/lupin/maize/oat/maize/wheat					
Soybean	Embrapa 48	(0, 44, 44)			
Maize	Cargill 805	(80, 44, 44)			
Wheat	Ocepar 18	(32, 28, 40)			
Oat	Embrapa 139	(0, 0, 0)			
Lupin	9710	(0, 0, 0)			

† NPK is mean amount of N, P_2O_5, and K_2O.
‡ (%S, Si, C) = % sand, % silt, % clay.
§ MAP is mean annual precipitation.
¶ MAT is mean annual air temperature.

aggregates were gently back washed off the sieve into an aluminum pan. Floating organic material (>2000 μm) was decanted and discarded because this large organic material is, by definition, not considered SOM. The aggregates were oven dried (50°C), weighed and stored in glass jars at room temperature.

The MWD was calculated as:

$$\text{MWD} = (M_{>2000} \times 5) + (M_{250\text{–}2000} \times 1.125) + (M_{53\text{–}250} \times 0.151) + (M_{<53} \times 0.0265)$$

Where M is the proportion of the soil weight in the aggregate class with a size given in the subscript.

Carbon and Nitrogen Analysis

Carbon and N concentrations were measured with a LECO CHN-100 analyzer (Leco Corp., St. Joseph, MI) for the aggregate-size fractions. For appropriate comparisons between treatments and sites it was necessary to correct for the sand content in each aggregate-size class (Elliott et al., 1991). The sand content was determined by isolating, drying, and weighing the >53-μm fraction after shaking 5 g of aggregates in 15 mL of water with 12 glass beads for 18 h.

Calculation of Carbon and Nitrogen Stocks

To correct for differences in soil bulk density between tillage and/or rotation treatments, stocks of C and N in the soil to a depth of 20 cm were calculated using the procedure described by Angers et al. (1997) based on equal mass of soil in the soil profile.

Iron and Aluminum Analysis

Non-crystalline inorganic forms of Fe and Al were determined by the dithionite-citrate method described by Blakemore et al. (1987). All aggregate-size classes from the Londrina site were analyzed by taking a 1-g subsample, which was dispersed in 50 mL of a solution containing 20 g L^{-1} of sodium dithionite and 220 g L^{-1} sodium citrate. This suspension was shaken overnight and left to stand for 24 h. A 1-mL aliquot was then diluted to 50 mL and left to stand for 2 d longer. The supernatant was analyzed for Fe and Al by atomic absorption spectrophotometry (Zeeman Atomic Absorption Spectrometer, 4100 ZL, PerkinElmer, Wellesley, MA).

Statistical Analysis

In Londrina, the field experiment (2 tillage treatments × 3 rotations) was arranged in a randomized complete block (factorial) design with four replicates. The Passo Fundo field experiment (2 tillage treatments × 4 rotations) was arranged in a randomized complete block (split plot) design with three replicates with the tillage treatments in the main plots and rotations in subplots. At both sites, the areas of NV were outside of the experimental design and therefore not included in the statistical analyses. The data were initially analyzed using MSTAT-C software (Michigan State University, East Lansing, MI) for ANOVA to determine the effects of the main variables (tillage and rotation) on the measured parameters. Where it was necessary to compare C or N contents of different aggregate-size classes, these size classes were considered as further split-plots.

Since the experiment at Londrina was a factorial design with all treatments in the main plots, it was necessary to examine the effect of the different crop rotation on any parameter within the same tillage treatment. Therefore, the variance associated with the difference between the individual means was compared with that of the residual and the F test was applied.

For the split plot design of the experiment at Passo Fundo, we used the procedure described by Little and Jackson-Hills (1978). The calculation of the least significant difference between means (LSD − Student) was applied where:

$$LSD_{0.05} = t_{ab}\sqrt{\{2[(b - 1)\text{Eb} + \text{Ea}]/rb\}} \qquad [1]$$

where b is the number of subplot treatments, r the number of replicates, Ea and Eb are the mean squares of the subplot and main plot errors, respectively, and t_{ab} is the weighted t value for main plots and subplots calculated as described by Little and Jackson-Hills (1978).

These procedures were performed on the software SISVAR, produced by the Federal University of Lavras (UFV), Lavras, Minas Gerais. Statistical significance was determined at the $P < 0.05$ level except if indicated differently.

RESULTS

Carbon and Nitrogen Inputs

In the Passo Fundo experiment, total C and N inputs in crop residues were higher in the 3-yr rotation (R2—58.1 and 55.6 Mg C ha^{-1}, and 1.92 and 1.85 Mg N ha^{-1} for NT and CT, respectively) than in the continuous soybean–wheat (R1—44.2 and 41.6 Mg C ha^{-1}, and 1.23 and 1.17 Mg N ha^{-1}, respectively), but there were only minor differences between the two tillage systems (Sisti et al., 2004).

