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Soil organic carbon fractions under conventional and no-till management in a long-term study in southern Spain

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Abstract. In dryland farming systems under a Mediterranean climate, soil quality and productivity can be enhanced by increasing the content of soil organic carbon (SOC) through alternative soil management systems. Some fractions of C are directly involved in increasing total SOC and therefore in enhancing any benefits in terms of soil properties. This study compares the viability of no-till farming (NT) with conventional (traditional) tillage (TT) for improving SOC levels. The influence of management practices was investigated for different fractions of C (particulate OC, active OC, humic acids, fulvic acids) and CO_2 emissions in clayey soils in the south of Spain. The experiment was conducted over three farming seasons (2006–07, 2007–08 and 2008–09) covering a crop rotation of peas (*Pisum sativum* L.), wheat (*Triticum aestivum* L.) and sunflowers (*Helianthus annuus* L.). The NT system improved the levels of the different fractions of C in the surface soil and reduced the amount of CO_2 released into the atmosphere compared with the TT system. Generally, the relationship between CO_2 and SOC content was greater in soils under NT for the farming seasons sampled.

Additional keywords: conventional tillage, CO_2 emissions, no tillage, particulate organic carbon, soil organic carbon.

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Introduction

The concentration of soil organic carbon (SOC) is generally considered an indicator of soil quality because of its agronomic and ecological functions. Factors that influence SOC content include land use, soil properties, rainfall, temperature, crop characteristics (such as the amount and fate of crop residues applied or root distribution), and management practices (Fantappiè *et al*. 2010; Farina *et al*. 2011). Especially under Mediterranean climate conditions, SOC stocks are constrained by the low production of biomass (reduced C input) as a consequence of the mismatch of favourable moisture and temperature conditions, and competition of livestock for crop residues (Álvaro-Fuentes and Paustian 2011).

In a review of several studies at different sites in the USA, Reicosky (2011) observed that intensive agriculture might have contributed to 30–50% of SOC depletion in the last two decades of the 20th Century alone. Changes in land-management systems directly affect SOC content (Ordóñez Fernández *et al*. 2007). A C-cycle modelling study has shown that changes in soil management systems have a greater impact on SOC content than that predicted for climate change models (Smith *et al*. 2005). Factors that may influence and differentiate experimental results are the length of the study (West and Post 2002; Blanco-Canqui and Lal 2008), the depth of the soil profile considered and crop rotations (Christopher *et al*. 2009).

Conventional tillage tends to boost the CO_2 flux the first few days after soil disturbance; however, in the long term, CO_2 emissions are lower and there may even be a net reduction compared with no-till (NT) farming (Oorts *et al*. 2007; Regina and Alakukku 2010). Complex interactions between the different factors governing CO_2 emissions (temperature, rainfall, soil moisture, SOC and its stratification, and crop residues) seem to determine the long-term CO_2 emission balance (Oorts *et al*. 2007).

Several authors have studied the effect of soil tillage practices on soil CO_2 emissions (e.g. Franzluebbers *et al*. 1995; Kessavalou *et al*. 1998). Franzluebbers *et al*. (1995)

reported that active fractions of soil organic matter (SOM) increased in the soil surface layers under no-till much more than under conventional tillage. According to Mikha and Rice (2004), increments in active fractions of SOC are the result of decreases in turnover.

The variability in the reported results for both SOC content and CO_2 emissions reveals the complexity of the processes that occur between the numerous SOC fractions, and the fact that SOM is composed of living biomass and compounds that are at different stages of decomposition and have a different degree of association with the mineral component of the soil (Kay and VandenBygaart 2002). The most abundant fractions in the soil are those with the slowest turnover rate, which can increase after many years of conservation management. This highlights the importance of long-term studies, as well as evaluation of the impact of agricultural management practices on changes in SOC. However, some SOC fractions have been identified as responding on a short-term basis to changes in land use and soil management (Franzluebbers and Stuedemann 2008). Dissolved OC (DOC) represents the most labile SOC fraction (Chantigny 2003). Active OC (AOC) obtained through oxidation by potassium permanganate ($KMnO_4$) is another SOC component that is very sensitive to changes in soil management because of its rapid turnover time (Li *et al.* 2006). AOC is recommended as useful for the assessment of soil quality. Although characterised as an intermediate stage in the continuum of active–slow–passive SOM, particulate OC (POC) has been shown to be much more sensitive to change than total SOM (Elliott *et al.* 1994), reacting rapidly to changes in soil management (Jastrow *et al.* 1996; Cambardella and Elliot 1992). Hence, POC content is considered an early indicator of long-term changes in soil quality (Rosell *et al.* 2001). According to Cambardella *et al.* (2001), POC is a transitory OM pool that lies between fresh biomass and humic stable OM. Quiroga *et al.* (1996) showed the importance of POC in regulating soil structure and soil susceptibility to compaction. Rhoton *et al.* (2002) found a positive correlation between percentage aggregate stability and labile SOC content.

Humic substances are characterised by a low turnover rate because they belong to the stable and very stable SOC fractions, which are less affected by short-term agronomic practices. However, while studying the influence of organic amendments on soil quality indicators, González *et al.* (2010) found that one of the treatments had a significant short-term effect on the concentration of fulvic acids.

This study examined the capacity of agriculture to increase OC content and different OC fractions in the soil, and assessed how weather conditions can influence these processes. A field trial was carried out in southern Spain, after 29 years of differentiated soil management practices.

Materials and methods

Experiment site and climate

The study was conducted in a 3.5-ha area within the Tomejil Experiment Station (37°24′07″N, 05°35′10″W; 79 m asl) as part of a long-term soil-management experiment in southern Spain.

