The effect of topography, tillage and stubble grazing on soil structure and organic carbon levels

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Abstract

This study reports the effect of topography, stubble grazing, tillage and the addition of fertilizer on the organic carbon content and structural stability of a typic Hapludoll topsoil under mixed agricultural production. The organic carbon content was significantly higher in the lower area of the slope when harvest residues were not grazed and when conservation tillage was performed. The interaction *tillage x residue* showed the highest carbon content to be attained with reduced tillage and no stubble grazing, and the lowest to be attained with conventional tillage with stubble grazing. Comparisons with minimally altered soil showed the loss of organic carbon to oscillate between 80% with conventional tillage when residues were grazed and 77% when conservation tillage systems were used. With respect to quantities of water-stable aggregates available (four diameter ranges), minimal alteration led to the highest percentages of the most coarse aggregates, while with the different treatments the finest and most coarse aggregates showed the highest percentages. The exception was under direct seeding where the distribution was similar to that for minimal soil alteration, though the percentage of the most coarse aggregates was lower. A linear, positive relationship was found between organic carbon and macroaggregate content. These results may help in the choice of technologies that can improve soil quality.

Key words: organic residue, aggregates, topographic position, technologies, alteration, fertilization

Resumen

Efecto de la topografía, las labranzas y el pastoreo de los rastrojos sobre el carbono orgánico y la estructura del suelo

Se estudió el efecto de la topografía, pastoreo de rastrojos, labranzas y fertilización sobre el contenido de carbono orgánico y la estabilidad estructural del horizonte superficial de un Hapludoll típico bajo producción mixta, y se comparó con el mismo suelo con mínima alteración. El contenido de carbono orgánico fue significativamente más elevado en la posición más baja de la pendiente, cuando no se pastorearon los residuos de cosecha y se usaron labranzas conservacionistas. La interacción *labranza x residuo* indicó que el mayor contenido de carbono se observa en labranza reducida no pastoreada y el menor en labranza convencional con pastoreo de rastrojos. La comparación con la situación de mínima alteración indicó que la pérdida de carbono orgánico oscila entre el 80% en labranza convencional cuando se pastorean los rastrojos y el 77% en labranzas conservacionistas. En cuanto a la cantidad de agregados estables al agua de cuatro rangos de diámetros, se observó que en la situación de mínima alteración los porcentajes más elevados se encontraron en los agregados más gruesos, mientras que en los tratamientos estudiados la distribución fue bimodal, con porcentajes más elevados en los agregados más finos y más gruesos, excepto en siembra directa, que tuvo una distribución semejante a mínima alteración, aunque con valores inferiores de agregados más gruesos. Se encontró relación lineal y positiva entre el carbono orgánico y los macroagregados. Los resultados obtenidos pueden contribuir a la elección de tecnologías para iniciar un proceso que llevaría al suelo a un nuevo estado de equilibrio tendiente a una mayor calidad.

Palabras clave: restos orgánicos, agregados, posición topográfica, tecnologías, alteración, fertilización.

Introduction

The natural, seasonal change in the condition of soils has been modified by Man, largely through the replacement of wild vegetation and by tillage. This has led to reductions in soil chemical, physical and biological functions, the extent depending on the soil's resistance to change (Herrick and Wander, 1998). Soil structure and organic matter content are indicators of this type of change. As the location of organic components is modified and their protection reduced, the speed of their biodegradation increases (Balesdent *et al*., 2000) and the aggregation of the soil diminishes.

The organic matter content of mineral soils is linked to factors involved with soil formation, such as climate, the vegetation and other organisms present, topography, starting material and time. When these factors (except for time) remain unaltered, the quantity and quality of the soil's organic matter enter into stable equilibrium (Jenny, 1941; Stevenson, 1985; Janzen *et al*., 1997). The climate and mineralogy of the soil have a very marked influence on the accumulation and storage of organic matter since temperature and humidity affect the amount of biomass produced and the ability of the mineral components to retain it (Carter and Stewart, 1996).