In the Londrina experiment, while residue C and N inputs from each crop were very different in different years (Sisti et al., 2004) the total C and N inputs for the different rotations and tillage treatments were very similar ranging from 45 to 46 Mg C ha^{-1}, and from 1.34 to 1.66 Mg N ha^{-1} (Sisti et al., 2004).

Whole Soil Characteristics

At both sites, the total organic C and N in the 0- to 5-cm depth interval decreased in the order NV > NT > CT (Table 2). The stocks of organic C and N in the two depth intervals were significantly higher under NT compared with CT at both Passo Fundo and Londrina except for C in the 5- to 20-cm depth interval at Passo Fundo. There were no significant differences in organic C when the crop rotations were compared within tillage systems. The organic C levels in the 0- to 20-cm depth at the Passo Fundo and Londrina sites were remarkably similar.

The bulk density in the 0- to 20-cm depth interval was not significantly affected by tillage at Passo Fundo (Table 2). At Londrina, there were no differences in bulk density between the two depth intervals under CT owing to the mixing of the soil in the plow layer. However, under NT the bulk density was 1.03 g cm^{-3} in the 0- to 5-cm layer, significantly lower than that in the 5- to 20-cm layer (1.23 g cm^{-3}). At the Londrina site, total porosity was significantly affected by tillage treatment; it was higher under NT compared with CT. In contrast, soil porosity was not affected by crop rotation, except in the 5- to 20-cm layer the wheat–soybean rotation (R1) differed from the other rotations (Table 2).

Table 2. Soil bulk density, soil porosity, and stocks of soil organic C and N in the soil surface layers (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) and four crop rotations in Passo Fundo versus three rotations in Londrina.†

	Crop rotation	0–5 cm C	0–5 cm N	0–5 cm Bulk density	0–5 cm Porosity	5–20 cm C	5–20 cm N	5–20 cm Bulk density	5–20 cm Porosity
		g m^{-3}	g m^{-3}	kg dm^{-3}	cm^3 dm^{-3}	g m^{-3}	g m^{-3}	kg dm^{-3}	cm^3 dm^{-3}
					Passo Fundo				
NV	–	1613	159	0.97	ND¶	3108	317	1.07	ND
NT	R1	1135 a‡	108 a	–	ND	3471 a	358 a	–	ND
	R2A	1134 a	108 a	–	ND	3483 a	344 ab	–	ND
	R2B	1139 a	103 a	–	ND	3419 a	308 b	–	ND
	R2C	1176 a	117 a	–	ND	3364 a	310 b	–	ND
	Mean	1146 A§	109 A	1.11 A		3457 A	330 A	1.37 A	
CT	R1	773 a	70 b	–	ND	3366 a	331 a	–	ND
	R2A	864 a	84 ab	–	ND	3432 a	310 ab	–	ND
	R2B	787 a	78 ab	–	ND	3380 a	287 b	–	ND
	R2C	856 a	87 a	–	ND	3359 a	315 a	–	ND
	Mean	820 B	80 B	1.10 A	–	3384 A	311 B	1.37 A	–
	CV, %	8.0	10.2	–	–	1.8	2.9		–
					Londrina				
NV	–	1954	230	0.94	583	2875	297	1.01	552
NT	R1	1161 a	111 a	1.03 a	601 a	2616 a	265 a	1.29 a	491 b
	R2	1112 a	100 a	1.03 a	600 a	2587 a	263 a	1.21 ab	560 a
	R3	1073 a	107 a	1.05 a	582 a	2425 a	251 a	1.20 b	542 a
	Mean	1116 A	106 A	1.03 A	594 A	2542 A	260 A	1.23 A	531 A
CT	R1	923 a	91 a	1.22 a	515 a	2303 a	246 a	1.21 a	550 a
	R2	865 a	87 a	1.23 a	511 a	2213 a	223 a	1.25 a	499 b
	R3	906 a	89 a	1.25 a	511 a	2270 a	267 a	1.29 a	500 b
	Mean	898 B	89 B	1.23 B	512 B	2264 B	245 B	1.25 A	516 B
	CV, %	9.3	11.5	7.1	4.2	9.3	8.6	4.5	4.5

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of C and N stocks, bulk density, or porosity are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same tillage treatment, depth interval and agricultural site.

§ Values followed by the same UPPERCASE letter indicate that the means of C and N stocks, bulk density, or porosity are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same depth interval and agricultural site.

¶ Not determined.

Aggregate-Size Distribution

The MWD was generally higher under NT than under CT, and this difference was significant ($P < 0.01$) at Londrina, being 55 and 26% higher in the 0- to 5- and 5- to 20-cm depth intervals at this site, respectively (Table 3). In the NT of the Passo Fundo site, MWD was higher in the soil under the more diverse rotations (R2) than under the continuous wheat–soybean (R1) but this difference was only statistically significant in the 5- to 20-cm depth interval. At Londrina, the last four crops were soybean, lupin, maize, and oats in R1; for R2 this sequence was soybean, wheat, soybean, and lupin; and for R3 maize, oats, maize, and wheat. Across the treatments, the MWD seemed to bear no relationship to legume–cereal content of the rotations.