In autumn 1982, a long-term field experiment was initiated at the site to compare crop production outcomes and changes in physical and chemical properties of soil under conventional (traditional) tillage (TT) and NT. Traditional agriculture is based on soil tillage. It includes farming practices such as deep soil inversion by tilling for weed control and seedbed preparation. TT consists of a primary tillage pass performed with mouldboard, disc or chisel ploughs, and several secondary tillage passes performed by disc harrows or cultivators to reduce clod size. Plough passes considerably increase soil deformation by compaction and soil erosion, as well as causing river contamination with sediments, fertilisers and pesticides. In addition, TT techniques increase the emission of CO_2 into the atmosphere, contributing to global warming, and reduce the sustainability of agriculture by decreasing SOM and fertility, along with further negative environmental effects (e.g. a decrease in biodiversity). NT minimises alteration to the soil and prevents degradation processes (e.g. soil erosion and compaction). NT in annual crops, and cover crops between tree-rows in perennial woody crops, are the main techniques constituting conservation agriculture. Generally, conservation agriculture includes any practice that reduces, modifies or eliminates soil tillage and avoids residue burning to maintain surface residue throughout the year for erosion control. Soil is protected from rainfall erosion and water runoff, soil aggregates are stabilised, organic matter and the fertility level naturally increase, and less surface soil compaction occurs. Furthermore, contamination of surface water and emissions of CO_2 into the atmosphere are reduced, and biodiversity increases.

Some trial characteristics are described in Ordóñez Fernández *et al.* (2007). The annual crop rotation was cereals–sunflower–legumes. The soil was formed on Miocene marl and it is classified as Chromic Haploxerert (Soil Survey Staff 1999). The soil has good natural fertility with high concentrations of potassium (K) and calcium (Ca), average levels of phosphorus (P) and low OM content and tends to be pH neutral. In terms of texture, clay is the main component (>60%). Of the total clay, 70% is montmorillonite, 20% is illite and 10% is kaolinite (Perea 2000). Table 1 shows the physical and chemical characteristics of the soil.

The climate is characterised by a cold, wet period during autumn and winter, which accounts for 80% of rainfall, and a very warm, dry period during spring and summer. The temperature regime is 'thermic'; the mean annual soil temperature is ≥15°C but lower than 22°C and the difference between mean summer and winter soil temperatures is >6°C at a densic, lithic or paralithic contact, whichever is shallower (Soil Survey Staff 1999).

We recorded the weather data in the area throughout the 3-year study, assessing rainfall as well as maximum (Max. T), average (Med. T) and minimum (Min. T) daily temperature. The data were taken from a weather station 50 m from the experimental plot, which is part of the network of agricultural weather stations of the Andalusia Regional Secretary of Agriculture and Fisheries (Spain). Figure 1 presents the monthly average and median temperatures and the rainfall recorded throughout the seasons for which data were collected.

Table 1. Characteristics of the studied soil for the 0–0.2 m profile
CEC, Cation exchange capacity

	Tillage				No-tillage			
	Plot 1	Plot 2	Plot 3	Median	Plot 4	Plot 5	Plot 6	Median
Texture (%)								
Sand	5.0	6.4	7.7	6.3	4.9	10.7	7.6	7.8
Silt	31.5	31.6	31.2	31.4	36.4	36.4	36.6	36.5
Clay	63.5	62.0	61.1	62.2	58.7	52.8	57.7	56.4
Chemical analyses								
pH	7.7	7.5	7.7	7.6	7.5	7.5	7.5	7.5
OC ($g\,kg^{-1}$)	8.3	9.3	10.8	9.5	10.8	11.8	13.4	12.0
P ($mg\,kg^{-1}$)	20.3	8.0	9.8	12.7	25.0	27.9	21.1	24.6
K ($mg\,kg^{-1}$)	705.0	587.0	635.0	649.0	912.0	844.0	819.0	858.0
Ca ($mg\,kg^{-1}$)	552.0	610.0	654.0	605.0	611.0	521.0	367.0	499.0
Mg ($mg\,kg^{-1}$)	31.2	27.0	28.0	28.7	28.9	25.6	31.1	28.5
CEC ($mol_c\,kg^{-1}$)	0.70	0.50	0.40	0.52	0.60	0.40	0.60	0.52
Bulk density ($g\,cm^{-3}$)				1.15				1.14

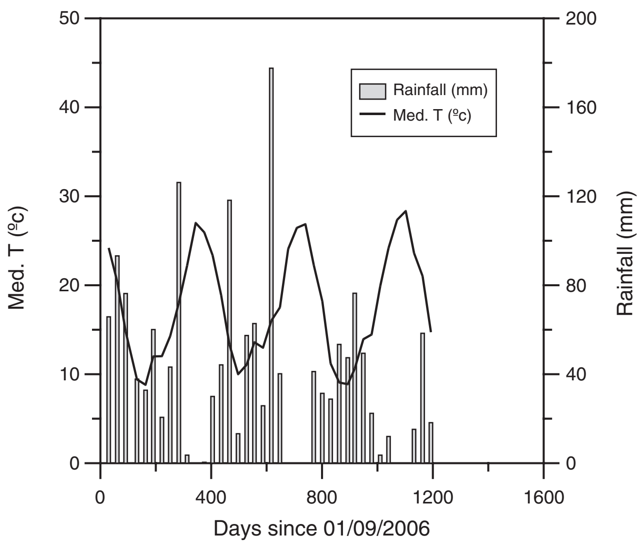


Fig. 1. Distribution of rainfall and average temperatures (Med. T) recorded during the study period at the experimental station.

Table 2. Operations carried out over the different seasons

Date	No-till	Tillage
Pea		
04 Oct. 06	Sprayer	
14 Nov. 06		Semi-chisel plough
29 Nov. 06	Sprayer	Sprayer
16 Jan. 07		Disc plough
17 Jan. 07	Sowing	Sowing
06 Apr. 07	Sprayer	Sprayer
07 June 07	Harvesting	Harvesting
Wheat		
20 Sept. 07		Semi-chisel plough
13 Nov. 07		Cultivator
25 Nov. 09	Sprayer	Sprayer
17 Dec. 07	Sowing	Sowing
12 Jan. 08	Fertiliser	Fertiliser
10 Feb. 08	Fertiliser	Fertiliser
14 Mar. 08	Fertiliser	Fertiliser
20 Apr. 08	Sprayer	Sprayer
10 July 08	Harvesting	Harvesting
Sunflower		
20 Oct. 08		Semi-chisel plough
20 Nov. 08		Disc plough
25 Nov. 08	Sprayer	
05 Apr. 09	Sprayer	
15 Apr. 09		Semi-chisel plough
20 Apr. 09	Sowing	Sowing
25 Apr. 09	Fertiliser + sprayer	Fertiliser + sprayer
22 Aug. 09	Harvesting	Harvesting

Experimental design

The TT treatment consisted of a disc plough pass after the stubble was incorporated into the soil, with successive cultivator passes to decrease soil clod size. In the NT treatment, the residue was left to decay on the soil surface. In this treatment, an adapted drilling machine was sometimes required. The operations were carried out over the three seasons (2006–07, 2007–08 and 2008–09; Table 2).