The organic matter content of unaltered soils is always higher than that of tilled soils since the native vegetation is not removed. Further, erosion is practically non-existent and oxidation is minimal (Rasmussen and Collins, 1991). However, when the natural vegetation is replaced and the soil tilled, an exponential loss of carbon occurs (Duiker and Lal, 1999). During the first stage (10-20 years), this loss is very rapid. This is followed by a period during which losses are slower until a new equilibrium is reached at 50-60 years (Jenny, 1941; Campbell, 1978; Mitchell *et al*., 1991; Buyanovsky *et al*., 1996). Fenton *et al*. (1999) calculated some 44% of organic carbon (OC) to be lost from the upper soil in the first 28 years, followed by a 33% loss over the next 46 before reaching a new equilibrium. Bricchi (1996) indicated a 65% loss occurred from the top 12 cm of soil over a 90 year period in an area where agriculture had been practised over the last 25 years and conventional tillage employed. In the majority of cases, such losses are accompanied by great deterioration of the soil structure.

Some authors indicate that the equilibrium reached varies with the crop sequence (Ridley and Hedlin, 1968; Unger, 1994), with the type and quantity of harvest residue (Rasmussen *et al*., 1980), and with the tillage practices employed (Unger, 1968; Janzen *et al*., 1997). Rasmussen and Collins (1991) report that the quantity of residue supplied to the soil has a greater effect than the actual type of residue. In a typic Hapludoll, Larson *et al*. (1972) found that similar quantities of different types of residue led to similar increases in the amount of OC. To prevent losses of organic matter, these authors indicate 6 t ha^{-1} year^{-1} of maize residue to be necessary, while 16 t ha^{-1} year^{-1} for 11 years would be necessary to increase soil organic matter content by 47%.

When the dry matter produced by crops is removed for food or forage and little is returned to the soil, the oxidation and decomposition of organic residues increases, and the soil begins to degrade (Rasmussen and Collins, 1991). Bauer and Black (1981) and Buyanovsky *et al*. (1996) showed that maize and wheat monoculture with complete removal of harvest residues for 35 years led to 23-28% losses of OC. However, this trend was reversible since in the following 40 years, during which residues were returned to the soil, continuous increments in OC were achieved, in some cases to beyond the original level recorded.

The speed at which residues decompose is controlled by a number of factors including humidity and temperature (Orchard, 1983). The location of residues in the soil, determined by tillage practices and the machinery employed (Johnson, 1988), is also important. Studies undertaken in temperate regions have shown important increases in soluble OC in direct seeded soils compared to conventionally tilled soils, especially close to the surface (Dick, 1983).

Conservation tillage has a direct impact on the soil environment in different ways, one of which is the maintenance or increase of OC through the return of crop residues to the soil (Larson *et al*., 1972; Havlin *et al*., 1990; Paustian *et al*., 1997). The results of several studies confirm that the moldboard plow reduces the surface organic matter content compared to conservation tillage practices such as direct seeding (Angers *et al*., 1992).

Crop residues increase the formation of microbial biomass, of metabolic products and organic matter, all of which help maintain soil aggregates (Stott *et al*., 1995). Further, biotic factors play an important role in the formation of aggregates in soils with clay contents of < 35% (Oades, 1993).

Organic matter is involved in the formation and stabilisation of aggregates, especially via the quantity

of carbohydrates, microbial biomass and fungal hyphae (Lynch, 1984). This is why pastureland soils have more stable aggregates than cultivated soils: non-tilled soils are more stable than tilled soils, and the stability of the latter tends to diminish over years of tillage (Tisdall, 1994). The organic matter surrounding aggregates helps protect them from collapse since it reduces the speed at which they take up moisture (Zhang and Hartge, 1992). Baldock and Kay (1987) showed that the rate of structural deterioration caused by maize cultivation under a conventional tillage regimen was greater than the rate of recovery promoted by the growth of *Bromus inermis* L. pasture.

A relationship exists between the size of aggregates and the persistence of the links between the particles composing them: aggregates of < 20 μ have persistent linkages that are unaffected by soil management, while those of 20-30 μ have linkages that are temporary, lasting months or years. Macroaggregates of 200-2,000 μ have linkages generated by transitory agents such as microbes and polysaccharides of plant origin. These linkages, which may last days or weeks, are produced when plant and animal remains are incorporated into the soil and later degraded by microbial activity. Such aggregates are affected by soil management (Tisdall and Oades, 1982; Elliott, 1986).

The aim of the present work was to determine the influence of the use of the soil, topographical position, and technological factors such as tillage, stubble grazing and the provision of fertilizer on the organic matter content and stability of soil aggregates belonging to a typic Hapludoll west of the River Cuarto, Argentina.

