Tillage influence on biophysical soil properties: the example of a long-term tillage experiment under Mediterranean rainfed conditions in South Spain

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Abstract

Long-term field experiments are important to provide information about how soil carbon (C) dynamics is affected by soil tillage systems. In this study we directly diagnose the influence of the topsoil's (0-5 cm depth) C concentration on soil quality in an Entisol under Mediterranean conditions, testing a new statistical method. The objective was to estimate the impact of conservation tillage (RT) as a C management practice, versus a traditional tillage (TT) system on biophysical soil properties. We analyzed the impact of the soil C management on biological (microbial biomass C, dehydrogenase and β-glucosidase activities), physical soil properties (aggregates stability, conductive mean pore diameter, aggregation index) and CO_2 fluxes. The concentrations for total organic carbon (TOC), the active carbon (AC) normalised by the total carbon (AC TOC^{-1}), served as a combined proxy for the soil C management related to the tillage system. Soil C management accounted for 0 to 46 % of the change of biophysical soil properties in RT versus TT. The RT led to a C increase (18.9%) of microbial activities, especially in the top 0-5 cm depth. Related to the physical soil properties, less C in TT led to a lower aggregation index, although this tendency was not observed for other physical parameters. The impact of soil C management was better correlated with soil microbial than with the physical properties. Our analysis directly quantified for the first time that the increase in the soil's carbon concentration can only explain a small fraction of the beneficial change in biophysical soil properties due to RT. In general the RT contributed to the long-term sustainability of the agroecosystem by improving biological and physical soil characteristics under dryland semi-arid Mediterranean conditions.

Keywords: Soil Carbon, Tillage, Enzymatic Activities, Soil Aggregates, Soil Quality.

1. Introduction

Intensive tillage frequently causes losses of total soil organic carbon (TOC) with a parallel loss of soil quality at long-term (Reicosky, 2002; Lal, 2004) and increases CO_2 emissions from soil to the atmosphere (Lal et al., 1989; Bauer et al., 2006; Venterea et al., 2006; Conant et al., 2007). Conservation agriculture has been promoted since approximately 1960 as a means to counteract all these constraints enhancing soil quality related to carbon (C) sequestration (Lal, 2004) that favours soil biology and physical conditions (Kandeler and Böhm, 1996; Kandeler et al., 1999; Broninck and Lal, 2005; Muñoz et al., 2007). However, so far, the positive relation between soil C sequestration and biological and physical soil properties has never been directly quantified.

Semi-arid Mediterranean conditions, such those of southern Spain (mild rainy winters and very hot dry summers) promote TOC decomposition by microbiological activity, which could be a limiting factor for TOC accumulation in the top soil layers. Nevertheless, those soils with low inherent levels of TOC could be the most improved with conservation tillage management (which avoid soil inversion by ploughing and maintains at least 30 percent of the soil surface covered by residues: Gajri et al., 2002), despite modest or no change in TOC within the rooting zone (Franzluebbers, 2004).

Small changes in TOC resulting from changes in soil management are often difficult to measure and several years are required to detect changes resulting from management practices (Roldán et al., 2005). But even with no consistent changes in TOC due to the crop residues incorporation, slight increases in labile fraction of TOC create particular conditions for the physico-chemical and biological soil dynamic. In fact, changes in small but relatively labile fractions of TOC may provide an early and useful indication of improvement in response to management practices, especially important under Mediterranean semi-arid conditions, where great increases in TOC are not expected. Active carbon (AC), water soluble carbon (WSC) or microbial biomass carbon (MBC)

(Melero et al., 2009a,b; López-Garrido et al., 2011) can serve to indicate these labile C fractions.

Not only TOC, but also soil biochemical properties (enzymatic activities) are probably the most widely known indicators of soil quality (Gil-Sotres et al., 2005). On the other hand, the overall study of tillage influence on TOC and its labile fractions and soil biochemical variables require long-term tillage studies under different soil and climatic conditions to understand the dynamics of soil organic matter under the wide diversity of environments in the world (Franzluebbers, 2004). Interaction between different soil properties may be critical for the soil functions at long-term. In this context Deurer et al. (2008) published a new method to quantify directly the impact of soil C management on biophysical soil properties focused on two production systems: an integrated apple orchard and an organic apple orchard. This study estimated that the soil C management accounted for 0 to 81% of the degradation or enhancement of biophysical soil properties in the integrated and organic system.

To our best knowledge, under semi-arid Mediterranean conditions there is no study that has directly estimated how much biophysical soil properties change as a result of a change in soil C versus other factors that is caused by different tillage management practices. We hypothesize that at long-term, conservation tillage increases the soil's C concentration in the topsoil and that this in turn explains most of the positive effects on biophysical soil properties.

In essence, this study estimates the influence of the aspect of C sequestration of a conservation tillage technique (reduced tillage, RT) compared to a traditional tillage (TT) with soil inversion, on biophysical soil properties of the topsoil (considering different depths) of a typical Mediterranean arable land soil. For that, we have applied a recently published method (Deurer et al., 2008) to a long-term tillage experiment. Following the soil quality framework (Karlen et al., 2001, 2003; Deurer et al., 2008), we define tillage management practices to be sustainable if key soil functions did not degrade. In this study, the MBC, dehydrogenase (DHA), β-glucosidase (β-Glu) and diphenol oxidase (DphOx) activities were used as microbiological soil characteristics. For describing the soil physical properties, we chose the mean weighted diameter (MWD) of aggregates, the conductive macro-pore diameter (CMD) of water infiltration, the aggregation index (AI) and the aggregates water stability (WAS). We also measured CO_2 fluxes, both as a biophysical process and an indicator for the quantification of the actual C loss from the system.