Sowing was done on the same day in both cultivation systems, but with a different drill. For NT, we used a tine drill. Tractor speed is very important in seeding. At high speeds, the tines exert great pressure on the soil and affect the surface profile. Thus, we chose a speed of $0.6\,m\,s^{-1}$, which guaranteed a good distribution of the seed and did not cause a pressure change in the surface soil.

The soil was fertilised in the same way in both treatments, except that in NT, the fertiliser grains remained on the soil surface until dissolved by infiltrating water. Weeds were controlled under NT by applying glyphosate (N-(phosphonomethyl)glycine) and MCPA (2-methyl-4-chlorophenoxyacetic acid) at rates of 0.6 and $0.5\,L\,ha^{-1}$, respectively. Occasional re-growth of weeds was dealt with by applying higher rates ($1\,L\,ha^{-1}$) of both herbicides. Sunflower stubble was broken into smaller pieces with sharpened boundary roller.

Plots were 15 m wide and 180 m long and were replicated three times in a random complete block design. This study was conducted for three consecutive farming seasons, 2006–07, 2007–08 and 2008–09. The crops grown in these seasons were peas (*Pisum sativum* L.), winter wheat (*Triticum aestivum* L.) and sunflowers (*Helianthus annuus* L.), respectively.

To evaluate the temporal evolution of the variables during the study, nine fixed points were geo-referenced in each plot according to Martínez *et al*. (2009). In addition, a tenth point was chosen in each plot, within 1 m of its central point, to evaluate the spatial variability of the study (Fig. 2). Although the first nine points were sampled throughout the study, the tenth point was randomly chosen for every field visit. An EM38-DD (Geonics Ltd, Mississauga, ON, Canada) was used for geo-referencing and the samples were collected according to a stratified random design (Webster and Oliver 1990). These samples and their analysis allowed us to identify areas in which soil properties are similar.

Sampling and analyses

Samples were extracted with a Veihmeyer tube and transported to the laboratory in a plastic bag. The soils were subsequently air-dried and passed through a 2-mm sieve. Total OC content was determined using the Walkley–Black method (Nelson and Sommer 1982).

Deep sampling is very important, and the parameters most influenced by changes in soil management, such as SOC, AOC and POC, were determined by monthly samples from three depths (0–5, 5–10, 10–20 cm). The method of Cambardella and Elliot (1992) was used with further oxidation by potassium dichromate ($K_2Cr_2O_7$) in a sulfuric medium (Walkley and Black 1934), and the method by oxidation with 0.02 M $KMnO_4$ and subsequent measurement of the absorbance of the $KMnO_4$ excess at 550 nm (Weil *et al*. 2003).

Humic acid (HA) and fulvic acid (FA) contents were estimated from the top layer (0–5 cm) and analysed by pyrophosphate extraction and subsequent oxidation by $K_2Cr_2O_7$ in a sulfuric medium. All methods and procedures are described in Swift (1996). Results were based on the oven-dry weight of soil.

Emissions of CO_2 were measured every month, as for soil sampling. The measurements were made at the same point at which the soil was extracted in order to evaluate the possible relationship between emissions and SOC. The number of monthly readings coincides with the number of soil samples collected.

Gas flow was estimated by means of a portable infrared absolute and differential EGM-4 gas analyser (PP Systems Co., Amesbury, MA, USA). This consists of a battery-run integrated data recorder and soil temperature sensor coupled with a respiration camera. This suction or respiration camera is ~15 cm high and 10 cm in diameter. The machine is calibrated automatically before each measurement by using

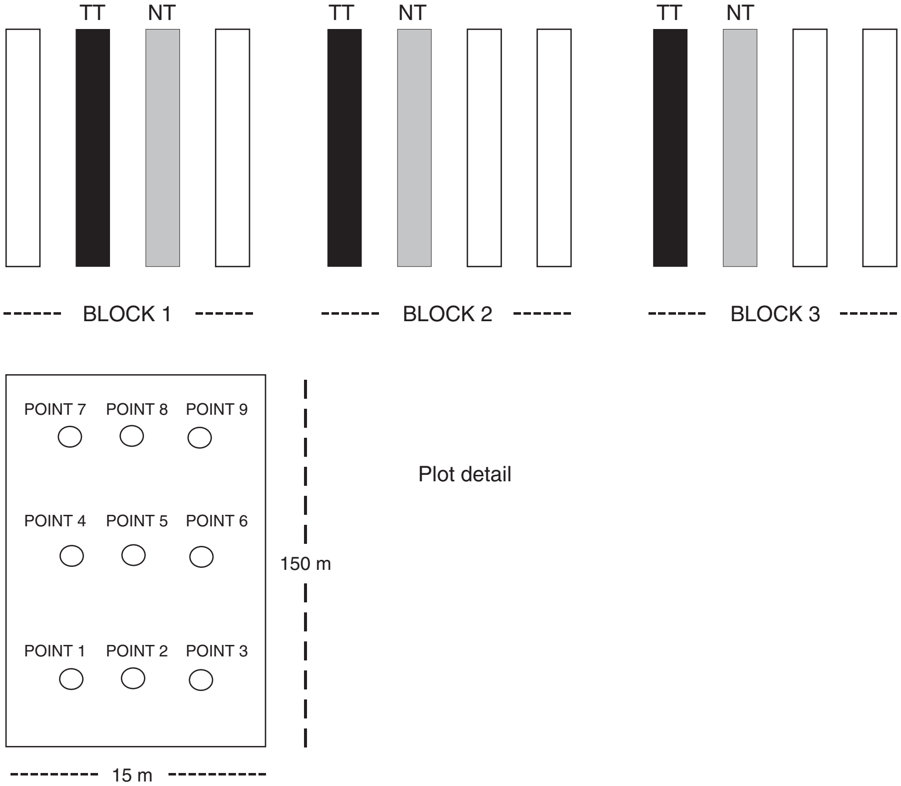


Fig. 2. Diagram of the distribution of the blocks at the Tomejil Experiment Station used for the field trials. Each block comprises four plots: one under traditional tillage (TT), one under no-till (NT), and two others (not used in this study). Lower diagram is a plot with the sampling points indicated (the tenth sampling point is not shown because it is random).

