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Improving soil surface properties: a driving force for conservation tillage under semi-arid conditions

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Abstract

The effect of long term conservation tillage (CT) application on soil organic carbon (SOC) concentration, and on stratification ratios (SR) of SOC, soluble organic carbon (SOCs), microbial biomass carbon (MBC) and protease activity (PA) has been studied. The SR was established dividing values of these variables at 0-5 cm depth by values at 10-25 cm depth. The results were compared with those obtained under traditional tillage (TT). The study was conducted in a wheat-sunflower crop rotation established in 1991 under rainfed conditions in south-west Spain. The results showed here correspond to the years 2001 (sunflower) and 2002 and 2004 (wheat). Despite a slight increase in SOC and the SR of SOC under CT compared to TT, noticeable and significant increases of SR of SOCs, MBC and PA were recorded in CT compared to TT. These increases reveal that the stratification of SOC under CT have consequences on soil functions beyond that of potentially sequestering more C in the soil. CT also improved soil quality by softening the loss of $CaCO_3$, compared to TT.

Additional key words: organic carbon, soil quality, stratification ratio.

Resumen

Mejora de las propiedades de la capa superficial del suelo: fuerza impulsora para el laboreo de conservación bajo condiciones semiáridas

Se han estudiado a largo plazo los efectos del laboreo de conservación (LC) sobre la concentración de carbono orgánico (CO) y las razones de estratificación (RE) del CO, CO soluble, C de la biomasa microbiana y actividad enzimática proteasa. Las RE se establecieron dividiendo los valores de estas variables en la profundidad de 0-5 cm por los valores obtenidos en la profundidad de 10-25 cm y los resultados se compararon con los obtenidos bajo laboreo tradicional (LT). El estudio se realizó sobre una rotación trigo-girasol establecida en 1991 bajo condiciones de secano, en el sur de España; los resultados presentados corresponden a los años 2001 (girasol) y 2002 y 2004 (trigo). El aumento de CO y estratificación del CO en LC sólo fue moderado respecto al registrado en LT. Sin embargo, los aumentos de los valores de estratificación de CO soluble, C de la biomasa microbiana y actividad proteasa fueron notables y significativamente más altos en LC que en LT. La estratificación del CO en LC no sólo refleja una acumulación de CO, sino que afecta a las funciones (dinámica) del suelo. El LC también mejoró la calidad del suelo mitigando, respecto a LT, las pérdidas de $CaCO_3$.

Palabras clave adicionales: calidad del suelo, carbono orgánico, razón de estratificación.

Introduction

Most agronomic studies do not consider soil surface (the first 5 cm) properties when defining soil properties, paying more attention to the plough layer (30 cm) and deeper horizons. However, the soil surface is the vital interface that receives fertilizers and pesticides applied to cropland, receives the intense impact of rainfall, and partitions the fluxes of gases and water into and out of soil. Surface organic matter is therefore essential to control erosion, water infiltration,

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and conservation of nutrients, all important soil functions (Franzluebbers, 2004).

Mrabet (2002) emphasized that a living, but stable structure at the soil surface is necessary to enhance water infiltration and prevent soil erosion. However, in the past, much of the focus of conservation tillage research was on the diagnosis of crop performance and controlling erosion. Research into the influence of tillage and cropping systems on soil aggregation and organic matter accretion has been limited, especially under arid or semi-arid conditions (Mrabet, 2002).

The efficiency of conservation tillage to improve water storage is universally recognized. This is very important in arid and semi-arid zones, where management of crop residues is of prime importance to obtain sustainable crop productions (Moreno *et al.,* 1997; Du Preez *et al.,* 2001; Lampurlanés and Cantero-Martínez, 2006). However, these climatic conditions may be a limiting factor to the accumulation of organic carbon in the top soil layers. Thus, the simple determination of the total content of organic carbon might not be the best indicator of the improvement caused by conservation tillage. Under these particular conditions, knowledge of the stratification ratio of the soil organic carbon (SOC) (SOC content at the surface layer/SOC content at deeper layers) may be more relevant (Franzluebbers, 2002; Moreno *et al.,* 2006). According to Franzluebbers (2004), soils with low inherent levels of organic matter (SOM) could be the most functionally improved with conservation tillage, despite modest or no change in the total standing stock of SOC within the rooting zone. Stratification of SOM pools with depth under conservation tillage systems has consequences on soil functions beyond those of potentially sequestering more carbon in the soil (Franzluebbers, 2004).