2. Materials and methods

2.1. Localization of the experimental area and tillage systems

A long-term field trial using soil conservation management was conducted on an Entisol (Xerofluvent, Soil Survey Staff, 1999) with a sandy clay loam texture, at the experimental farm of the "Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC)" (37º 17' N, 6º 3' W), located 13 km southwest of the city of Seville (Spain). Some characteristics of the soil at 25 cm depth are: pH of around 7.8 (calcareous) and alkaline-earth carbonates 280 g ⁄ kg. The soil has a clay content of about 24% (60% montmorillonite, 25% illite, and 15% caolinite), 18% silt and 58% sand. The climate of the zone is typically Mediterranean, with mild rainy winters (484 mm mean rainfall for the time period 1971 to 2008 at the experimental site, hydrological year) and very hot and dry summers. Rainfall along the period of study was 547 mm. The mean annual daily temperature at the experimental site is around 17 ºC, with maximum and minimum temperatures of 33.5 ºC and 5.2 ºC in July and January, respectively.

An area of about 2500 m^2 was selected for establishing the experimental plots in 1991. In autumn of that year, wheat was grown. After harvesting the wheat in June 1992, the area was divided into six plots of approximately 300 m^2 (22 m x 14 m) each in a completely randomised experimental design (three replicates per treatment). Two tillage treatments were compared: traditional tillage, TT and conservation tillage (reduced tillage, RT). TT consisted of mouldboard ploughing (to a depth of 25-30 cm) after the straw of the preceding crop had been burned. We should note that straw burning has not occurred since 2003, when it was banned by the local government. RT was characterized by lack of mouldboard ploughing and a reduction in the number of tillage operations (retaining only chiselling at a depth of 25-30 cm) as well as by leaving the crop residues on the soil surface.

A wheat (*Triticum aestivum*, L.)-sunflower (*Helianthus annus*, L.) crop rotation was established for both TT and RT. However, in 2005, a fodder pea crop (*Pisum sativum*, L.) was included in the rotation. Thus, from 2005, the annual crop rotation consisted of a basic cereal-sunflower-legumes rotation for both treatments. The sunflower and fodder pea crops were not fertilized (as is traditional in this zone), while wheat received deep fertilization with 400 kg ha^{-1} of a complex fertilizer ($15N-15P_2O_5-15K_2O$) before sowing and a top dressing with 200 kg ha^{-1} urea (46% N). Since 2002, fertilization has been reduced to 100 kg ha^{-1} (fertilizer complex) with no top dressing fertilizer. Weeds are controlled by tillage in TT and by the application of pre-emergence herbicides in RT, at a rate of 2 l ha^{-1} trifluraline (18%) (applied to the sunflower crop) and 4 l ha^{-1} glyphosate (18%) (applied to the wheat and fodder pea crop).

In essence, when we compare the impact of TT and RT on the biophysical soil properties, then we compare the result of a different tillage management in the time from the beginning of the experiment in 1992 to our measurements in 2008 that is over 16 years.

2.2. Sampling and soil analysis

Chemical, biochemical and physical analysis

Soil was collected at three depths: 0-5, 5-10 and 10-25 cm, in different soil samplings along 2008. Four samples were taken in each plot to create a composite sample per replicate and treatment. The moist field soil was sieved (2 mm) and divided into two sub-samples. One was immediately stored at 4 ºC in loosely tied plastic bags to ensure sufficient aeration and prevent moisture loss prior to assaying for microbiological and enzymatic activities. The other was air-dried for chemical analysis. Biochemical analyses were carried out within two weeks.

Total organic carbon (TOC) was analysed by dichromate oxidation and titration with ferrous ammonium sulphate (Walkley and Black, 1934). Active carbon (AC) was determined by oxidation of 5 g of dry weight of soil with 2 ml of 0.2 M $KMnO_4$ in 1M $CaCl_2$ (pH 7.2) and non-reduced Mn^{7+} was colorimetrically determined at 550 nm (Weil et al., 2003). Water soluble carbon (WSC) was determined in a 1/10 aqueous extract using a TOC-V-CSH/CSN analyser. Microbial biomass carbon (MBC) content was determined by the chloroform fumigation-extraction method modified by Gregorich et al. (1990). Dehydrogenase activity (DHA) was determined according to Trevors (1984) using INT (iodonitrotetrazolium chloride) as substrate. β-glucosidase (β-Glu) was measured as indicated by Eivazi and Tabatabai (1988). Diphenoloxidase (DphOx) was measured following the procedure described by Perucci et al. (2000). For each microbiological analysis, three replicates per collected sample were done. Results were based on the oven-dried weight of the soil.

The mean weight diameter (MWD) was determined in 1-2 mm dry aggregates following the wet sieving method of Kemper and Rosenau (1986). It was expressed in mm and corrected following the Younker and McGuiness (1956) recommendations. The aggregation index (AI) was determined following the Dobrzanski et al (1975) method, using the aggregate fractions percentage and a weighting factor assigned to each one. Aggregate water stability (WAS) was determined on dry aggregates of 1-2 mm diameter following the method of Kemper and Rosenau (1986). We weighted 4 g of dry soil which was sieved (0.25 mm) in a wet sieving apparatus (Yoder Ejkelkemp). The results obtained were expressed in stable aggregates percentage. Conductive macro-pore diameter (CMD) between -20 and -60 mm tension was determined following Sauer et al. (1990) using an infiltrometer. The conductive pore diameter represents the average pore size for water infiltration near saturation.