the surrounding air as a reference and it automatically transfers the data obtained to a computer. The camera is placed on the surface of the soil for 2.5 min, during which time data are collected every 4 s, giving the average value over the whole period as a final value. It is capable of measuring CO_2 at a range of 0–9.99 g CO_2 m^{-2} h^{-1} with a precision of ±1 and a resolution of 1 ppm. The analyser consists of a column with space for ~10 mL of a silica-derived substance, which absorbs the moisture in the air circulating in the system and transforms it into dry air to prevent interferences in the detection of CO_2.

Statistical analyses

An analysis of variance was carried out using the Statistix 8 (Analytical Software 2008) program. For the comparison of means, a Tukey test was employed at $P \leq 0.05$. Regression models were fitted using the linear regression module in the Statistix 8 program.

To analyse the spatial and temporal stability of SOC and POC content for the different measurement points, a method similar to that proposed by Vachaud *et al.* (1985) was used, based on the concept of temporal stability of calculating the average for each point (Eqn 1) and its variability (Eqn 2) over time. In this case, unlike the method proposed by Vachaud *et al.* (1985), the temporal means of each zone, not the relative differences, were used because they were more appropriate for finding average SOC and POC content.

$$AC_{zone}i = \sum_{t=1}^{n} \frac{X()it}{n} \quad (1)$$

Here, $AC_{zone}i$ is the temporal mean of SOC or POC in zone i ($i = 1,\ldots$), n is the number of samples taken at each measurement point, and $X()it$ is the percentage SOC or POC for zone i at time t.

$$\delta(AC_{zone}i) = \left[\frac{\sum_{t=1}^{n}(AC_{zone}i - X()it)^2}{n-1}\right]^{1/2} \quad (2)$$

Here, $\delta(AC_{zone}i)$ is the standard deviation of the mean, calculated as an estimate of temporal stability.

The SPSS Release 2008 (SPSS 2008) was used for a principal component analysis (PCA) (Davis 1973); briefly, beginning with an initial number of variables, a smaller number of variables was calculated that were a linear combination of the former. The first principal component (PC) explains most of the variance in the data and each successive PC accounts for a small part of the remaining variance. The different PCs are related to processes that affect all of the variables.

Results and discussion

Labile fractions are more sensitive to the effects of land use and can therefore be used as early indicators of the effect of crop rotation, fertilisation or the soil-management system on soil quality (Haynes and Naidu 1998; Six *et al.* 2004). Oyonarte *et al.* (2007) suggested that AOC content is a good indicator of the organic fraction in environmental programs aimed at recovering dry areas.

The average and maximum values of the different forms of C studied were always higher in soils under NT (Fig. 3). The largest differences were for SOC and POC content, where NT soil showed increases of >10% over TT soil. In relation to the CO_2 emissions, although the values of the median were similar in both management systems, the extreme values were found in the tilled soil.

The NT soil released less CO_2, which could be the result of fewer tillage operations reducing the exposure of soil aggregates to the atmosphere, which in turn reduced the weathering of organic compounds. Both processes tend to increase the concentration of OC in soil as well as reducing the amount of CO_2 released into the atmosphere. However, the magnitude of the response of these systems varies considerably depending on soil and climate conditions (Álvaro *et al.* 2007). In addition, in TT systems the diverse population of soil microorganisms is in direct contact with the residues tilled into the soil (Magdoff and Weil 2004), which favours the flow of gas into the atmosphere.

As will be shown below in the results for principal components analysis, CO_2 emissions data were strongly affected by climate conditions, particularly by rainfall and temperature. This could be why Fig. 3 does not clearly show the changes in the data obtained over the duration of the test period.

Apart from one specific date, the emission values recorded in NT plots were significantly lower than those in tillage plots (Fig. 4).

In our experiment, the increase SOC, AOC and POC in the surface soil in the NT system was probably associated with the high input of crop residues on the soil surface. In NT systems, crop residues are left on the soil surface, resulting in much slower crop residue incorporation and decomposition than in tilled systems in which crop residues are mechanically incorporated into the soil. This slower decomposition of crop residues under NT leads to the accumulation of SOC in the upper soil layers (Reicosky *et al.* 1997; Salinas-García *et al.* 2002).

Differences were apparent between TT and NT in terms of the distribution of SOC throughout the soil profile (Table 3). NT continued to show higher SOC content at 5–10 cm and 10–20 cm depths; in most cases, the difference between NT and TT was significant. The increases in SOC content under NT management were in line with those observed by other authors in field trials with similar soils in southern Spain (Madejón *et al.* 2007; Melero *et al.* 2008).

Under NT, SOC decreased over the 3 years of the study. Several authors (e.g. Martino 2011) have suggested that SOC content increases rapidly during the first 10 years after the change from conventional management systems to systems using conservation agriculture. After this period, increases in OM content are very small, which indicates that the soil has reached a balance. In this study, the soils in the experimental plot have been under NT for 26 years. We have compared the values obtained with those provided by Ordóñez Fernández *et al.* (2007) in a 21-year study on the same plots. We found that SOC content in the NT plots in 2001 was higher than the values presented in this paper. Decreases of 10.2%, 11.1%