The aggregate-size distribution was dominated by macroaggregates (>2000 plus 250- to 2000-μm sized aggregates) at both sites (Table 4). At Passo Fundo the proportions of macroaggregates were between 820 g kg^{-1} for NT and 770 g kg^{-1} for CT (means of both depth intervals). Regardless of crop rotation a higher proportion of large macroaggregates were found under NT compared with CT, except the difference was not significant in the 0- to 5-cm layer at Passo Fundo.

At Londrina, the CT-R2 treatment (sampled immediately after lupin preceded by soybean) had the fewest large macroaggregates (>2000 μm—37 g kg^{-1} in the 0- to 5-cm depth) and the greatest amount of microaggregates (<250 μm—475 g kg^{-1}) (Table 4) of all treatments. In both tillage treatments, the Londrina-R1 (sampled immediately after oats, preceded by maize) showed the highest MWD and proportion of macroaggregates.

The proportion of macroaggregates in the NV areas was higher than in cropped areas. At Londrina, the macroaggregates constituted approximately 94% of total soil dry weight (0–5 cm) in the NV area, 21 and 36% higher than under NT and CT, respectively. In contrast, the macroaggregate proportion at Passo Fundo (0–5 cm) was 84% of total dry soil weight for NV and only decreased by 4% under NT, and 14% under CT.

Aggregate Carbon and Nitrogen Concentrations and C/N Ratio

At Passo Fundo, organic C and N concentrations were significantly higher in the three larger aggregate-size classes (>53 μm) under NT when compared with CT in the 0- to 5-cm depth interval (Tables 5 and 6) and this was reflected in the total C and N stocks at this depth interval (Table 2). No significant differences in C and N content of these aggregate classes were found between NT and CT in the 5- to 20-cm depth interval. In the 0- to 5-cm depth interval of the NT at Passo Fundo, there were generally lower organic C and N contents of the micro- and macroaggregates in the R2A rotation than in the other rotations.

Table 3. Mean weight diameter (MWD) (mm) of aggregates in the soil surface layers (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) and four crop rotations in Passo Fundo versus three rotations in Londrina.†

	Tillage treatment							
	Depth interval 0–5 cm				Depth interval 5–20 cm			
Rotation	NV	NT	CT	Mean	NV	NT	CT	Mean
	mm							
				Passo Fundo				
R1	–	1.54 a‡	1.34 a	1.44 *a*§	–	1.41 c	1.55 b	1.48 *c*
R2A	–	1.96 a	1.42 a	1.69 *a*	–	1.85 ab	1.84 ab	1.85 *ab*
R2B	–	1.92 a	1.36 a	1.64 *a*	–	1.81 b	1.68 ab	1.75 *bc*
R2C	–	1.95 a	1.27 a	1.61 *a*	–	2.20 a	1.98 a	2.09 *a*
Mean	1.64	1.84 A¶	1.34 A	–	2.06	1.82 A	1.76 A	–
Coef. variation, %		19.58				14.88		
				Analysis of variance				
Factor: Tillage (T)		ns				ns		
Rotation (R)		ns				*		
Interaction T × R		ns				ns		
				Londrina				
R1	–	1.58 a	1.03 a	1.31 *a*	–	1.41 a	1.06 a	1.23 *a*
R2	–	1.30 b	1.01 a	1.25 *a*	–	1.21 b	0.95 b	1.08 *b*
R3	–	1.50 ab	0.79 b	1.05 *b*	–	1.15 b	0.96 ab	1.05 *b*
Mean	2.41	1.46 A	0.94 B	–	1.46	1.25 A	0.99 B	–
Coef. variation, %		10.80				6.17		
				Analysis of variance				
Factor: Tillage (T)		**				**		
Rotation (R)		**				**		
Interaction T × R		ns				ns		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of MWD are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same tillage treatment, depth interval, and agricultural site.

§ Values followed by the same italic lowercase letter indicate that the means of MWD are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same depth interval and agricultural site.

¶ Values followed by the same UPPERCASE letter indicate that the means of MWD are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same depth interval and agricultural site.

At the Londrina site, organic C concentrations in the aggregates of <2000 μm were significantly higher under NT than under CT in the 0- to 5-cm layer. The N concentration showed the same trend, except for that the difference in N concentration in the <53-μm fraction was not significant, and the N concentration was significantly higher under NT than CT in the largest aggregate fraction (>2000 μm). In addition, immediately after the sequence soybean/lupin–maize/oats (R1) at this site, the aggregate C and N contents were higher in the 0- to 5-cm depth interval under NT (significantly so for most aggregate-size classes) than in the samples taken immediately after the sequences soybean/wheat–soybean/lupin (R2) or maize/oats–maize/wheat (R3).