Soil CO_2 fluxes

Soil CO_2 fluxes were measured by attaching a 6400-09 chamber with an area of 71.6 cm^2 to a 6400 LICOR gas-exchange system (LI-COR, Environmental Division, Lincoln, NE, USA). The period of measurement was 2008. The system was provided with a thermocouple probe to measure soil temperature. To minimise soil surface disturbances, the chamber was mounted on PVC soil collars sharpened at the bottom and inserted into the soil to about 3.8 cm. To prevent an overestimation of soil fluxes, typically observed immediately after the collars have been installed, the latter were inserted some days before the measurements were made. Furthermore, 6 collars were placed at random locations in each treatment in order to describe statistically the spatial variability. Only one measurement was made on each collar on each observation day. The sampling time in each collar varied in accordance with the CO_2 concentrations inside the chamber, ranging from 3 to 8 min. All the observations were performed during daylight hours, beginning at variable times ranging from 10:30 to 13:00 h. Measurements made at this time of the day were assumed to represent the average flux of the day (Kessavalou *et al*., 1998; Álvaro-Fuentes *et al*., 2007).

Statistical data analysis

Statistical analyses were carried out using SPSS 11.0 for Windows, and the results were expressed as mean values. Significant differences between management systems (TT, RT) were shown based on an analysis of variance (ANOVA) and a Student's t-test at $p<0.05$. A correlation matrix of different properties was based on Pearson correlation coefficients ($p<0.05$). Data normality was tested prior to analysis; when necessary, variables were transformed to achieve normality. If, after transformation, the data still did not have a normal distribution, we used non-parametric tests: the Mann-Whitney U test for comparison of mean values and the Kruskal-Wallis ANOVA by ranks test for variance analysis.

2.3. Definition of soil carbon management

The soil C management cannot be identified as one particular management practise. Soil C management is defined as a specific management practice that maintains or increase soil C (Kimble et al., 2007). Several management practices and other variables, such as soil type and climate, influence a soil´s C status. We used TOC and AC normalised by AC TOC^{-1}, served as a combined proxy for the soil´s C status related to the tillage system. The TOC describes the size of the entire soil C pool and the AC characterizes de labile C fraction that is well correlated with microbial activities (Ghani et al., 2003).

2.4. Framework to quantify the impact of soil carbon management on biophysical soil properties

This framework is based on a recently published concept (Deurer et al., 2008) and was adapted for comparing the influence of the soil C management component of different tillage treatments (TT and RT). In the following we briefly outline the concept as it applies to our study.

The observation time (Δt), for should be long enough to represent the interaction of the local climate with the biophysical soil properties (f). Originally (Deurer et al., 2008) a minimum measurement period of 1 year was suggested. Our study covers a period of 16 years.

Formal Setup of Variables

The values of a biophysical soil property f at location $\mathbf{x_i}$ and $\mathbf{x_j}$ over a time interval Δt were compared. The location $\mathbf{x_j}$ served as a reference, which represents TT, comparable to $\mathbf{x_i}$ which represents RT. This means, that $\mathbf{x_i}$ and $\mathbf{x_j}$ had the same soil type, texture and climatic conditions and the same initial conditions when the experiment started in 1992.

Calculation of the impact of the soil carbon management component when reducing tillage

The impact of the C management on the biophysical soil property at $\mathbf{x_i}$ and over the time interval Δt, $f(x_i;\Delta t)$, was calculated in five steps (Fig.1), as it was done by Deurer et al., 2008. The term ‘soil C management’ is defined in detail in section 2.3.

Step 1: Are the proxies of soil C management, TOC and AC TOC^{-1}, in the managed treatment in our case RT and the reference in our case TT statistically different (checked by step 1)? When this applies, then proceed. We selected a measurable proxy for the soil C management P in the soil at $\mathbf{x}$. For our study, we used TOC and the AC (AC TOC^{-1}) as a combined proxy for the soil C management at $\mathbf{x}$ (see section 2.3). If $P(\mathbf{x_i};\Delta t)$ and $P(\mathbf{x_j};\Delta t)$ were statistically significantly different ($p<0.05$), then a potential impact of the soil C management on the biophysical soil property $f(\mathbf{x_i};\Delta t)$ was probable, and we proceeded to the next step.

Step 2: Are the selected biophysical parameters between RT and TT statistically different? When this applies, then proceed to step 3. We tested if the soil biophysical property of the soil under RT $f(\mathbf{x_i};\Delta t)$ and of the soil under TT $f(\mathbf{x_j};\Delta t)$ were statistically significantly different. Only if this was the case, we assumed that there was an impact of reduced tillage on $f(\mathbf{x_i};\Delta t)$, and we proceeded to the next step.

Step 3: What is the total impact of reducing tillage on the biophysical soil property in RT? The ratio $\boldsymbol{\phi}$ of the biophysical soil property measured at $\mathbf{x_i}$ and $\mathbf{x_j}$ and averaged over Δt yielded the overall impact of reducing tillage on $f(\mathbf{x_i};\, \Delta t)$:

$$\Phi\left[f(x_{i,j},\Delta t)\right] = -\left[1-\frac{f(x_i;\Delta t)}{f(x_j;\Delta t)}\right] \qquad (1)$$

The value of $\boldsymbol{\phi}$ multiplied by 100 denoted the percentage difference (larger = positive value and smaller = negative value) in the biophysical soil property at x_i (RT) compared with the reference xj (TT). Therefore, $\boldsymbol{\phi}$ is a measure of the impact of the reduction in tillage on the biophysical soil property at $\mathbf{x_i}$.