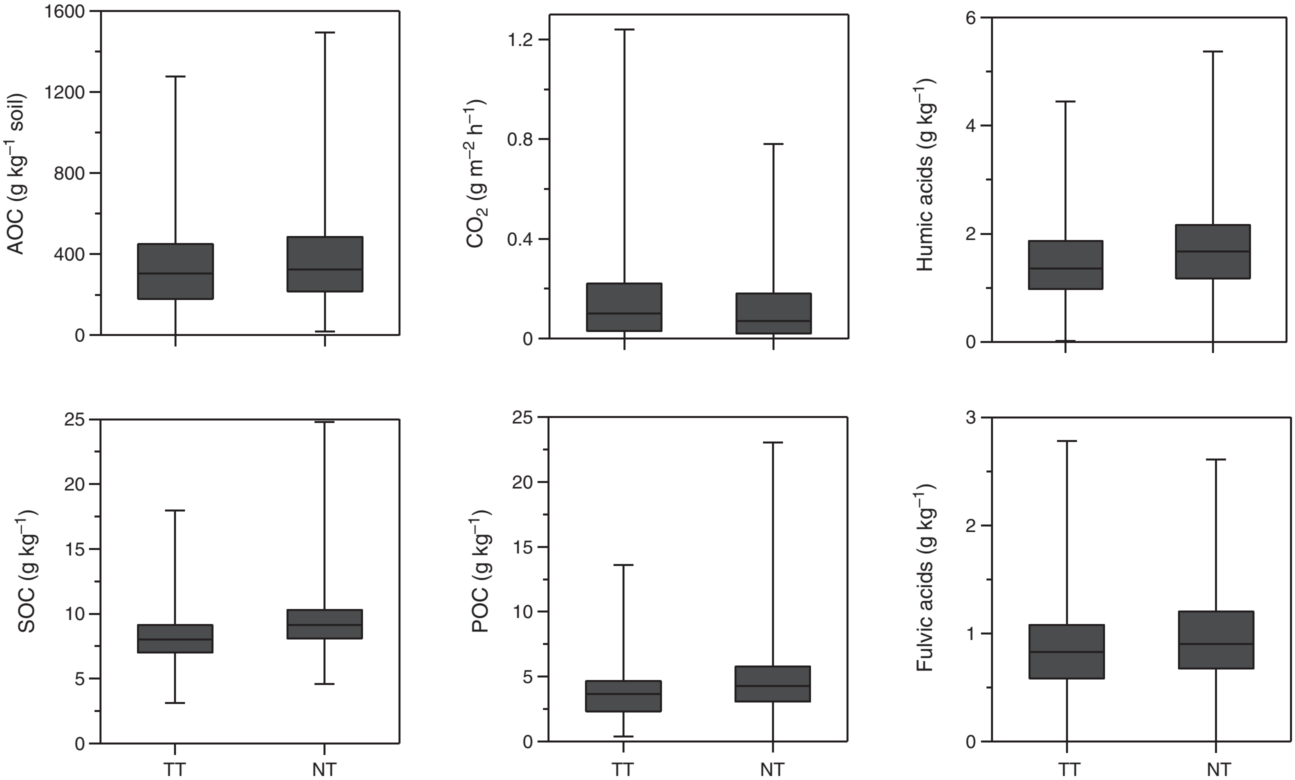


Fig. 3. Average values for the various forms of carbon studied in the soil and air in the different farming seasons and under two different soil management systems (TT, traditional tillage; NT, no-till). The box is defined by the lower and upper quartile, and the line in the centre is the median. The capped lines from each box show the extreme values, maximum and minimum. SOC, AOC, POC: Total (soil), active, particulate organic carbon.

and 2.3% were observed for depths of 0–5, 5–10 and 10–20 cm, respectively.

Reviewing the potential of conservation agriculture practices in Spain as a means of reducing the concentration of CO_2 in the atmosphere through C-sequestration processes, González-Sánchez *et al.* (2012) concluded that fixation rates were high in newly implemented systems, during the first 10 years (3.14 t ha^{-1} $year^{-1}$), after which the increase in SOC content diminished markedly (0.60–1.48 t ha^{-1} $year^{-1}$). By contrast, Franzluebbers and Arshad (1996) showed that the differences in SOC content for both traditional and conservation systems were not affected, or at least only minimally so, in the first 2–5 years. However, a significant increase was observed in SOC at 5–10 years in favour of the soil under conservation agriculture.

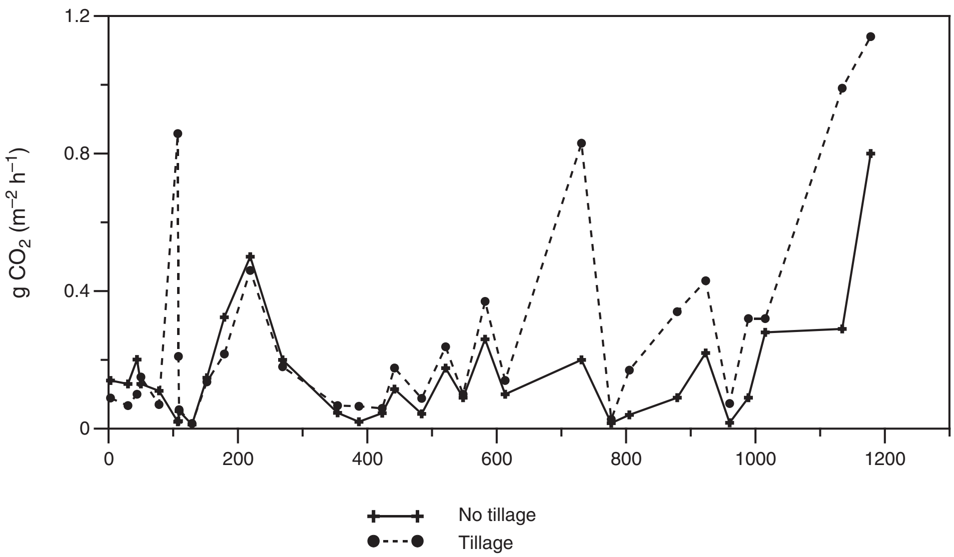
Our results differ from those of Álvaro-Fuentes *et al.* (2008) in a study of the influence of soil-management practice on SOC and POC in semi-arid agroecosystems of the Ebro River valley. Those authors also found significantly higher SOC and POC concentrations in the surface soil (0–5 cm depth) under NT at all experimental sites compared with TT. However, at depths greater than 10 cm, SOC and POC concentration was similar to or lower than under other tillage treatments.