Material and Methods

Description of the experimental site

This experiment was performed at the teaching and research facility of the *Facultad de Agronomía y Veterinaria, Universidad Nacional de Río Cuarto*, in the Province of Córdoba, Argentina (latitude 32° 57' S, longitude 64° 50' W, altitude 562 m). The mean temperatures of the region vary between 8ºC for the coldest month and 23ºC for the warmest. Mean annual precipitation is 850 mm (80% of this falling in spring-summer). The natural vegetation is open broadleaf woodland fragmented by pastureland. The relief is rolling with slopes of 3-4%. Mean slope length is 1500

m, with an east-west direction. The original soil-forming material is a loess sediment with a very fine sandy loam texture. The soil is a typic Hapludoll with a coarse, mixed thermal texture (Cantero *et al.*, 1984).

The area where the trial was performed had been worked since 1920 following extensive subdivision of the land. The first crops grown were winter crops such as wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.) and rye (*Secale cereale* L.). These were later replaced by summer crops such as maize (*Zea mays* L.), sunflower (*Helianthus annuus* L.) and soybean (*Glycine max* L.). Presently the land is used for both agriculture and stock raising, depending on international markets.

Experimental design

Starting in August 1994, the experiment involved a production system with a maize-maize-sunflower-maize-sunflower sequence. The sunflower variety used was 'Maiten' and the maize hybrid employed was «DK4F37». These were raised as follows: a) in two topographical positions – on the high mid slope (I) and the low mid slope (II); b) under three tillage systems: conventional tillage (CT, one pass with a moldboard plow plus two passes with an eccentric fire disk harrow), reduced tillage (RT, two passes with a chisel plough at 25-30 cm depth followed by working with the eccentric fire disk harrow), and no tillage (i.e., direct seeding, DS, using a specialised seeding machine); c) with different post-harvest treatment of the crop residues – either allowing them to be grazed (without chopping into small pieces) by breeding cattle of around 300 kg live weight until very large amounts had been removed (G), or not allowing cattle to feed on them in any season (NG); and d) with either the application of fertilizer (F) or no fertilizer (NF). In the fertilizer treatment, 100 kg ha^{-1} of diammonium phosphate was supplied to the maize crops at sowing, and then another 100 kg ha^{-1} of urea at the eight-leaf stage. For the sunflower crops, 80 kg ha^{-1} of diammonium phosphate and 100 kg ha^{-1} urea were supplied at sowing. The trial had a simple random block design with two repetitions. The plots used were 25 m wide and 70 m long. Crops were planted in a north-south direction, perpendicular to the slope.

Table 1 shows the quantities of residue produced by the different crops for each treatment. These were determined annually after grazing. Six areas of 0.25 m^2 were sampled for each treatment plot by collecting all

Table 1. Maize and sunflower residues supplied to the soil. Mean annual values for the period 1994-99 according to the cultivation sequence maize-maize-sunflower-maize-sunflower (in tonnes of dry mater per hectare and year)

			Quantity of residue (t dm ha^{-1} year^{-1})			
Treatments			Position I		Position II	
			Sunflower	Maize	Sunflower	Maize
NG	F	DS	4.1	8.5	4.7	8.4
		RT	4.1	7.7	4.1	6.8
		CT	3.6	6.6	3.0	6.2
	NF	DS	3.6	5.8	3.3	4.6
		RT	3.7	5.2	4.1	4.4
		CT	2.7	4.9	3.0	3.9
G	F	DS	3.1	3.8	3.4	3.5
		RT	3.0	3.0	2.9	2.8
		CT	2.6	2.9	2.2	2.5
	NF	DS	2.7	2.6	2.3	2.0
		RT	2.6	2.3	3.0	1.9
		CT	1.9	2.1	2.2	1.7

dm: dry matter. NG: not grazed. G: grazed. F: fertilizer added. NF: no fertilizer added. DS: direct seeding. RT: reduced tillage. CT: conventional tillage. Position I: high mid slope. Position II: low mid slope.

plant material, alive or dead. This was dried in a forced air oven at 105ºC until constant weight was reached. The values obtained are expressed as annual means and in tonnes of dry matter per hectare.