Depending upon soil texture, carbon accumulates either in the soil surface with or without reduction at lower depths (Mrabet *et al.,* 2001; Franzluebbers, 2004). Higher SOC and SOM contents are often associated with aggregation improvement under conservation tillage, besides improvement of other important physico-chemical and biological properties of the soil surface (Moreno *et al.,* 2006). Franzluebbers (2004) emphasized that SOC is not only stratified with depth but can also be stratified three-dimensionally according to soil aggregation.

Crop residue incorporation by ploughing and, especially, straw burning or removal (other uses) would avoid an adequate suitable SOM stratification, losing the benefits that could derive from it. This paper deals with studying the stratification of SOC and other derived soil properties under a conservation tillage system established in 1991 for a rainfed crop rotation (wheat-sunflower) under semi-arid conditions. The influence of conservation tillage on the loss of soil $CaCO_3$ is also studied. The results are compared to those obtained under traditional tillage, with straw burning and ploughing.

Material and Methods

Study area: climate and tillage treatments

The field experiment was carried out on a sandy clay loam soil (Xerofluvent, Soil Survey Staff, 1996) at the experimental farm of the *Instituto de Recursos Naturales y Agrobiología de Sevilla* (IRNAS-CSIC) located 13 km southwest of the city of Seville (Spain). The climate of the experimental area is typically Mediterranean, with mild rainy winters (500 mm mean annual rainfall, average of 1971-2004) and very hot, dry summers. Rainfall in 2001, 2002 and 2004 were 710, 662 (higher than the mean) and 450 mm (lower than the mean) respectively. Year 2003 was very rainy (785 mm, 500 mm during the period October-December) with heavy rain during the wheat sowing period. For this reason, the results of 2003 are not included in this work. Rainfall was obtained from the weather station located at the experimental farm (200 m far from the experimental plots).

A plot of approximately 2,500 m^2 was selected to carry out the experiment that started in 1991. During the autumn of that year the plot was cropped with wheat under rainfed conditions. The tillage operations applied were the traditional ones used in the region. After harvesting the wheat in June 1992, the plot was divided into six subplots each of approximately 300 m^2 (22 × 14 m). Two tillage treatments were established: a traditional tillage (TT) used in the area for rainfed agriculture and a conservation tillage (CT).

The TT consisted mainly of using mouldboard ploughing (to a 30 cm depth), after burning the straw of the preceding crop. Straw burning had been suppressed since 2003. No mouldboard ploughing was practiced in CT, reducing the number of tillage operations and leaving the crop residues on the surface. Table 1 shows