Regarding POC content in the present study, the highest values were found in the NT soils, where soil structure is maintained (Table 3). Our results coincide with those of Galantini (2002), who estimated POC concentrations of 1.4%, 1.6% and 2.9% in soils under TT, vertical tillage and NT, respectively.

Some authors link high POC content to soil aggregates stability and, therefore, improved soil structure (Wander *et al.* 2002). Meanwhile, others such as Loveland and Webb (2003) believe that POC as a proportion of total C is more important as an indicator than POC content *per se*. Quiroga *et al.* (1996) demonstrated the importance of POC in regulating structure, given the susceptibility of the soil to compaction. Rhoton *et al.* (2002) found a positive correlation between the percentage aggregate stability and labile SOC content. Chaney and Swift (1984) produced similar results in 26 British soils, as did Caravaca *et al.* (2001) in two semi-arid soils in south-eastern Spain.

At field level, it is difficult to detect short-term changes in SOC in response to management changes because of high initial contents and the high spatial variability of SOC (van Kessel *et al.* 1994; Hungate *et al.* 1996). Studies suggest that measures of POC can provide an indication of longer term changes in SOC due to tillage effects (Six *et al.* 1998).

A spatial and temporal stability analysis of SOC and POC was therefore performed to assess the persistence of C content over time in each zone compared with the others. Figure 5 shows the mean SOC and POC percentages. The analysis shows that management system influenced the spatial distribution of both SOC and POC. For SOC content, NT soil displayed greater spatial variability, with minimum of 0.888 g kg^{-1} and maximum



DAYS	3	30	44	50	78	107	108	109
	ND	ND	***	ND	*	*	*	*
DAYS	129	152	179	219	269	354	387	423
	ND	ND	**	ND	ND	**	**	
DAYS	442	484	521	548	582	613	731	777
	**	*	ND	ND	**	ND	***	ND
DAYS	805	879	923	960	989	1015	1134	1178
	***	***	**	**	***	ND	***	*

Fig. 4. Evolution of CO_2 emissions for the duration of the three seasons studied. The table shows significant differences between the two soil management systems using Tukey's *t*-test at significance levels: $*P \leq 0.05$; $**P \leq 0.01$; $***P \leq 0.001$. ND, No significant difference at $P = 0.05$.

of 1.07 g kg^{-1}, compared with the TT soil estimates, which ranged from 0.718 to 0.858 g kg^{-1}. In the case of POC content, it was minor in the soil under TT, due to tillage operations breaking up soil aggregates and paving the way for microorganisms to attack the POC. This fraction is mainly composed of fine root fragments and other organic debris and serves as a readily decomposable substrate for soil microorganisms (Mrabet 2001). Soil POC content ranged from 0.28 to 0.45 g kg^{-1} under TT, and from 0.37 to 0.53 g kg^{-1} under NT. Our results agreed with those of Lee *et al*. (2009), who conducted a study on the effects of NT and TT on POC in two neighbouring 15-ha fields between 2003 and 2004. Those authors concluded that the variability of POC was primarily affected by tillage and was further influenced by clay content and bulk density.

In general, the standard error was lower under TT than NT for both parameters, which indicates that the different forms of C varied less over time in tilled soil because tillage operations created a mixed soil profile. Ordóñez Fernández *et al*. (2007) and Melero *et al*. (2009) studied soil with similar characteristics to our site, observing that TT operations homogenised the content of nutrients both in the surface soil and in deeper layers.

When intensive tillage was applied, two effects could have occurred. First, SOC and POC could have been redistributed throughout the soil profile, and second, SOC and POC might have mineralised faster in the topsoil, due to better soil microclimatic conditions for microbial activity (Gale *et al*. 2000). Greater variability was observed in POC content than in SOC content under TT, indicating that this form of C was more sensitive to alterations in the soil than SOC. Staricka *et al*. (1991) produced similar results in a study evaluating residue distribution throughout the profile, comparing disc, chisel and mouldboard ploughs. Those authors found that the depth at which residues were found was 28 cm for mouldboard ploughing and 10 cm for the other two types of plough. Because this refers to POC content, it should be remembered that this C fraction is formed from the freshest organic material, that is, root remains, residues from previous seasons, etc. In TT plots, we found that the POC fraction is incorporated at depth, whereas in NT plots the POC content is greater nearer the surface.

The relationship between labile OC and total OC is an indicator of the effect of different farming systems on the organic fraction of the soil (Galantini 2002). This indicator is used to assess changes in SOC associated with the tillage system, land use and productive capacity (Fig. 6). Regardless of the soil-management system studied, the POC as a proportion of SOC in the topsoil ranged from 40% to 50%. These results contrast with those of Wander *et al*. (1998), who observed 70% more POC under NT than under TT, and Hussain *et al*. (1999), who found that POC made up a greater proportion of SOC under NT than under conventional tillage, when only the soil surface was considered. Álvaro-Fuentes *et al*. (2008) found that the POC fraction under NT contributed 32% of the total SOC at a depth of 0–10 cm.

Table 3. Total (soil), active and particulate organic carbon contents ($g\,kg^{-1}$) at 0–5, 5–10 and 10–20 cm depths and for the whole profile for both soil management systems (TT, traditional tillage; NT, no-till)

Comparisons are of means between treatments (TT *v.* NT), for each carbon fraction and within year and depth, by analysis of variance and a Tukey's post-hoc test at $P = 0.05$. Level of significance is indicated after NT mean: *$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; means followed by the same letter are not significantly different at $P = 0.05$