At both sites, there were no consistent differences in C/N ratio of any aggregate-size class between rotations or tillage treatments. However, there was clearly a considerably lower C/N ratio in all aggregate-size classes (>53 μm) of the soil under the NV than those under NT and CT treatments at both sampling depths.

With regard to the C content of the aggregate-size classes, we did not observe any trends across aggregate-size classes, except the largest aggregate-size class in Londrina had a higher C content than the other aggregate-size classes (Table 5). The same was observed for the N content of the aggregates (Table 6). In addition, there were no significant differences in C/N ratio between aggregate-size classes (Table 7).

Iron and Aluminum Concentration in the Aggregates

The concentration of Fe and Al did not vary with treatment or depth for any aggregate-size class in Londrina (data not shown). The average Fe concentration was 130 g kg^{-1} of aggregates, and the Al was 4.8 g kg^{-1}. Both soils are characterized by a clay mineralogy dominated by kaolinite.

DISCUSSION

Carbon and Nitrogen Stocks

The long-term experiment at Passo Fundo was installed in 1986 to compare the effects of different tillage treatments on crop yields and on the incidence of crop diseases and pests in several soybean-based crop rotations. It was found that increasing the diversity of crops in the two-crop rotation soybean–wheat (R1), by introducing vetch, maize, and oats (R2), improved crop yields and reduced the incidence of root diseases, especially of wheat (Santos et al., 2000). As management of the crops, including fertilizer supply, was identical under both NT and CT, this experiment was ideal to study the long-term effects of the different rotations and tillage treatments on soil structure and organic matter. Sisti et al. (2004) made a detailed study of the SOM stocks to a depth of 100 cm under these rotations and it was

Table 4. Aggregate-size distribution (g kg^{-1} soil) in the soil surface layer (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) and four crop rotations in Passo Fundo versus three rotations in Londrina.†

Site	Crop rotation	0–5 cm				5–20 cm			
		<53 μm	53–250 μm	250–2000 μm	>2000 μm	<53 μm	53–250 μm	250–2000 μm	>2000 μm
		g kg^{-1} soil							
		Passo Fundo							
NV	–	7	150	669	173	7	132	584	277
NT	R1	13 ab‡	176 a	593 a	218 a	8 a	188 a	679 a	124 c
	R2A	9 b	226 a	551 a	214 a	8 a	166 ab	594 b	232 ab
	R2B	19 a	155 a	575 a	251 a	15 a	148 ab	614 ab	219 b
	R2C	13 ab	182 a	541 a	262 a	7 a	121 b	560 b	312 a
	Mean	14 A§	185 A	565 A	236 A	9 B	156 A	613 A	222 A
CT	R1	16 a	301 a	546 a	136 a	11 a	176 a	657 a	157 b
	R2A	13 a	257 a	583 a	144 a	8 a	135 a	634 a	223 ab
	R2B	29 b	248 a	592 a	131 a	25 a	170 a	610 a	195 ab
	R2C	17 a	299 a	567 a	116 a	9 a	122 a	645 a	225 a
	Mean	19 A	276 A	572 A	132 A	13 A	150 A	629 A	200 B
	CV, %	24.1	32.7	4.8	56.33	4.23	16.0	3.7	2.9
		Londrina							
NV	–	6	55	593	346	22	172	671	135
NT	R1	39 a	222 a	552 a	187 a	39 a	262 a	549 a	151 a
	R2	40 a	248 a	591 a	121 b	39 a	273 a	585 a	103 b
	R3	24 b	233 a	583 a	161 a	36 a	289 a	586 a	89 b
	Mean	34 B	234 B	575 A	156 A	38 A	275 B	573 A	114 A
CT	R1	42 b	336 b	550 a	72 a	41 a	296 a	592 a	70 a
	R2	57 a	418 a	488 a	37 a	46 a	326 a	578 a	51 a
	R3	41 b	349 ab	540 a	71 a	46 a	304 a	601 a	49 a
	Mean	47 A	367 A	526 B	60 B	44 A	309 A	590 A	56 B
	CV, %	16.3	17.0	7.6	22.1	17.9	13.2	7.3	17.1

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of the aggregate-size distribution are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same tillage treatment, depth interval and agricultural site.

§ Values followed by the same UPPERCASE letter indicate that the means of the aggregate-size distribution are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same aggregate-size class, depth interval and agricultural site.

found that there was no significant difference in C and N stocks between NT and CT in the continuous soybean–wheat rotation (R1). However, under the more diverse R2, stocks of C and N to 30-cm depth were 9.1 Mg C and 1.38 Mg N ha^{-1} greater under NT than CT, and to 100-cm depth this difference was even greater amounting to 17 Mg C and 2.0 Mg N ha^{-1}. The existence of higher stocks of soil C and N under NT across all treatments were confirmed in this present study even though samples were taken only to a depth of 20 cm (Table 2). However, the effect of higher C and N inputs in the more diverse crop rotations was not observed at Passo Fundo. The lack of effect by diverse crop rotations was expected at Londrina because residue-C and N input levels were not different between crop rotation treatments and it has been shown that more complex crop rotations only lead to a sequestration of C and N if they result in greater C and N inputs (e.g., Havlin et al., 1990).