Determinations and statistical analysis

In 1999 (after the trial had been underway for 5 years) two pooled samples per treatment were taken from the top 5 cm of soil (obtained by taking six samples of similar volume extracted at regular distances from one another and in a straight line along the long axis of the plot). These samples were used to determine the OC content via oxidation with a mixture of potassium dichromate and sulphuric acid, and followed by the evaluation of the excess of the first of these compounds with ammonium ferrous sulphate (Nelson and Sommers, 1982). The results are expressed as g of OC kg^{-1} of soil.

The size distribution of the water-stable aggregates was determined according to the method of Pla Sentis (1983). Dry soils were first sieved through a 4 mm and then a 2 mm mesh. Thirty grams were then taken and agitated in water for 10 min through a set of 2 mm, 1 mm, 0.5 mm and 0.1 mm sieves. The soil was then collected from each sieve, dried at 110ºC in an oven, and each subsample was weighed before the addition

of 10% calgon solution. They were then mechanically shaken and the suspensions passed through the sieves with which they were originally obtained; all remaining material was dried and weighed. The percentages of water-stable aggregates with diameters of 0.1-0.5, 0.5-1, 1-2 and 2-4 mm were calculated according to the following expression:

$$\%AEA \approx \left(\frac{b-c}{a-c}\right) \times 100$$

where %AEA = the percentage weight of water-stable aggregates, a = the initial dry weight of the sample, b = the dry weight after shaking in water, and c = the dry weight after adding calgon solution.

All data were treated using the Statistical Package for the Social Sciences (SPSS, 1998), employing the general linear model, the Kruskal-Walis non-parametric test (1952), and the Bonferroni multiple comparison test (1950). Significance was set at 95%.

To determine the changes that occurred over time, the values of the variables studied were also assessed in conditions of minimum alteration (MA, on a little used area of relic vegetation, with relief similar to that of the experimental plots), both at high mid slope (MA-I) and low mid slope (MA-II). The OC values for these plots were related to those of the treatment plots by estimating the percentage losses, assuming MA to retain 100% OC.

Results

Soil organic carbon content

Table 2 shows the soil OC content at the end of the trial for all treatments as well as under MA conditions. With respect to topographical position, the OC values for site type II (the lower mid slope) were significantly higher than those for site type I, with a difference of 14%. This has its origins in the difference observed between conditions MA-I and MA-II (approximately 15%), and because of trial baseline differences (8.46 g kg^{-1} for I and 9.72 g kg^{-1} in II, i.e., OC was 13% lower in the former).

The highest OC values were obtained with the NG treatment; values were significantly higher than those obtained with the G treatment (Table 2).

Table 2. Organic carbon contents attained with the different treatments, levels of significance, interactions *residue x tillage* and *residue x position,* and percentage differences in weight compared to the minimal alteration (MA) condition (MA = 100%)

Factor	Level	OC (g kg^{-1})	Differences (%)
Position	I	8.72 b	–77.98
	II	10.17 a	–78.19
Significance		0.000	
Grazing	NG	10.06 a	–76.66
	G	8.83 b	–79.52
Significance		0.001	
Tillage	DS	9.76 a	–77.36
	RT	9.76 a	–77.36
	CT	8.60 b	–80.05
Significance		0.030	
Fertilizer	F	9.36 a	–78.29
	NF	9.47 a	–78.03
Significance		0.832	
Residue x tillage Significance		0.025	
Residue x position Significance		0.067	
MA-I		39.60	
MA-II		46.63	

OC: organic carbon. I, high mid slope position. II: low mid slope position. NG: not grazed. G: grazed. DS: direct seeding. RT: reduced tillage. CT: conventional tillage. F: fertilizer added. NF: no fertilizer added. MA-I: minimum alteration at position I. MA-II: minimum alteration at position II. In columns, different small case letters indicate significant differences between treatments according to the Bonferroni multiple comparison test.

With respect to tillage type, OC values were identical for the DS and RT systems; both provided significantly higher levels than the CT system (Table 2).

The interaction *residue x tillage* (Tables 2 and 3) had a significant effect on OC levels. The NG treatment gave the highest soil OC values, the greatest percentages being obtained with the RT system followed by the DS and finally the CT system. In the G treatment, the OC values followed the following order with respect to tillage practice: DS > RT > CT. The differences were not, however, significant.

Figures 1A and 1B show the OC content at each topographic position according to tillage system type and whether the plot was grazed. At position I in the NG treatment, the only significant difference was seen between the RT and CT regimens. No differences were seen at all with respect to tillage system in the G treatment. At this position on the slope, the highest organic matter content was attained with RT and DS. At position II, the only significant differences found in the NG treatment were for CT compared to other tillage practices.