Date	0–5 cm		5–10 cm		10–20 cm		0–20 ($t\,ha^{-1}$)	
	TT	NT	TT	NT	TT	NT	TT	NT
Soil organic carbon								
Initial	7.4b	0.3a***	8.0b	9.4a**	8.2a	8.4a	18.1	21.4
2006	7.5b	0.2a***	8.0b	9.3a**	7.8b	0.3a***	17.7	23.8
2007	8.1b	9.1a***	7.8b	9.8a***	8.9a	8.0b*	19.2	20.5
2008	8.6a	9.7a*	7.1b	8.8a**	7.0b	8.6a**	16.4	20.6
Active organic carbon								
Initial	0.44a	0.55a	0.44a	0.59a	0.45a	0.54a	1.0	1.3
2006	0.36a	0.56b**	0.36b	0.55a**	0.37b	0.50a*	0.8	1.2
2007	0.27a	0.34a	0.29a	0.38a	0.32a	0.41a	0.7	0.9
2008	0.22b	0.93a***	0.17b	0.79a***	0.19b	0.59a***	0.6	1.8
Particulate organic carbon								
Initial	1.6a	1.8a	1.7a	1.9a	1.8a	2.08a	3.8	4.4
2006	3.6b	4.1a***	3.4b	4.1a**	3.5a	3.7a	8.0	9.0
2007	4.3b	6.2a**	4.3b	6.9a**	4.6b	7.3a***	10.1	15.5
2008	4.5b	7.7a	3.4a	4.9a	3.1a	4.4a	8.3	13.2

The PCA was performed to identify the variables responsible for the majority of total variability in the data and to explore correlations between the parameters analysed (Davis 1973). The data used as the basis for the analysis were CO_2 emissions, weather conditions recorded over the sampling period, temperature at the times that readings were taken, and OC, POC, AOC, HA and FA contents.

The PCA started with the initial variables: rainfall, Max. T, Med. T, Min. T, CO_2, HA, FA, SOC, AOC and POC. The final variables PC1 and PC2 were determined via a linear combination of the initial variables (Table 4, Fig. 7). Very low emission values were recorded for group 1 in Fig. 7, ranging from 0 to $0.05\,g\,CO_2\,m^{-2}\,h^{-1}$. At the same time, temperatures were quite high in all cases, with values ranging from 18°C to 30°C. However, perhaps the most striking result in this group of points is that no rainfall was recorded. This group includes the points with the highest values of AOC and very low POC content. Rainfall was recorded for group 2, and average temperatures were similar to those recorded for group 1, with minimum ~11°C and maximum 30°C. Group 2 includes points with the highest emission values, which average $\sim 0.15\,g\,CO_2\,m^{-2}\,h^{-1}$. For C content, this group registered high values of POC and AOC, low values of HA and the highest values of FA.

Group 3 recorded similar emission values, $\sim 0.11\,g\,CO_2\,m^{-2}\,h^{-1}$, but temperatures were somewhat cooler, with maximum 20°C and minimum 2°C. Average rainfall was 70 mm. This group recorded the highest SOC content and average values of POC and AOC.

The last group included the highest rainfall rates at nearly 150 mm. Temperatures were similar to those recorded by groups 1 and 2, with maximum 30°C and minimum 10°C. Noteworthy results for this group are the emissions values, which averaged $0.4\,g\,CO_2\,m^{-2}\,h^{-1}$, with values that exceeded $1.5\,g\,CO_2\,m^{-2}\,h^{-1}$. These high emission scores coincided with the highest POC contents. POC, as indicated previously, is part of the freshest OM and is therefore in the process of decomposing, which is the reason for this increase in emissions.

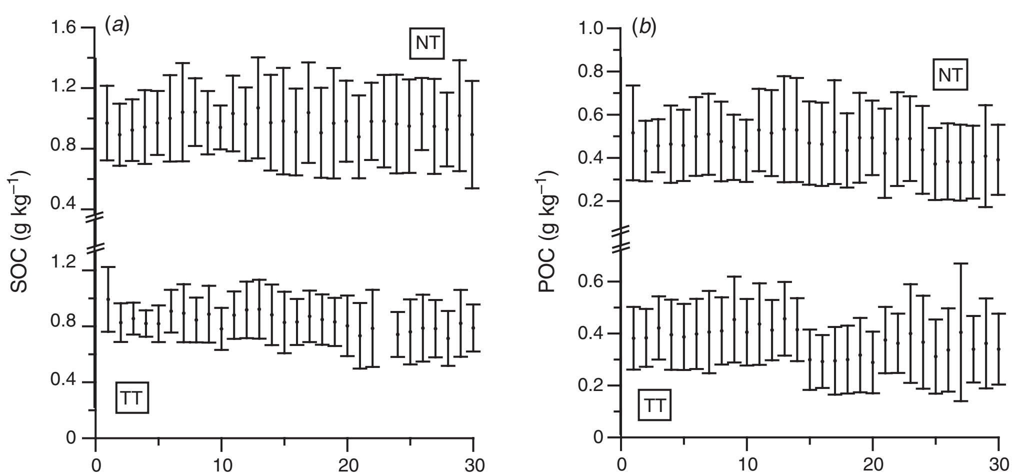


Fig. 5. Mean of total (soil) and particulate organic carbon contents (SOC and POC) in order of range in each of the sampling points for no-till (NT) and traditional tillage (TT) management systems. Capped vertical lines denote the standard error obtained at each point.

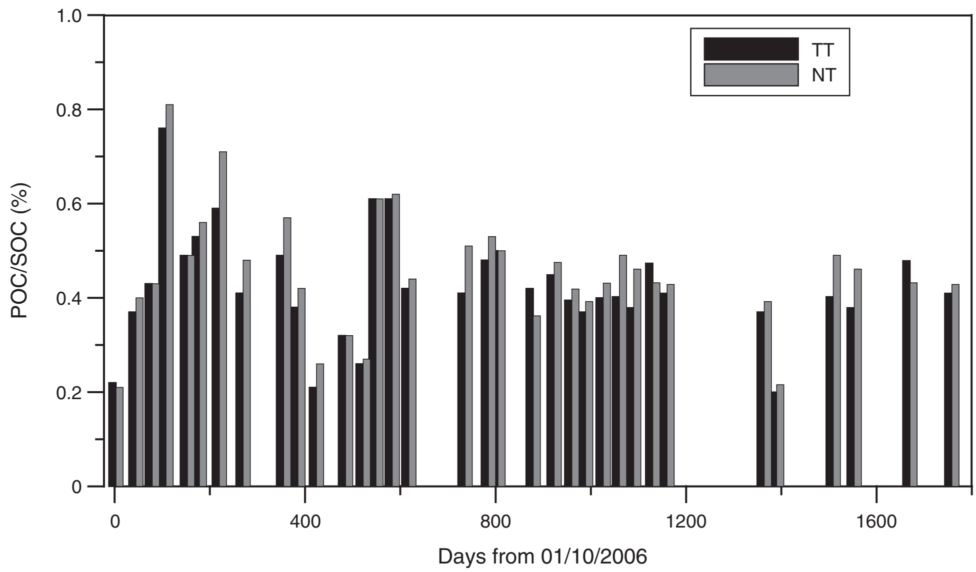


Fig. 6. Degree of decomposition of soil expressed as the relationship between the percentage of particulate and total (soil) organic carbon (POC/SOC) for no-till (NT) and traditional tillage (TT) management systems.