Even though the Londrina experiment had only been established 4 yr before the time of sampling for this study, it was already possible to detect significantly higher stocks of C and N in the 0- to 5- and 5- to 20-cm depth intervals in the soil under NT compared with CT (Table 2). This fast response might be related to the high clay content (720 g kg^{-1}) and/or depleted soil C level due to at least 15 yr of CT practices before the installation of the experiment. Similarly, the long-term CT practices at Londrina probably resulted in the similar organic C and N concentration in Londrina and Passo Fundo, even though the higher clay content at Londrina than at Passo Fundo (630 g kg^{-1}) would be expected to lead to greater organic C concentration at Londrina (Feller and Beare, 1997).

Aggregation

At both sites the data showed consistently that CT decreased the proportion of the largest macroaggregate class (>2000 μm) in comparison with NT management and there was a corresponding increase in the proportion of the 53- to 250-μm aggregate class. This breakdown of the larger aggregates by tillage was also evidenced by the lower MWD of aggregates under CT, which was statistically significant ($P < 0.05$) at both sites except in the 5- to 20-cm depth interval at Passo Fundo.

At Passo Fundo, the composition of crops in the three R2 rotations was identical (soybean twice and maize once as a summer crop, and wheat, oats, and vetch as winter crops), only the year in which the rotation started was different. However, the R1 rotation consisted of a continuous annual cycle of wheat–soybean. Our results suggest that the addition of vetch, maize, and oats to the wheat–soybean rotation, favored aggregate formation under NT in that the MWD of the aggregates and the proportion of macroaggregates in R2 was higher than in R1, especially in the 5- to 20-cm depth interval.

The observation that in both tillage treatments, the Londrina-R1 (sampled immediately after oats, preceded by maize) showed the highest MWD and proportion of

Table 5. Aggregate C concentration (g C kg^{-1} sand-free aggregates) in the soil surface layer (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) and four crop rotations in Passo Fundo versus three rotations in Londrina.†

Site	Crop rotation	0–5 cm				5–20 cm			
		<53 μm	53–250 μm	250–2000 μm	>2000 μm	<53 μm	53–250 μm	250–2000 μm	>2000 μm
		g C kg^{-1} aggregates							
					Passo Fundo				
NV	–	7.3	52.9	36.2	37.2	7.1	26.3	26.2	23.8
NT	R1	12.9 ab‡	32.1 ab	33.1 a	34.9 a	8.4 b	22.4 a	21.2 a	21.9 a
	R2A	9.1 b	30.6 b	29.7 b	32.5 a	7.6 b	21.9 a	20.4 a	22.5 a
	R2B	18.6 a	31.9 ab	34.5 a	33.9 a	14.8 a	22.8 a	22.3 a	23.3 a
	R2C	13.1 ab	34.9 a	32.9 a	33.8 a	6.6 b	18.8 b	21.1 a	22.0 a
	Mean	13.4 *a*§B¶	32.1 *a*A	32.5 *a*A	33.8 *a*A	9.4 *b*B	21.5 *a*A	21.29 *a*A	22.4 *a*A
CT	R1	16.2 b	24.1 a	21.0 a	20.8 a	10.9 b	23.7 a	20.6 a	21.4 b
	R2A	13.1 b	20.6 a	21.5 a	23.0 a	8.1 c	19.2 ab	20.3 a	21.8 ab
	R2B	28.6 a	20.5 a	21.6 a	21.7 a	24.4 a	20.6 b	29.7 b	29.8 a
	R2C	16.5 b	21.5 a	22.4 a	26.5 a	8.6 ab	17.9 c	20.3 a	21.6 ab
	Mean	18.6 *a*B	21.7 *b*A	21.6 *b*A	23.0 *b*A	13.0 *a*C	20.3 *a*B	22.7 *a*AB	23.6 *a*A
	CV, %	24.0	3.9	6.9	15.2	4.2	6.5	18.1	17.2
					Londrina				
NV	–	36.5	43.8	43.9	42.1	19.3	18.0	19.0	23.10
NT	R1	23.6 a	23.3 a	25.0 a	27.6 a	16.7 a	18.1 a	18.6 a	21.2 a
	R2	21.6 ab	19.1 b	20.5 b	25.4 a	16.8 a	17.9 a	18.7 a	22.6 a
	R3	19.2 b	20.2 ab	20.5 b	26.0 a	17.5 a	18.2 a	18.8 a	21.7 a
	Mean	21.5 *a*B	20.9 *a*B	22.0 *a*AB	26.4 *a*A	17.0 C	18.1 *a*BC	18.7 *a*B	21.8 *a*A
CT	R1	17.8 a	18.9 a	19.5 a	27.0 a	17.4 a	18.8 a	18.8 a	21.9 a
	R2	17.2 a	18.6 a	18.8 a	24.2 a	16.8 a	18.3 a	18.8 a	25.8 a
	R3	18.2 a	19.1 a	19.5 a	28.2 a	17.4 a	19.1 a	18.8 a	23.1 a
	Mean	17.7 *b*B	18.9 *b*B	19.3 *b*B	26.4 *a*A	17.2 *a*B	18.7 *a*B	18.8 *a*B	23.6 *a*A
	CV, %	9.1	11.2	7.4	15.6	9.2	11.9	8.1	15.0