The application of the fertilizer led to no significant differences in organic matter content (Table 2).

The interaction *residue x position* seemed to have no significant effect.

Column 4 of Table 2 shows the differences in organic matter content between the different treatments and the MA condition. The greatest loss of OC occurred with CT under the G treatment (around 80%). Values of around 77% were recorded for DS and RT practices and in NG treatments.

Aggregate stability

Table 4 shows the percentage weights of the four diameter ranges of water-stable aggregates and the

Table 3. The interaction *residue x tillage* and organic carbon content

Residue x tillage	OC (g kg^{-1})
NG x DS	10.58 a
NG x RT	10.81 a
NG x CT	8.72 b
G x DS	8.95 b
G x RT	8.72 b
G x CT	8.48 b

x: interaction. NG: not grazed. G: grazed. DS: direct seeding. RT: reduced tillage. CT: conventional tillage. In columns, different small case letters indicate significant differences between treatments according to the Bonferroni multiple comparison test (5% probability level).
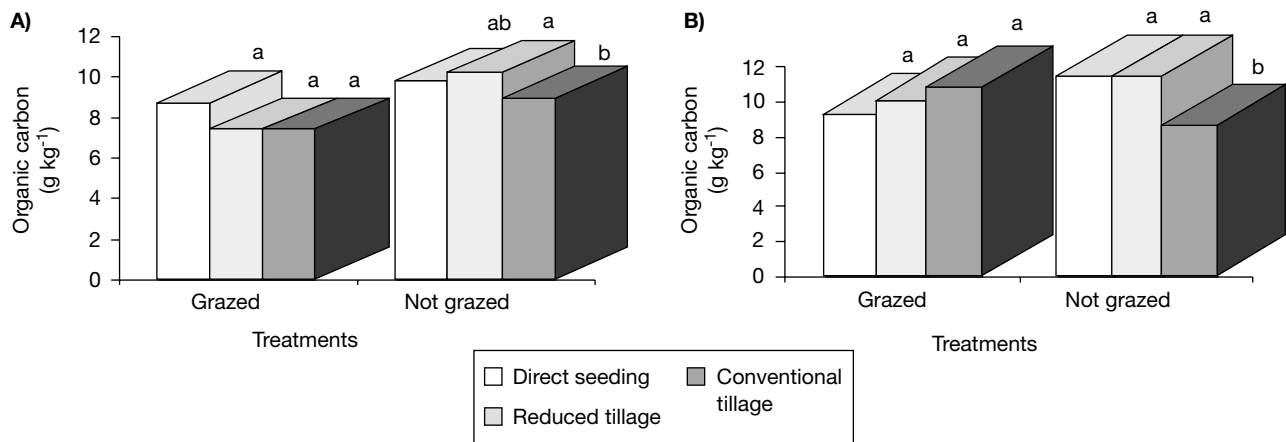
Figure 1. Effect of the different tillage systems and the quantity of residue on organic carbon content at the high mid slope (A) and low mid slope (B) positions. Different small case letters indicate significant differences between treatments according to the Bonferroni multiple comparison test.

levels of significance for each treatment. The percentages associated with the MA condition and all other treatments were significantly different. In MA, the greater part of the aggregates were of the largest size, while those obtained with the other treatments showed a bimodal distribution (with the highest percentages for the most coarse and the finest aggregates). The DS treatment provided the results closest to those for the MA condition, though it produced more fine aggregates and fewer large aggregates.

Differences were seen with respect to tillage system for all diameter classes, except for the 1-2 mm range. Topographic position had no effect on aggregate sizes, neither did the grazing of the crop residue nor the addition of fertiliser. No significant interactions were seen between treatment procedures.