Table 4. Component values of principal component analysis and the correlation matrix
Max. T, Med. T, Min. T: Maximum, average, minimum temperature; SOC, AOC, POC: total (soil), active, particulate organic carbon; HA, FA: humic, fulvic acids; PC, principal component

Factor	Rainfall	Max. T	Med. T	Min. T	CO_2	HA	FA	SOC	AOC	POC
PC1	0.999	0.034	0.023	0.01	0.001	0.540	0.763	0.492	0.323	0.084
PC2	0.038	–0.588	0.582	–0.558	–0.000	–0.492	0.083	0.027	0.030	0.540
	CO_2	Rainfall	Max. T	Med. T	Min. T	SOC	AOC	HA	FA	POC
Rainfall	0.424									
P-value	0.000									
Max. T	0.191	0.267								
	0.000	0.000								
Med. T	0.121	0.186	0.978							
	0.000	0.000	0.000							
Min. T	0.006	0.080	0.874	0.950						
	0.855	0.020	0.000	0.000						
SOC	–0.362	0.393	0.151	0.131	0.089					
	0.000	0.000	0.000	0.000	0.353					
AOC	–0.232	0.191	0.032	0.013	0.121	0.131				
	0.000	0.000	0.012	0.000	0.333	0.000				
HA	0.028	0.077	0.002	0.005	0.065	0.226	0.089			
	0.466	0.038	0.001	0.898	0.171	0.000	0.181			
FA	0.032	0.033	0.001	0.003	0.024	0.091	0.081	–0.385		
	0.413	0.012	0.018	0.737	0.002	0.021	0.000	0.000		
POC	-0.078	0.568	0.434	0.189	0.212	0.288	0.233	0.018	0.031	
	0.046	0.000	0.000	0.0033	0.005	0.000	0.000	0.181	0.432	
PC1	0.424	1.000	0.268	0.187	0.081	0.333	0.232	0.089	0.333	0.445
	0.000	0.000	0.000	0.000	0.018	0.000	0.000	0.018	0.008	0.000
PC2	0.254	0.658	–0.531	–0.615	–0.671	0.252	0.111	0.666	0.011	0.272
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.188	0.000

For the conditions of our study, temperature did not play the same role as rainfall; in fact, group 1 and group 2 recorded temperatures within the same range. However, group 1 did not record any rainfall, whereas group 2 did, which explains why the second group registered greater emissions than the first.

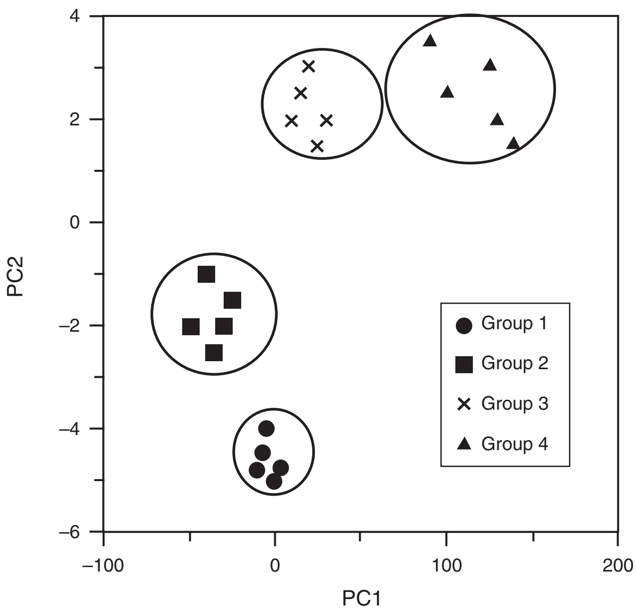


Fig. 7. Representation of principal component (PC) values.

Álvaro *et al.* (2007) observed an increase of ~0.10–0.15 g CO_2 m^{-2} h^{-1} in three tillage treatments (TT, reduced tillage and NT) following a rainfall event of 22 mm. A similar trend has been observed in other studies (Ellert and Janzen 1999; Alvarez *et al.* 2001). Akinremi *et al.* (1999) suggested that greater CO_2 fluxes after a rainfall event are the result of two processes: first, a physical release of the CO_2 trapped in the soil structure and displaced by water filling soil pores, and second, the stimulation of soil microbial activity.

All groups in the PCA analysis include data from both the farming systems under study, highlighting the importance of weather conditions in the release of gases into the atmosphere, regardless of the system employed. Other authors such as Reicosky *et al.* (1997) and Prior *et al.* (2004), in studies comparing the influence of the soil management system used on CO_2 emissions, conclude that differences in CO_2 fluxes between years for the same site are related to differences in microbial activity before tillage operations.

Conclusions

The results of this study indicate that the NT method is particularly beneficial for improving the quality of agricultural soil. This is demonstrated by the increased content of the different forms of C in NT soils compared with TT soils.

These results are important in terms of OM turnover and nutrient availability under semi-arid Mediterranean climatic conditions in dryland agriculture systems.

The lower spatial and temporal variability of SOC content, including labile and recalcitrant C forms, observed in TT soil indicates a homogenisation of the soil profile and a more modified structure than in NT soil. This is confirmed by the fact that in the NT system high values in POC content are observed.

Regardless of soil improvement and the reduced CO_2 emissions recorded in NT soils, it would be beneficial to encourage these practices in the farming community because the regulations of the new common agricultural policy (PAC) closely follow the principles of this soil management system.

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