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of C concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same aggregate-size fraction, tillage treatment, depth interval, and agricultural site.

§ Values followed by the same italic lowercase letter indicate that the means of C concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same aggregate-size fraction, depth interval and agricultural site.

¶ Values followed by the same UPPERCASE letter indicate that the means of C concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between aggregate-size classes within the same tillage treatments, depth interval and agricultural site.

macroaggregates suggests a positive influence of the cereal root systems on macroaggregate formation. Campos et al. (1999) found a similar tendency when comparing the effect of different cover crops on soil aggregation under NT: Oats promoted a greater aggregate stability when compared with lupin, vetch, or fallow. However, Paladini and Mielniczuk (1991) and Campos et al. (1999) observed that 3 yr of cultivation of legume cover crops with CT practices, but alternated with NT maize, promoted a higher proportion of macroaggregates.

The smaller differences in macroaggregation between the cultivated systems and the NV in Passo Fundo than in Londrina are probably due to different site histories. The long-term experiment at Passo Fundo was sampled 14 yr after its establishment, before this time the area was NV. In contrast, the Londrina experiment had only been established 4 yr before sampling but the area was previously under CT for at least 15 yr.

Aggregate Associated Carbon and Nitrogen

Within tillage treatments, the effect of crop rotation was observed in the largest aggregate class of CT. Under the R3 at Londrina, where there was a larger input of residues with high C/N ratio in the year of sampling, a higher concentration of C in the macroaggregates was observed as compared with the R2, which was under soybean following lupin at the time of sampling. Both of these legume crops have a low C/N ratio. At the Passo Fundo site, in rotation R2C (soybean/wheat–soybean/vetch–maize/oats) there was a higher input of residues of high C/N ratio in the year immediately before sampling than in the other three rotations (Sisti et al., 2004), where in the last year the crop sequence was either soybean–wheat (R1 and R2A) or soybean–vetch (R2B). However, there was no apparent tendency for the C/N ratio of the organic matter associated with the aggregates to be any lower in these latter treatments (Table 7). The results from the Londrina study were very similar; in the year immediately before sampling, in R2 the sequence was of two legumes (soybean followed by lupin) and for R1 and R3 the crops were both cereals (maize–oat and maize–wheat, respectively), but this did not result in consistent differences in C/N of all aggregate-size classes.

The lack of differences in C and N content and C/N ratio across aggregate-size classes indicate that, in contrast to 2:1 clay-dominated soils, the 1:1 clay plus oxide dominated soils we studied, do not express an aggregate hierarchy (Tisdall and Oades, 1982). This is in accordance with several studies (Elliott et al., 1991; Feller et al., 1996; Oades and Waters, 1991; Six et al., 2002), which reported the inexistence of aggregate hierarchy in 1:1 clay plus oxide dominated soils. The high Fe and Al contents, along with kaolinite, in the Londrina and Passo Fundo soils suggest that Fe and Al oxides serve as the principal agents of aggregation. Therefore, aggre-

Table 6. Aggregate N content (g N kg^{-1} sand-free aggregate) in the surface layer (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) and four crop rotations in Passo Fundo versus three rotations in Londrina.†