Step 4: What is the correlation between the proxy for soil C management and the biophysical soil property? We performed a regression of the biophysical soil property $f(\mathbf{x}_{i,j};\Delta t)$ (dependent variable) versus the respective C management proxy values $P(\mathbf{x}_{i,j};\Delta t)$ (independent variable). This yielded the variance fraction (R^2) that could be explained by the C management proxy. We denoted it by $R(f(\mathbf{x}_{i,j};\, \Delta t);P)$. The C management proxy had to be a statistically significant variable in the regression.

Step 5: What is the impact of soil C management on the biophysical soil property in RT? The correlation between the biophysical soil property and the proxy for the soil C management, $R(f(\mathbf{x}_{i,j};\Delta t);P)$ (step 4), was multiplied by the impact of reducing tillage on the biophysical soil property $\boldsymbol{\phi}$ (step 3). By this we estimated the partial impact I of the soil C management as only one consequence of reducing tillage, P on the biophysical soil property at $\mathbf{x_i}$:

$$I\lfloor f(x_{i,j};\Delta t);P\rfloor = \Phi\lfloor f(x_{i,j};\Delta t)\rfloor R\lfloor f(x_{i,j};\Delta t);P\rfloor \qquad (2)$$

The value of **I** multiplied by 100 denoted the percentage increase in the partial impact of the soil C management P on the particular biophysical soil property at $\mathbf{x_i}$.

Reference

We used the soil from the TT treatment as the reference for the managed soil in the comparison between treatments. We selected the top soil, 0.25 m depth, which is the main soil affected by the mouldboard ploughing and other tillage practices. For analysis, we separated the samples into three increments (0-5, 5-10 and 10-25 cm). This enabled us to estimate the depth of the impact of soil C management on the biophysical soil properties.

3. Results

Proxies for the soil carbon management

In general, TOC, AC, AC TOC^{-1} and WSC variables tended to have greater values in RT than in TT, with statistical differences ($p<0.05$) at 0-5 cm depth (Fig. 2). AC was the only parameter that showed statistical differences at 5-10 cm depth. This shows that after 16 years of reducing tillage, soil C management, indicated by TOC and AC TOC^{-1}, had a significant impact only down to a soil depth of 5 cm.

Soil microbial functioning and CO_2 fluxes of the soil: comparison of TT and RT

Values of MBC, DHA, β-Glu and DphOx enzymatic activities were higher at 0-5 cm depth in RT, compared to TT, with statistical differences for MCB, DHA and β-Glu (Table 1). DphOx activity, also showed greater values in RT, although differences were not significant. At 5-10 cm depth, the tendency was the same, but without statistical differences between treatments. At 10-25 cm depth, results were practically the same in RT and TT. In general, the CO_2 flux was higher in TT (0.40 ± 0.03 g m^{-2} h^{-1}) compared to RT (0.31 ± 0.02 g m^{-2} h^{-1}), with statistical differences between treatments (Table 2).

We conclude that four (MBC, DHA, β-Glu, CO_2 fluxes) of the five indicators for soil biological activities increased in parallel with an increase in the proxies for soil C management in the top 5 cm of the soil.

Physical functioning of the soil: comparison of TT and RT

We did not find clear results for the different methods used for assessing a possible change of the soils aggregate structure and stability in the different treatments. On the one hand, greater values of WAS were recorded under TT, in the three depths, although statistical differences were only found at 5-10 cm depth (Table 3). On the other hand, RT tended to enhance the MWD and AI variables in all depths (with statistical differences for AI at 0-5 cm depth). The tillage treatments made no difference for the water infiltration characteristics near saturation. The CMD near water saturation was measured only at the soil surface. We conclude that there is no clear difference of soil physical properties between the tillage treatments, and consequently also no clear influence of soil C management on the set of soil physical properties that we selected.

Correlation of biophysical soil properties with proxies for soil carbon management

The proxies for soil C management explained a fraction of the variability of the biophysical soil properties between treatments. We use these fractions to quantify how much soil C management is responsible for any change in biophysical soil properties (see equation 2 in Step 4). For example, the proxies explained 46% of the variation of DHA, which means that the TOC and AC TOC^{-1} explained 46% of the variation of DHA in both tillage systems (TT and RT) (Fig. 3A). For the β-glucosidase activity, the TOC and AC TOC^{-1} explained 37% ($R^2 = 0.37$) of the variation (Fig. 3B). For the MBC, 25% could be explained, and only AC TOC^{-1} was a significant variable in the regression (Fig. 4). In our multiple step-wise regressions the TOC was a significant variable for two of the biological soil properties studied (DHA and β-Glu) and AC TOC^{-1} was a significant variable in all cases.

In general, the soil physical properties that we considered were not (MWD, CMD and WAS) or only poorly (AI) correlated with the proxies for C management. For example, the AI tended to be slightly correlated with AC TOC^{-1}, which explained 8.4 % of the variation of this soil property.

Total and partial impact of the soil carbon management on the microbial and physical functioning of the soil

The microbial properties decreased between 0 and 75% in the TT system compared to RT (Table 4). We could attribute 0 to 46% of the change in microbial properties to soil C management (Table 4). Therefore, the impact that can directly be attributed to the change of the soil C management on the microbial properties was always less than half of the total impact of the treatments. For example, the DHA decreased in total by 46% in TT versus RT, but we attributed only a reduction of 17% to the soil C management.