Table 1. Tillage and agronomic operations carried out in the experimental plot

<table>
<tr><th rowspan="2">Date</th><th colspan="2">Treatments</th></tr>
<tr><th>Traditional tillage (TT)</th><th>Conservation tillage (CT)</th></tr>
<tr><td>20-07-2000</td><td>Burning straw (wheat crop)</td><td>Leaving straw (wheat crop) on soil surface</td></tr>
<tr><td>25-07-2000</td><td>Mouldboard ploughing (25-30 cm depth)</td><td>Chiseling (25-30 cm depth)</td></tr>
<tr><td>18-10-2000</td><td>Cultivator application (15 cm depth)</td><td></td></tr>
<tr><td>18-11-2000</td><td colspan="2">Disc harrowing (15 cm depth)</td></tr>
<tr><td>30-11-2000</td><td></td><td>Weed control (trifluraline, 1.5 l ha^{-1})</td></tr>
<tr><td>30-03-2001</td><td>Cultivator application (15-20 cm depth)</td><td></td></tr>
<tr><td>02-04-2001</td><td colspan="2">Seeding sunflower by precision line seeder (seed density ~60,000 ha^{-1})</td></tr>
<tr><td></td><td></td><td>Application of terbutryn (2 l ha^{-1})</td></tr>
<tr><td>30-04-2001</td><td>Cultivator application between rows (12-15 cm depth)</td><td></td></tr>
<tr><td>08-08-2001</td><td colspan="2">Harvesting</td></tr>
<tr><td>14-08-2001</td><td>Burning the straw</td><td>Leaving the straw on the soil surface</td></tr>
<tr><td>24-09-2001</td><td>Mouldboard ploughing (25-30 cm dpth)</td><td></td></tr>
<tr><td>17-11-2001</td><td>Disc harrowing (10 cm depth)</td><td>Weed control (glyphosate, 4 l ha^{-1})</td></tr>
<tr><td>29-11-2001</td><td colspan="2">Fertilisation
($15N\text{-}15P_2O_5\text{-}15K_2O$, 400 kg ha^{-1})</td></tr>
<tr><td>30-11-2001</td><td colspan="2">Sowing winter wheat by boot seeder
(~350,000 seeds ha^{-1}), and disc harrowing (5 cm depth)</td></tr>
<tr><td>02-01-2002</td><td colspan="2">Weed control (Banvel D Dicamba 48%, 0.4 l ha^{-1})</td></tr>
<tr><td>23-05-2002</td><td colspan="2">Harvesting</td></tr>
<tr><td>21-11-2003</td><td colspan="2">Sowing winter wheat by boot seeder</td></tr>
<tr><td>03-06-2004</td><td colspan="2">Harvesting</td></tr>
<tr><td>22-07-2004</td><td>Mouldboard ploughing (25-30 cm dpth)
(straw burning suppressed)</td><td>Chiseling (25-30 cm depth)
(leaving the straw on the soil surface)</td></tr>
<tr><td>16-11-2004</td><td colspan="2">Disc harrowing (15 cm depth)</td></tr>
<tr><td>14-12-2004</td><td colspan="2">Application of trifluraline (1.5 l ha^{-1}) and two application of rotavator</td></tr>
<tr><td>15-12-2004</td><td colspan="2">Sowing of fodder pea
(~200 kg kernels ha^{-1})</td></tr>
<tr><td>28-05-2005</td><td colspan="2">Harvesting</td></tr>
</table>

the recent tillage and agronomic operations carried out for both tillage treatments. A wheat (*Triticum aestivum* L.)-sunflower (*Helianthus annuus* L.) crop rotation was established for both treatments. Three replications per treatment were used, distributed in random blocks.

Sunflower was not fertilized (as it is traditional in this zone), while wheat received 400 kg ha^{-1} of a complex fertilizer 15-15-15 before sowing and a top dressing with 200 kg ha^{-1} urea (46% N). Since 2002, fertilization was reduced to 100 kg ha^{-1} (fertilizer complex) and no top soil fertilizer was applied (Murillo *et al.,* 2004). This work is included in a larger research project, for which annually numerous physical and chemical parameters of soils have been determined as well as several characteristics of the crops. Results in this work correspond to years 2001 (sunflower), 2002 and 2004 (wheat) and only refer to soil characteristics.

Soil sampling and analysis

Soil was sampled on 10th November 2001, 3rd December 2002 and 11th November 2004, at two points of each individual subplot at depths of 0-5 cm, 5-10 cm, 10-25 cm and 25-40 cm (except in sampling of November 2001, when samples at 25-40 cm were not taken). The SOC content was determined according to Walkley and Black (1934), $CaCO_3$ following Demolon and Leroux (1952), and active carbonate using a 0.2 N ammonium oxalate solution with no further pH adjustments (Loeppert and Suarez, 1996). Water-soluble carbon (SOCs) was determined in a 1/10 aqueous extract using a TOC-V-CSH/CSN analyser (Shimadzu Corporation, Instrument Div. Kyoto, Japan). Microbial biomass carbon (MBC) content was determined by the chloroform fumigation-extraction method as modified by Gregorich *et al.* (1990). The concentration of C in the extract was measured using the TOC analyser. An extraction efficiency coefficient of 0.38 was used to convert the difference in soluble C between the fumigated and the unfumigated soil to microbial biomass carbon (Vance *et al.,* 1987). Protease activity (PA) was measured following the procedure described by Ladd and Butler (1972). Bulk density was determined from the ratio mass/volume of soil cores taken at different depths with stainless-steel cylinders of 8 cm diameter and 4 cm height.