Site	Crop rotation	0–5 cm				5–20 cm			
		<53 μm	53–250 μm	250–2000 μm	>2000 μm	<53 μm	53–250 μm	250–2000 μm	>2000 μm
		g N kg^{-1} aggregates							
					Passo Fundo				
NV	–	3.66	5.48	3.59	2.47	2.84	2.80	2.71	2.59
NT	R1	2.31 a‡	2.79 b	2.83 a	2.93 a	2.20 a	2.20 a	1.87 a	2.02 a
	R2A	2.40 a	2.90 b	2.80 a	3.03 a	2.23 a	2.16 a	1.90 a	2.15 a
	R2B	2.17 a	2.97 ab	3.26 a	3.08 a	1.98 a	2.20 a	1.98 a	2.22 a
	R2C	2.38 a	3.31 a	2.76 a	3.03 a	2.20 a	2.11 a	1.91 a	2.10 a
	Mean	2.31 *b*§B¶	2.99 *a*A	2.91 *a*A	3.02 *a*A	2.13 *a*A	2.17 *a*A	1.91 aA	2.12 *a*A
CT	R1	1.98 a	1.78 a	1.88 a	2.14 a	2.08 a	2.11 a	1.86 c	1.92 a
	R2A	2.01 a	1.81 a	1.90 a	2.08 a	2.08 a	1.93 a	1.91 ab	1.98 a
	R2B	1.94 a	1.95 a	1.89 a	2.02 a	1.73 a	1.94 a	2.79 a	2.94 a
	R2C	1.88 a	1.99 a	2.10 a	2.90 a	2.08 a	1.92 a	1.92 ab	1.97 a
	Mean	1.93 *a*B	1.89 *b*B	1.94 *b*B	2.26 *a*A	1.99 *a*A	1.97 *a*A	2.12 *a*A	2.19 *a*A
	CV(%)	18.29	8.07	13.87	53.16	20.18	17.46	24.50	28.06
					Londrina				
NV	–	4.72	5.43	5.36	5.11	2.51	2.32	2.33	0.37
NT	R1	2.58 a	2.36 a	2.49 a	2.62 a	1.91 ab	1.90 a	1.87 a	2.57 a
	R2	2.16 b	2.00 b	2.08 b	2.53 b	1.72 b	1.89 a	1.91 a	2.12 b
	R3	2.17 b	2.13 ab	2.12 b	2.55 ab	2.06 aB	1.90 a	2.01 a	2.11 b
	Mean	2.30 *a*B	2.17 *a*C	2.23 *a*BC	2.57 *a*A	1.89 *a*B	1.88 *a*B	1.93 *a*B	2.11 *a*A
CT	R1	2.01 a	1.98 a	2.05 a	2.34 a	1.93 a	2.01 a	1.91 a	2.12 a
	R2	1.98 a	1.93 a	1.92 a	2.37 a	1.97 a	1.97 a	1.98 a	2.26 a
	R3	2.22 a	1.97 a	1.92 a	2.26 a	1.95 a	2.01 a	1.92 a	2.22 a
	Mean	2.07 *a*B	1.99 *b*B	1.96 *b*B	2.32 *b*A	1.95 *a*B	2.00 *a*B	1.94 *a*B	2.21 *a*A
	CV(%)	8.68	8.07	9.31	23.49	9.74	12.62	6.76	17.86

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of N concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same aggregate-size fraction, tillage treatment, depth interval, and agricultural site.

§ Values followed by the same italic lowercase letter indicate that the means of N concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same aggregate size fraction, depth interval and agricultural site.

¶ Values followed by the same UPPERCASE letter indicate that the means of N concentration are not significantly different (at $P < 0.05$ according to the Student LSD test) between aggregate size classes within the same tillage treatments, depth interval and agricultural site.

gate formation is less reliant on the binding action of SOM, resulting in no aggregate hierarchy being expressed (Oades and Waters, 1991; Six et al., 2000a, 2000b, 2002).

The lack of existence of aggregate hierarchy and the decrease in C and N content within an aggregate-size class in the order NV > NT ≥ CT precludes the direct linkage between C and N accumulation and aggregation as proposed by Elliott (1986) and Six et al. (2000a). These two studies, based on long-term tillage experiments in temperate soils, suggested that the loss of C with increasing cultivation intensity (i.e., NV < NT < CT) could be partly explained by the observed loss of C-rich macroaggregates and increase in C-depleted microaggregates. These observations were made in temperate soils dominated by 2:1 clays expressing an aggregate hierarchy. In our two Oxisols, we observed a decrease in macroaggregates and increase in microaggregates, but one aggregate-size class was not depleted in C compared with the other. Consequently, the direct link between aggregate loss and C loss is not shown in our data. Six et al. (2000b) also failed to observe this link in a soil with mixed mineralogy from Kentucky.

At Passo Fundo the C concentration in the aggregates under both tillage treatments and in both depth intervals were quite similar to the C concentrations found in the forest. This indicates that the soil aggregation and the C status after 14 yr of NT adoption are close to those under the NV. At the Londrina site, in the 0- to 5-cm depth, in all classes of aggregates, the C concentrations in the forest were higher than in the cultivated area, but similar in the 5- to 20-cm depth. Similar results were found by Elliott et al. (1991), Feller et al. (1996), and Six et al. (2000a) in kaolinitic soils.