Table 4. Percentage weight of water-stable aggregates (four diameter ranges) attained with the different treatments and under MA conditions

| Factor | Level | Water-stable aggregates (%) | | | |
| | | Diameters | | | |
		0.1-0.5 mm	0.5-1 mm	1-2 mm	2-4 mm
Position	I	17.85 a	7.72 a	10.56 a	19.85 a
	II	16.87 a	8.08 a	11.89 a	20.78 a
Significance		0.610	0.509	0.274	0.805
Grazing	NG	16.92 a	7.78 a	11.39 a	23.92 a
	G	17.79 a	8.01 a	11.06 a	16.71 a
Significance		0.653	0.902	0.934	0.180
Tillage	DS	11.64 b	4.90 c	12.60 a	33.06 a
	RT	18.25 a	8.03 b	10.20 a	15.69 b
	CT	22.19 a	10.69 a	10.87 a	12.20 b
Significance		0.000	0.000	0.140	0.002
Fertilizer	F	17.46 a	7.83 a	12.09 a	21.74 a
	NF	17.26 a	7.96 a	10.37 a	18.89 a
Significance		0.919	0.934	0.174	0.187
Minimal alteration conditions	MA	5.19	1.91	15.09	52.50

I: high mid slope position. II: low mid slope position. NG: not grazed. G: grazed. DS: direct seeding. RT: reduced tillage. CT: conventional tillage. F: fertilizer added. NF: no fertilizer added. MA: minimum alteration. In columns, different small case letters indicate significant differences between treatments according to the Bonferroni multiple comparison test (5% probability level).

The tillage system used affected the distribution of the 0.1-0.5 and 2-4 mm aggregates. Both RT and CT produced more of the former than did the DS system, while DS produced more of the latter than either the RT or CT systems. The DS system produced more 0.5-1 mm aggregates than the RT system, and more again compared to the CT system.

With respect to the percentage quantity of aggregates greater than 0.5 mm in diameter, the DS system produced approximately 49% more than either RT or CT.

Figure 2 shows that the increase in OC is directly related to the increase in the number of 2-4 mm aggregates at both slope positions. The differences seen with respect to topographic position, in terms of the slope of the regression lines, shows that OC content had a greater effect on the proportion of macroaggregates at position II than at position I.

Discussion

Soil organic carbon content

A comparison of the baseline OC values with those obtained at five years shows an increase of 3.07% in OC at position I and of 4.6% at position II. This coincides with that indicated by Jenny (1941) and Yonker *et al.* (1988), in that sites lower down a slope have better humidity and temperature conditions for the production of biomass. This, in turn, is the main source of crop residues for transformation and storage as OC (Carter, 1996).
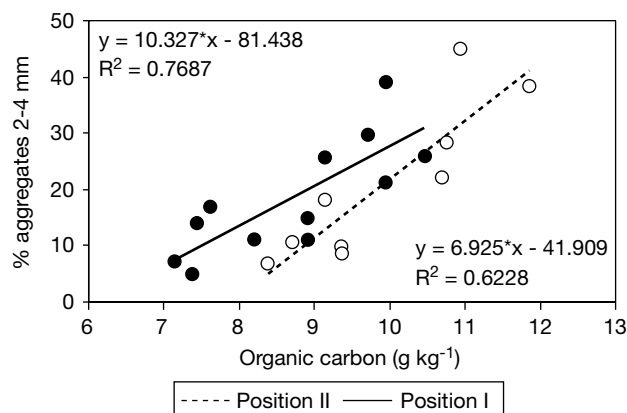
Figure 2. Relationship between organic carbon content and percentage of 2-4 mm diameter aggregates with respect to topographical position. * Linear regression analysis (5% probability).

In the present study, OC levels fell when crop residues were grazed. Larson *et al.* (1972), Black (1973) and Ressia *et al.* (1998) found that removing crop residues for animal feed or for fuel led to a decrease in soil OC content. They also indicate that this phenomenon might be potentiated in semi-arid and sub-humid regions where, since biomass production is low, a fall in soil OC content cannot be avoided when the removal of crop residues is extensive.

At the end of the trial, the OC content achieved with conservation tillage (RT and DS) was some 13.5% higher than that attained with the CT system. Rasmunsen and Collins (1991) and Hill *et al.* (1998) indicated that despite the supply of crop residues, OC continues to be lost if the quantity is insufficient and the location of that which is provided is inadequate. This shows that cultivation and residue management practices have an important effect on the maintenance of soil OC. Voroney *et al.* (1989) indicated that the greater the incorporation of crop residue by machinery, the greater the mineralisation that occurs. In addition, at the end of the trial, the conservation tillage plots had 7.4% more OC than the mean for either topographic position at the start of the experiment. This shows that an improvement occurs with conservation tillage, and that this tends to produce a new equilibrium, whereas CT leads to deterioration. Bauer and Black (1981) found that after 40 years of continuous cultivation using conventional tillage with very little residue supply, the use of conservationist tillage and leaving a high residue coverage led to an increase in OC, and that a new equilibrium was reached. Voroney *et al.* (1989) showed that 20-30% of the aggregated carbon content begins to stabilise in the organic matter after 10 years. After a seven year study of the top 5 cm of soil, Costantini *et al.* (1999) found that DS led to 15% more OC than RT and 50% more than CT.