An impact of the soil C management on the physical soil properties was only significant for AI, which decreased between 0 and 5% in the TT system compared to RT, but only between 0 and 0.4% can be attributed to soil C management.

This disproves our hypothesis that soil C management is able to explain most of the impact of reduced tillage on biophysical soil properties.

4. Discussion

Soil carbon management

The soil quality framework was not helpful in the decision as to which soil depths should be selected for an assessment of the influence of tillage management (Letey et al., 2003). Initially, we chose the depth of the ploughing layer (0.25 m), and only after using the new framework with clear decision criteria we selected the 0.05 m depth, because the greatest differences between treatments were found only to this depth (Fig. 2). In this study, a tendency for improvement derived from the conservation tillage was also reported at 5-10 cm depth. From an agro-ecological point of view it is an important fact, as the superficial layer (0.05 m) is the interface between soil and atmosphere and is considered a very important part of the soil for various ecosystem services, and also where the most important biological processes take place (Madejón et al., 2007; López-Garrido et al., 2011). Although conservation tillage will progressively introduce improvements in the soil profile, it is desirable to have a robust statistical tool to establish at which depth these benefits are currently consolidated.

In our case, a Xerofluvent calcareous soil cropped under rainfed agriculture for 16 years, RT has managed to reduce losses of organic C that is typically caused by TT with soil inversion. These higher values, not only for TOC, but also for AC and WSC in RT compared to TT (Fig. 2) can be associated to the crop residues left at surface under conservation tillage treatments (RT in our case) and with the lower decomposition process (Reeves, 1997; Salinas-García et al., 2002), resulting in lower emissions of CO_2 to the atmosphere (Álvaro-Fuentes et al., 2008; López-Garrido et al., 2009), a fact also reported here (Table 2). One of these parameters, AC has been considered to be more sensible to soil management (tillage) than even TOC (Weil et al., 2003), and it has been evaluated as a possible soil quality index under rainfed, semi-arid Mediterranean conditions (Melero et al., 2009a,b).

Greater values for TOC, AC and WSC at 0.05 m depth under RT compared to TT have been reported for other scenarios (De la Horra et al., 2003; Madejón et al., 2007; Melero et al., 2009a,b). In general, differences were detectable during the first two to five years of the experiment, but significant increases often occurred only five to ten years after the conservation tillage system was established (Franzluebbers and Arshad, 1996). For this reason, long-term experiments, such as that studied here, are very important to evaluate differences in soil C in a reliable way. Soil organic matter increase is a very important objective in Mediterranean areas, where most agricultural soils have low organic matter values (typically around 1-2%, Madejón et al., 2009).

However, as pointed out before, under Mediterranean conditions TOC accumulation near the soil surface is not common, due to the high temperature which promotes microbial activity and organic matter mineralisation. Although moderate increase of TOC at the soil surface has been postulated to trigger an increase in some biological properties (Madejón et al., 2007; Melero et al., 2009a,b; López-Garrido et al., 2011) there is little literature (Deurer et al., 2008) that directly assessed to which degree a change in soil C stocks (TOC) are responsible for an improvement of soil biophysical properties versus other effects of agronomic management such as the use of fertilizers or pesticides.

Soil microbial functioning and CO2 fluxes

Soil microbial properties, such as microbial biomass C and soil enzyme activities, have been used in other studies to predict soil biological status and the effect of farm managements in soil quality (Eivazi et al., 2003). Soil enzyme activities have also been used as discriminatory indicators for a wide range of soil management practices (Kandeler and Böhm, 1996; Kanderler et al., 1999; Eivazi et al., 2003; De la Horra et al., 2003; Roldán et al., 2005; Melero et al., 2009a,b) and evaluated as productivity, contamination and nutrient recycling index (Nannipieri et al., 1990; Pérez-De-Mora et al., 2006). It means that enzymatic activity changes are interpreted as changes in soil quality (Dick, 1994; Madejón et al., 2007), being early indicators to different soil management practices (Albiach et al., 1999; Benítez et al., 2006; Melero et al., 2006).

Therefore, it is important to quantify at long-term the influence that small C increases could have on these variables that are considered to be good indicators of soil quality. It would be desirable for this knowledge to be extended to other semi-arid Mediterranean areas, for which large increases in C in the soil surface derived from conservation tillage practices cannot be expected.

Small increases of organic C fractions under conservation tillage have influence on the DHA, associated to respiratory microorganisms processes (Nannipieri, 1994), thus being one of the most important indicators of soil quality (García et al., 1997). This corroborates previous studies on this subject (Madejón et al., 2007; Melero et al., 2007a,b; Madejón et al., 2009). The C increase could explain 46% of the variability of the DHA (Fig. 3A), a high value indicating the sensibility of this enzymatic activity with respect to the C management component of tillage treatment.

Organic C also influences β-Glu, explaining 37% of its variability (Fig. 3B). β-Glu belongs to the enzymes group that catalyzes hydrolysis of various glycosides, providing substrate for soil microorganisms (De la Horra et al., 2003; Madejón et al., 2003). This could be related to the MBC increase under RT, which could explain 25% of its variability (Fig. 4). Both values of β-Glu and MBC could be considered normal four our soil-climatic conditions (Angers et al., 1993; García et al., 1994; Smith et al., 1995; Bandick y Dick, 1999; Moore et al., 2000; Pascual et al., 2000) and significantly greater at soil surface in RT in relation to TT.