Stratification ratios (SR) for SOC, SOCs, MBC and PA were defined as the quotient of values of these variables in the soil surface (0-5 cm) and at the bottom of the arable layer (10-25 cm) (Franzluebbers, 2002). Variables SOCs, MBC and PA were only determined on November 2004.

All statistical analyses were carried out with the program SPSS 10.0 for Windows. Data normality was tested prior to analysis; and when necessary, variables were transformed logarithmically. Significant statistical differences of all variables between the two treatments were assessed by the Student t-test. If, after transformation, the data did not have a normal distribution, the non-parametric test Mann-Whitney U was used for comparison of mean values.

Results

In general, the SOC concentration was higher in CT than in TT, with significant differences in years in which the residues of the preceding crop were burnt in TT (years 2001 and 2002). As burning had been suppressed in TT since 2003, with the corresponding incorporation by ploughing of organic residues into the plough layer, SOC differences between CT and TT were slightly lower, and not significant, in 2004 (Table 2).

However, when data were expressed as g C m^{-2} (taking into account bulk density at different depths),

Table 2. Mean values of soil organic carbon (SOC, g kg^{-1}) in the soil treated by traditional tillage (TT) and conservation tillage (CT) in the autumn of different years

Depth (cm)	Treatment	Year		
		2001[1]	2002[1]	2004[1]
0-5	TT	8.1*	8.7*	11.4
	CT	9.8	11.3	12.9
5-10	TT	8.1*	7.8*	10.1
	CT	9.5	11.9	11.1
10-25	TT	6.7	7.5	6.7
	CT	6.5	7.5	7.0
25-40	TT		7.2*	5.7
	CT		5.0	6.4

[1] Values are for December (2001 and 2002) and November (2004). *: Significant differences ($P < 0.05$) between treatments, per year and depth.

the difference in SOC was significant ($P < 0.05$) for the 0-5 cm depth in 2004 (763 g C m^{-2} for TT and 912 g C m^{-2} for CT, Fig. 1). The bulk density tended to be slightly greater in CT than in TT, although the differences were not significant in any case (1.41 Mg m^{-3} for CT and 1.33 Mg m^{-3} for TT at the depth of 0-5 cm; 1.63 Mg m^{-3} for CT and 1.59 Mg m^{-3} for TT at the depth of 5-10 cm and 1.78 Mg m^{-3} for CT and 1.76 Mg m^{-3} for TT at the depth of 10-25 cm). The SOC increase in surface represented an accumulation of 1.5 Mg C ha^{-1} more in CT than in TT, the difference being significant ($P < 0.05$). The difference was not significant when considering greater volumes of soil (up to 20 and 30 cm depth, Fig. 1).

Although there is not a great enrichment of SOC at the surface in CT, this slight increase in SOC could have improved the physical, chemical and biological properties in this treatment. Despite the fact that the SR for the total SOC was not significantly higher in CT, not even when data were expressed as g C m^{-2}, other properties related to the biological dynamics of the soil, such as SOCs, MBC and PA showed a clear enrichment at the surface in CT, with higher, and significant values of SR compared to those obtained in TT (Fig. 2).

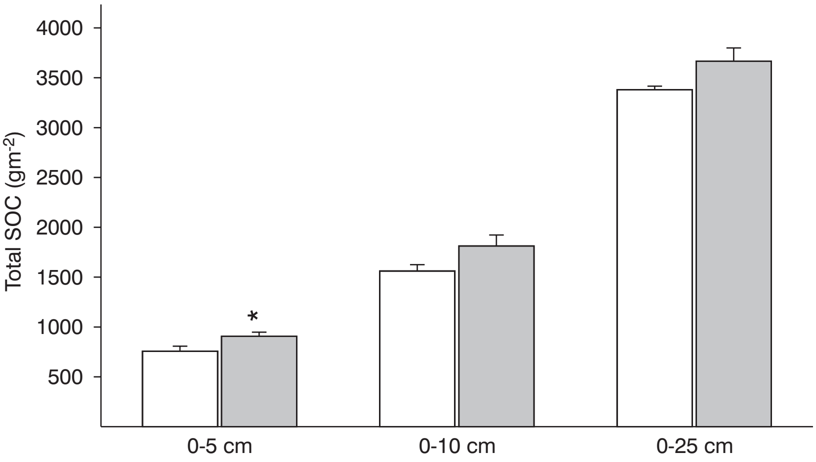

Figure 1. Total SOC (mean values ± standard error) at different depths under TT (white bars) and CT (grey bars). Significant differences between treatments are marked by an asterisk ($P < 0.05$). November 2004.