After eight years of experimentation, Duiker and Lal (1999) found that the quantity of crop residues applied had a positive, linear effect on the amount of soluble OC, both with conservation and non-conservation tillage systems, and that the increase in organic matter was only significant for the top 5 cm with direct seeding. In the present study, greater OC contents were achieved when residues were not grazed and conservation tillage was employed. When the plots were grazed, however, no differences were seen between tillage systems.

When the residues were grazed, neither topographical position nor tillage system influenced the organic

matter content of the soil. However, when the residues were not grazed, conservation tillage at slope position II generated greater quantities of OC. At position I the RT system was the most efficient. Voroney *et al.* (1989) indicated that conservation tillage generates better conditions for the processing of organic remains, delaying its mineralisation.

During the time of the trial, the addition of fertiliser led to no changes in soil organic matter content, possibly because of the small differences in the amount of residues supplied to the soil (Table 1). Similar results were reported by Black (1973), who found that fertilization with nitrogen and phosphorus had no influence on the amount of carbon retained by the soil, although it did increase the production of grain and residues. Prasad and Power (1997), however, indicated that five out of eight experiments provided evidence that soil organic matter content rose after the addition of fertilizer.

Fenton *et al.* (1999) estimated that 74 years of continuous cultivation produced a 77% drop in soil OC content. The present study suggests that the 80 years during which the soil was used has caused a similar fall. However, Voroney *et al.* (1989) found that the decomposition of soluble organic matter runs at a mean rate of 2-5% per year, with a more rapid renovation of the new humus than the older humus. Taking this into account, plus the values recorded in the present study, annual losses can be estimated of around 1% if values at different points in the process are unknown.

In summary, the results as a whole indicate that the alterations made to the soil in this experiment overcame its natural resistance. Further, the OC content of the first few centimetres of the soil increased when crop residues were left behind and conservation tillage systems were employed. This type of tillage was most efficient on the lower slope position. The above implies that changes in the OC content lead to the development of a new equilibrium.

Aggregate stability

The MA condition led to a greater percentage of water-stable aggregates than did the different treatments. This agrees with that reported by Barzegar *et al.* (1994). It also led to a trend towards more macroaggregates (> 1 mm in diameter), as reported by Cambardella and Elliott (1993) for a fine gypsum Haplustoll under natural conditions, and by Chan and Hulugalle (1999) for natural pasture over a Paleustalf.

The opposite tendency found with the CT and RT systems also agrees with that indicated by Chan and Hulugalle (1999), who compared natural pasture with wheat monoculture under a CT regimen with the burning of crop residues.

In the present study, the DS system produced the greatest quantities of macroaggregates, and the greatest reduction of aggregates of < 1 mm diameter. This agrees with the results of Unger (1982) and Dormaar and Lindwall (1989), who showed that increased tillage intensity increased the number of aggregates < 0.84 mm in diameter. Arshad *et al.* (1999) also reported that the formation of water-stable aggregates improved with direct seeding compared to conventional tillage systems. The same authors indicated that at the soil surface, the quantity of water-stable macroaggregates was 50-60% greater with conservation tillage than with conventional tillage.

The increase in OC was related to the proportion of macroaggregates in the different positions on the slope, especially with respect to the lower slope position. Similar results were reported by Amézketa (1999), while Angers *et al.* (1992), Chan and Mead (1988), and Golchin *et al.* (1995) report that changes in the aggregation of cultivated soils are not always associated with the total amount of organic matter they contain since only a part of it is involved in aggregation (the carbohydrate fraction in particular).

The results of the present study show that the use of conservation tillage systems which cause little soil disturbance, plus the return of all crop residues (in positions where temperature and humidity are at their best for the development of biomass and residue transformation) increases the soil OC content. Regression analysis confirmed the relationship between OC content and the quantity of water-stable macroaggregates. The tillage system that best produces macroaggregates appears to be that which does not disturb the soil. These findings may help in the choice of technologies that can improve soil quality.

Acknowledgements

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