The CO_2 fluxes were not correlated with the soil C contents. Apart from the immediate physical losses of CO_2 following tillage operations that are especially high with deep tillage and soil inversion (Prior et al., 1997; Reicosky et al., 1997; Ellert y Janzen, 1999; Álvarez et al., 2001; Álvaro-Fuentes et al., 2007), soil respiration is a complex ecosystem process. For example, the release of CO_2 occurs not only via microbial decomposition of TOC, and litter, but also via plant root and faunal respiration (Luo and Zhou, 2006). Root respiration can account for a half of the total soil respiration, which usually varies from 10 to 90% (Hanson et al., 2000). On the other hand, soil respiration usually responds to the most limiting factor in the soil; when both temperature and moisture are not extreme, both factors influence interactively, accounting for most of its variability at the field scale. For croplands, literature (Luo and Zhou, 2006) reports a mean value of about 550 ± 80 g C m^{-2} yr^{-1}, with intermediate values ranging from the low value of tundra (60 ± 6 g C m^{-2} yr^{-1}) and tropical moist forests (1260 ± 60 g C m^{-2} yr^{-1}). In our soils this value is around 800 g C m^{-2} yr^{-1} between results reported by Luo and Zhou (2006) for croplands and forest. As a general rule, root contributions for sites dominated by forest vegetation account, on average, for 48.6% of soil respiration. The values of root contributions in the non-forest ecosystems are widely scattered throughout the entire range (10 - 90%), with an overall average of 36.7%. Also, root contributions exhibit a strong seasonality, increasing dramatically during the active growing season, when roots receive a consistent supply of carbohydrates from canopy photosynthesis (Luo and Zhou, 2006).

Soil physical functioning

In general, soil C management was better correlated with biochemical than with physical properties, a fact so far only observed by one study in an orchard system and a humid climate (Deurer et al., 2008). However, the smaller increase of TOC at surface under RT could occasion a slight but non significant increase in the AI and MWD (Table 3). Nevertheless, the two variables show seasonal variability, being somewhat higher in spring than in summer, when plants are scarce (Yang and Wander, 1998; Álvaro-Fuentes et al., 2007, 2008). Plant development, root growth specially, can promote soil aggregation, due to the release of organic compounds, aggregating soil particles and promoting microbial activity (Angers y Caron, 1998; Six et al., 2004).

The opposite tendency was observed for WAS (Table 3), in discordance with other authors which observed that less C usually leads to lower aggregate stability (Franzluebbers and Arshad, 1996; Le Bissonais and Arrouays, 1997; Deurer et al., 2008). In our case, it is possible the decrease of WAS could be due to somewhat soil hydrophobicity in the TT treatment at the sampling date, derived from the straw burning followed in the TT treatment from 1992 to 2003. Fire is considered an important factor that could have influence in soil aggregation, affecting its hydrophobicity (MacDonald and Huffman, 2004; Poulenard et al., 2001). Some authors have been found important hydrophobicity in soils after 22 months from the straw burning (Huffman et al., 2001).

5. Conclusions

The statistical framework to quantify the impact of soil C management on biophysical soil properties was successfully applied to a tillage treatment. Important conclusions from this study are:

- In this study a change of soil quality related biophysical soil properties as a function of soil C management (reduced versus traditional tillage) occurred after 16 years mainly at 0-5 cm depth. This shows how much time is needed for any management change to have an impact under these environmental conditions.

- The soil C management proxies increase by 15.9 % for TOC and 37.4 % for AC TOC^{-1} at 0-5 cm depth over 16 years in the reduced compared to the traditional tillage caused an improvement in microbial activity between 28.4 to 42.9 % at this depth. This agrees with other studies, that soil carbon management mainly affects soil biological activities.

- The improvement of the soil C management proxies in the reduced compared to the traditional tillage over 16 years had very little impact on soil physical properties. For example the aggregation index decreased due to a change in the carbon management only by 0.4%. This agrees with other authors that soil physical properties are less representatives of changes by soil C management.

- The soil C management component of a tillage management explained less than half of the total impact of reducing tillage on various biophysical soil properties. More research is needed to identify the other factors associated with tillage management that cause a change in soil quality.

Overall and over 16 years conservation management (reduced tillage) improved soil quality, enhancing organic C content and particularly the biological status of the soil, but was limited mainly to in the upper layer (0.05 m).

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Table 1: Mean values ± standard error of biochemical properties for traditional (TT) and reduced tillage (RT) at 0-5, 5-10 and 10-25 cm depth. The results were derived from a 16 year tillage experiment.

Treatment	Depth	MBC	DHA	β-Glu	DphOx
TT	0-5	620 ± 76.4	1.69 ± 0.16	126 ± 13.1	1.51 ± 0.06
	5-10	627 ± 88.6	1.04 ± 0.18	97.4 ± 11.3	1.66 ± 0.08
	10-25	637 ± 119	0.88 ± 0.22	98.9 ± 12.9	1.68 ± 0.12
RT	0-5	885 ± 84.8*****	2.96 ± 0.49*****	185 ± 13.4*****	2.11 ± 0.28
	5-10	732 ± 119	1.06 ± 0.15	133 ± 25.3	1.92 ± 0.26
	10-25	624 ± 121	0.33 ± 0.16	59.7 ± 9.04	1.70 ± 0.06

MBC: microbial biomass carbon (mg kg^{-1}); DHA: dehydrogenase activity (mg TPF dwt kg^{-1} h^{-1}); DphOx: diphenol oxidase (mg cathecol 10 $min^{-1}g^{-1}$ dwt); β-Glu: β-glucosidase activity (mg p-nitrophenol kg^{-1} dwt h^{-1}). Differences between treatments are indicated by (*) ($p< 0.05$).