CONCLUSIONS

We found that NT increased the number of large water-stable aggregates and maintained higher SOM levels compared with CT in both Oxisols. However, in contrast to reports for soils with high activity clay (2:1) mineralogy, C and N concentrations were similar across aggregate-size classes, that is, there was no clear aggregate hierarchy (Tisdall and Oades, 1982) in these Oxisols. This suggests that while organic matter accumulation was favored by a reduction in tillage disturbance, organic matter plays a secondary role in aggregate formation in these soils with low activity clay (1:1) mineralogy, probably owing to the predominating effect of mineral–mineral binding processes, as previously postulated by Six et al. (2000b). Therefore, our results indicate that an increase in aggregate stability in response to NT implementation seems to be a generality across soil types, but the tight feedback between increases in aggregate stability and SOM content cannot be generalized across

Table 7. Aggregate C/N ratio in the soil surface layer (0–5 and 5–20 cm) of two agricultural sites (Passo Fundo and Londrina) with three treatments (NV = native vegetation; NT = no tillage; CT = conventional tillage) with four crop rotations in Passo Fundo and three rotations in Londrina.†

Site	Crop rotation	0–5 cm				5–20 cm			
		<53 μm	53–250 μm	250–2000 μm	>2000 μm	<53 μm	53–250 μm	250–2000 μm	>2000 μm
					Passo Fundo				
NV	–	11.1	9.7	10.4	10.7	8.5	9.4	9.7	9.2
NT	R1	9.7 a‡	11.5 a	11.7 a	11.9 a	9.3 a	10.2 a	11.3 a	10.9 a
	R2A	9.2 a	10.6 a	10.6 a	10.7 c	9.05 a	10.2 a	10.7 a	10.5 a
	R2B	9.9 a	10.7 a	10.6 a	11.0 ab	10.0 a	10.4 a	11.3 a	10.5 b
	R2C	9.7 a	10.6 a	12.0 a	11.2 ab	9.6 a	8.9 a	11.1 a	10.5 a
	Mean	9.6 A§	10.8 A	11.20 A	11.2 A	9.5 A	9.9 A	11.1 A	10.6 A
CT	R1	9.6 a	13.6 a	11.2 a	9.8 b	9.3 a	11.3 a	11.1 a	11.2 a
	R2A	9.7 a	11.4 b	11.3 a	11.1 a	9.2 a	10.0 a	10.7 a	11.0 a
	R2B	10.3 a	10.5 b	11.4 a	10.8 a	10.3 a	10.7 a	11.0 a	10.2 a
	R2C	9.9 a	10.8 b	10.7 a	9.2 b	10.0 a	9.3 a	10.6 a	11.0 a
	Mean	9.9 A	11.6 A	11.2 A	10.19 B	9.7 A	10.3 A	10.8 A	10.82 A
	CV, %	8.75	10.7	11.2	3.19	8.6	14.1	5.7	18.1
					Londrina				
Forest	–	7.8	8.1	8.2	8.3	7.7	7.8	8.2	8.4
NT	R1	9.2ab	9.9 a	10.0 a	10.5 a	8.7 a	9.6 a	9.8 ab	10.1 a
	R2	10.1 a	9.5 a	9.9 a	10.1 a	8.4 a	9.6 a	10.0 a	10.8 a
	R3	8.9 b	9.5 a	9.7 a	10.2 a	8.4 a	9.6 a	9.3 b	10.3 a
	Mean	9.4 A	9.6 A	9.9 A	10.3 B	8.5 A	9.6 A	9.7 A	10.4 A
CT	R1	8.9 a	9.6 a	9.5 a	11.5 ab	9.1 a	9.3 a	9.8 a	10.4 a
	R2	8.7 a	9.7 a	9.8 a	10.2 b	8.5 a	9.7 a	9.5 a	11.5 a
	R3	8.2 a	9.8 a	10.2 a	12.5 a	8.9 a	9.5 a	9.8 a	10.3 a
	Mean	8.8 A	9.7 A	9.8 A	11.4 A	8.8 A	9.5 A	9.7 A	10.7 A
	CV, %	8.3	5.5	4.7	8.4	5.9	4.4	3.4	12.4

† Crop rotations for the two research sites. Passo Fundo: R1–soybean (*Glycine max* L.)/wheat (*Triticum aestivum* L.); R2A–soybean/vetch (*Vicia villosa*)/maize (*Zea mays* L.)/oat (*Avena sativa*)/soybean/wheat; R2B–maize/oat/soybean/wheat/soybean/vetch; R2C–soybean/wheat/soybean/vetch/maize/oat. Londrina: R1–soybean/wheat/soybean/lupin/maize/oat; R2–maize/oat/soybean/wheat/soybean/lupin; R3–soybean/lupin/maize/oat/maize/wheat.

‡ Values followed by the same lowercase letter indicate that the means of the aggregate C/N ratio are not significantly different (at $P < 0.05$ according to the Student LSD test) between crop rotations within the same tillage treatment, depth interval and agricultural site.

§ Values followed by the same UPPERCASE letter indicate that the means of the aggregate C/N ratio are not significantly different (at $P < 0.05$ according to the Student LSD test) between tillage treatments within the same aggregate size class, depth interval and agricultural site.

soil types. In Oxisols, there is no direct linkage between SOM accumulation and increased aggregate stability under NT.

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