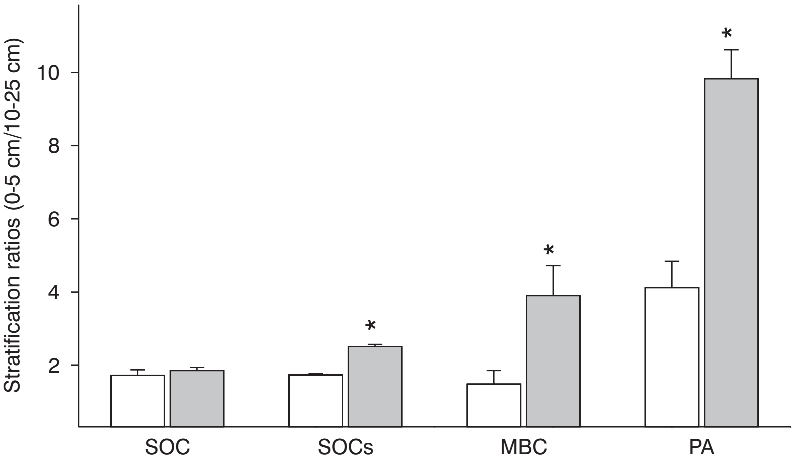

Figure 2. Stratification ratio (SR) values (mean values ± standard error) for total soil organic carbon (SOC, g kg^{-1}), soluble organic carbon (SOCs, mg kg^{-1}), microbial biomass carbon (MBC, mg kg^{-1}) and protease activity (PA, mg tyrosine kg^{-1} h^{-1}) under TT (white bars) and CT (grey bars). For each variable, significant differences are marked by an asterisk ($P < 0.05$). November 2004.

Table 3. Calcium carbonate and active calcium carbonate concentrations (g kg^{-1}; mean values ± standard error) at different soil depths under traditional tillage (TT) and conservation tillage (CT). December 2002

Variable	Treatment	Depth (cm)			
		0-5	5-10	10-25	25-40
$CaCO_3$	TT	129 ± 12*	123 ± 13*	117 ± 12	131 ± 19
	CT	191 ± 9.0	192 ± 12	172 ± 24	201 ± 42
Active $CaCO_3$	TT	67 ± 4.0*	60 ± 1.9*	64 ± 3.0*	61 ± 5.0
	CT	104 ± 5.0	108 ± 7.0	97 ± 11	102 ± 23

* Significant differences ($P < 0.05$) between treatments per variable and depth.

On the other hand, under both tillage treatments a decrease in $CaCO_3$ content was observed compared to the initial content (28%) in 1991. However, the decrease in $CaCO_3$ content was, in general, significantly lower in CT than in TT (Table 3). The same pattern was also found for the active $CaCO_3$.

Discussion

Soil organic carbon and related variables

Climatic conditions of southern Spain (high temperatures during summer) are the limiting factor for the accumulation of organic carbon in the top soil layers. Thus, the simple determination of total organic carbon content cannot be the best indicator of the improvement caused by conservation tillage. Calculation of the SR of SOC could be more useful under Mediterranean conditions. In general, under any conditions of soil and climate, high stratification ratios indicate a good soil quality. In degraded soils, values of SR of SOC are frequently lower than 2 (Franzluebbers, 2002). This approach could also be applied to other variables (Fig. 2). There is a need for a universal index that includes a composite of key soil biological, chemical and physical parameters. The measurement of selected soil enzyme activities and microbial indicators are potential candidates for this (Dick, 1994; Turco *et al.,* 1994).