Table 2: Mean values ± standard error of measurements of CO_2 fluxes (g m^2 h^{-1}) for traditional (TT) and reduced tillage (RT) at ten different times in the period of study (2008). The results were derived from a 16 year tillage experiment. Differences between treatments are indicated by (*) (p< 0.05).

Measurement	**TT**	**RT**
1	0.31 ± 0.03	0.30 ± 0.00
2	0.56 ± 0.03	0.42 ± 0.02*
3	0.32 ± 0.04	0.21 ± 0.01*
4	0.26 ± 0.02	0.21 ± 0.02
5	0.27 ± 0.02	0.21 ± 0.01*
6	0.22 ± 0.02	0.34 ± 0.03*
7	0.48 ± 0.11	0.30 ± 0.04
8	0.70 ± 0.11	0.50 ± 0.08
9	0.38 ± 0.02	0.32 ± 0.01*
10	0.50 ± 0.04	0.31 ± 0.02*
Average	*0.40 ± 0.03*	*0.31 ± 0.02*

Table 3: Mean values ± standard error of physical properties for traditional (TT) and reduced tillage (RT) at 0-5, 5-10 and 10-25 cm depth. The results were derived from a 16 year tillage experiment.

Treatment	Depth	WAS	MWD	AI	CMD
TT	0-5	49.1 ± 2.82	2.45 ± 0.12	505 ± 7.73	0.33 ± 0.08
	5-10	49.4 ± 1.82*	2.93 ± 0.07	521 ± 20.8	
	10-25	49.8 ± 2.04	2.86 ± 0.10	524 ± 27.3	
RT	0-5	42.4 ± 2.77	2.73 ± 0.17	532 ± 8.54*	0.28 ± 0.03
	5-10	39.1 ± 1.96	3.03 ± 0.12	533 ± 19.7	
	10-25	43.0 ± 3.21	2.99 ± 0.19	532 ± 16.2	

WAS: water aggregate stability (%), MWD: mean weigh diameter (mm), AI: aggregation index, CMD: conductive macro-pore diameter between -20 and -60 mm tension (mm). Differences between treatments are indicated by (*) ($p<$ 0.05).

Table 4: Impact of all management practices (¥), and of only the soil organic C management (I) on soil microbial parameters and aggregation index. The values are given only when the differences were statistically significant. The value of R refers to a linear regression with total organic C (TOC) or (given in brackets) to a multiple linear regression with TOC and AC TOC^{-1}.

Properties	¥	R	I
MBC	0.75	(0.46)	0.34
DHA	0.46	(0.37)	0.17
β -Glu	0.43	0.25	0.11
AI	0.05	0.08	0.004

FIGURE CAPTIONS

Fig. 1: Schematic overview of the framework to quantify the impact of soil C management on biophysical soil properties. Adapted from Deurer et al., 2008.

Fig. 2: Mean values (N=7) ± standard errors of total organic carbon (TOC), active carbon (AC), AC TOC^{-1} and water soluble carbon (WSC) in the top 0.25 m of the soils under TT and RT. Values with asterisk were significantly different ($p<0.05$). The results were derived from a 16 year lasting tillage experiment.

Fig. 3: Prediction of measured enzyme activities by the proxies for the soil C management. The predictive power of the proxies for the soil C management was quantified by multiple regression. **A)** Dehydrogenase activity (iodo-nitrotetrazolium formazan [INTF] with N = 21 for each treatment). The R^2 is 0.46. Total organic carbon (TOC) and active carbon fractions (AC TOC^{-1}) were significant variables. **B)** β-Glucosidase activity (β-Glu) with N = 21 for each treatment. The R^2 is 0.37. Both, TOC and AC TOC^{-1} were significant variables.

Fig. 4: Prediction of measured microbial biomass carbon (MBC) by the proxies for the soil C management. The predictive power of the proxies for the soil C management was quantified by multiple regression. We used N = 21 samples for each treatment. The R^2 is 0.25. Only the factor AC TOC^{-1} was a significant variable.

Figure

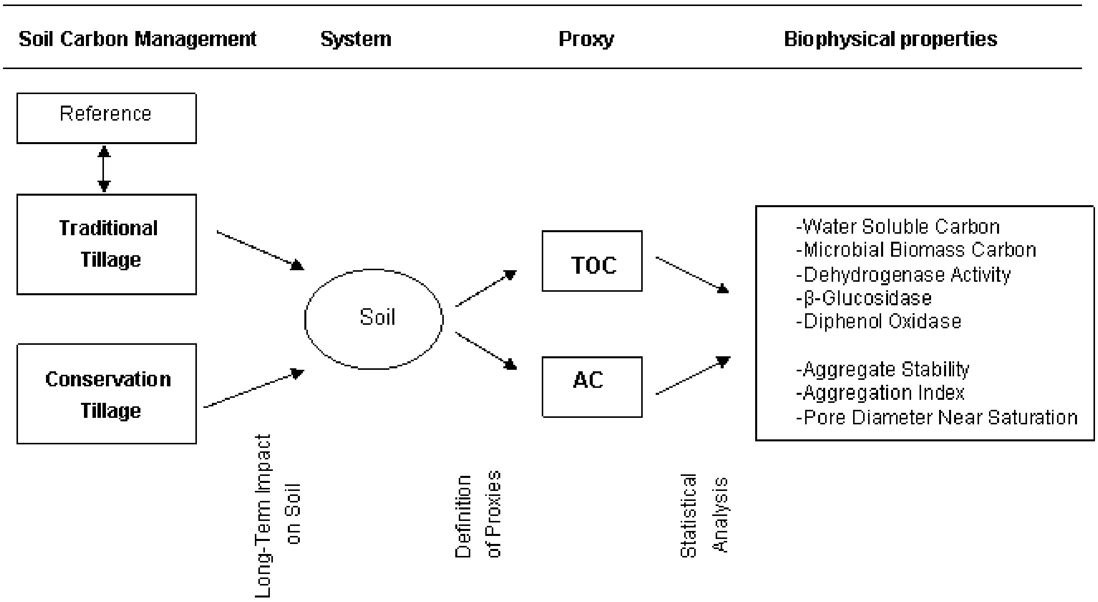
Soil Carbon Management
System
Proxy
Biophysical properties
Reference
Traditional Tillage
Conservation Tillage
Soil
TOC
AC
-Water Soluble Carbon
-Microbial Biomass Carbon
-Dehydrogenase Activity
-β-Glucosidase
-Diphenol Oxidase
-Aggregate Stability
-Aggregation Index
-Pore Diameter Near Saturation
Long-Term Impact on Soil
Definition of Proxies
Statistical Analysis