Monitoring soil properties is a key point for the technical changes implied with conservation tillage, since farmers have to adapt their practices to the new states of the system. Suitable indicators for conservation tillage different from those used in conventional agriculture are required. The results of this study may be an example: for moderate increases occurred in total SOC and SR of SOC in CT noticeable increases in other important related variables were observed (Fig. 2). This corroborates the suitability of the SR of SOC to define the benefits derived from CT under semi-arid conditions. Soils with low inherent levels of SOM can be the most functionally improved with CT, despite modest or no changes in the total standing stock of SOC within the rooting zone (Franzluebbers, 2004).

Sparling *et al.* (2003) emphasized that rather than defining a maximum value of SOC, it would be much more informative for agricultural systems to define a justifiable minimum SOC below which there would be loss of desirable soil characteristics (biological activity, structure) productive capacity, and ecological functions that were not readily restored within an acceptable timeframe.

The «more is better» argument referred to SOC, is weaker when applied to agricultural productivity, where the benefits of higher organic matter contents on intensively managed arable soils are sometimes obscure (Sojka and Upchurch, 1999). In the absence of a clear critical point and demonstrable ecological consequence, the setting of soil quality targets within a continuum requires human value judgements (Sparling *et al.,* 2003).

In general, enrichment of the soil surface with crop residues usually leads to significantly greater macroaggregation (water-stable macroaggregates > 0.25 mm), especially in soils with coarse texture, because their level of macroaggregation is frequently lower than that in soils with a fine texture (their higher inherent level of aggregation can prevent further improvement with adoption of conservation tillage) (Franzluebbers, 2004). In our case (a soil with approximately 20% of clay) macroaggregation at the surface is expected to be higher in CT than in TT (in study), which can condition many soil variables at this layer.

Losses of $CaCO_3$

Water-stable macroaggregates could have contributed to reduced losses of $CaCO_3$ at the surface in CT compared to TT, a hypothesis that must be verified in future studies. According to Del Campillo *et al.* (1992), the relatively low rainfall (and leaching) typical of the Mediterranean environment of southern Spain, may account for greater stability and persistence of very fine carbonate particles in the soil. However, losses of these fine particles have been detected; the pattern of losses found for the active $CaCO_3$ was the same as those found for the $CaCO_3$ contents (Table 3). At the beginning of the experiment (1991), the active $CaCO_3$ content was around 50% of the total $CaCO_3$ content. After 10 years, this proportion remains practically the same in both tillage treatments. However, the active $CaCO_3$ content was, in general, significantly greater in CT than in TT (Table 3).

The decrease in $CaCO_3$ and active $CaCO_3$ contents can be due in part to the effect of N fertilizers, which can originate losses of calcium by leaching as reported by Blevins and Frye (1993) and Motta *et al.* (2002). In southern Spain, farmers using wheat-sunflower crop rotation apply a heavy N fertilization to wheat. This is designed to create a reserve of available N for the next sunflower crop which does not appear to be an advisable strategy, according to Lopez-Bellido *et al.* (2003). The possible effect of this high N fertilization (160 kg N ha^{-1}) on the $CaCO_3$ losses was much more pronounced in the TT treatment.

Losses of $CaCO_3$ in CT and TT can produce, at long term, a decrease in the stability of soil structure. In this case, this could be more relevant in TT than in CT, especially at the surface. The increase in organic matter and lower losses of $CaCO_3$ minimize the degradation of soil structure. As indicated by Wallace (1994), among others, Ca is the most important cementing agent (for organic matter and clay) in the soil structure, and it is often considered recommendable to apply Ca together with the organic residues in order to improve the aggregate stability.

In summary, suitable indicators for conservation tillage (CT) are required. This is especially important under semi-arid conditions, where SOM accumulation at the soil surface may be rather low despite leaving crop residues on the soil surface. Under these conditions, the simple determination of the total SOC cannot be the best indicator of the improvement caused by CT (SOC increase may be considered as low from an agronomic point of view). The SR of SOC could be proposed as a more reliable index to detect soil improvement. A slight increase in this variable may be accompanied by important increases in the SR of other biological and biochemical properties. Stratification of SOC with depth under CT has consequences on soil functions beyond that of potentially sequestering more C in soil. The increase in SOC in CT, despite being moderate, may contribute to reducing potential losses of $CaCO_3$ at long term, compared to those in TT (possibly due, in part, to excessive N fertilizations).

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