Fig. 1.

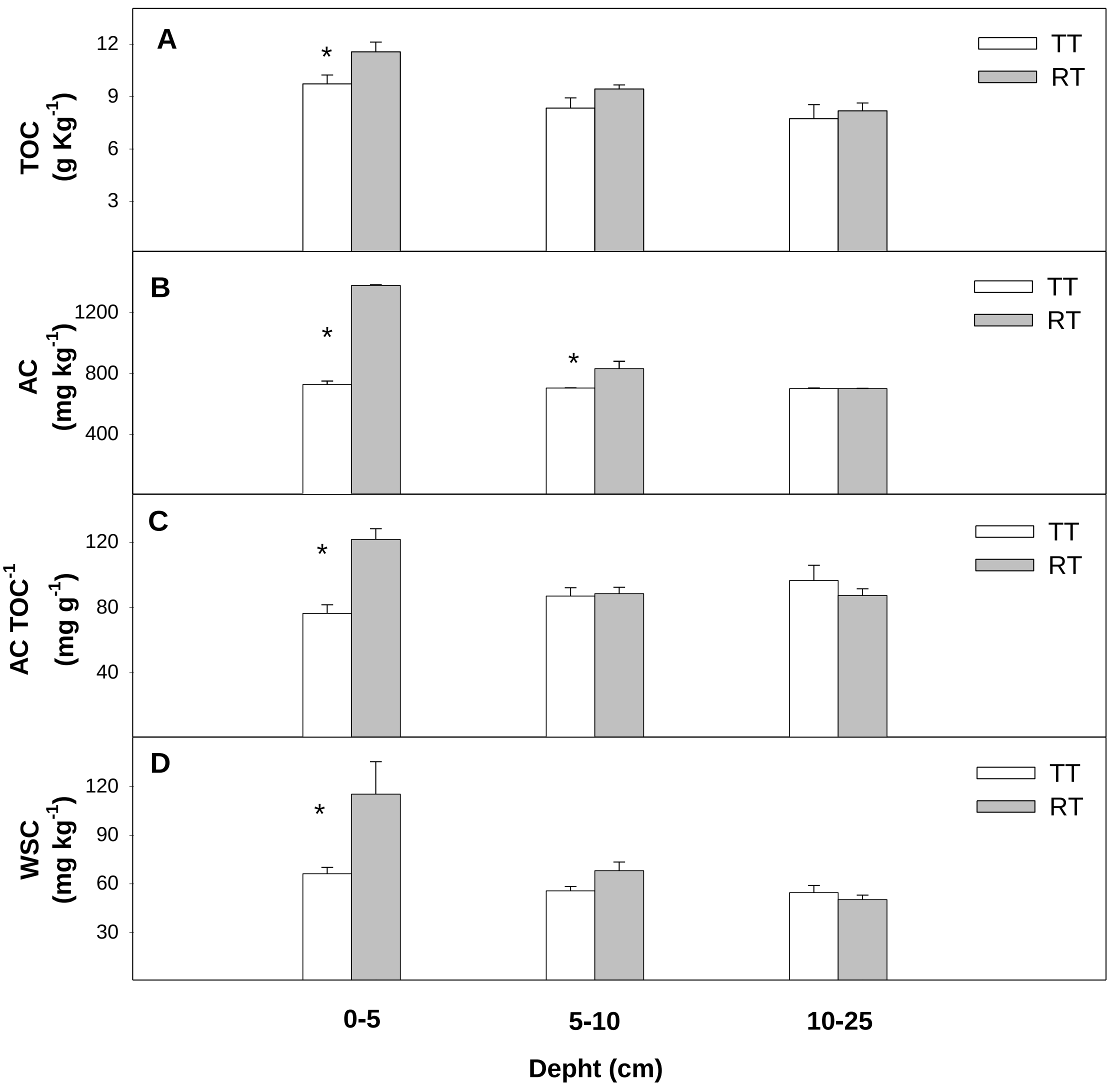
A
TOC
(g Kg^{-1})
3
6
9
12
*
TT
RT
B
AC
(mg kg^{-1})
400
800
1200
*
*
TT
RT
C
AC TOC^{-1}
(mg g^{-1})
40
80
120
*
TT
RT
D
WSC
(mg kg^{-1})
30
60
90
120
*
TT
RT
0-5
5-10
10-25
Depht (cm)

Fig. 2.

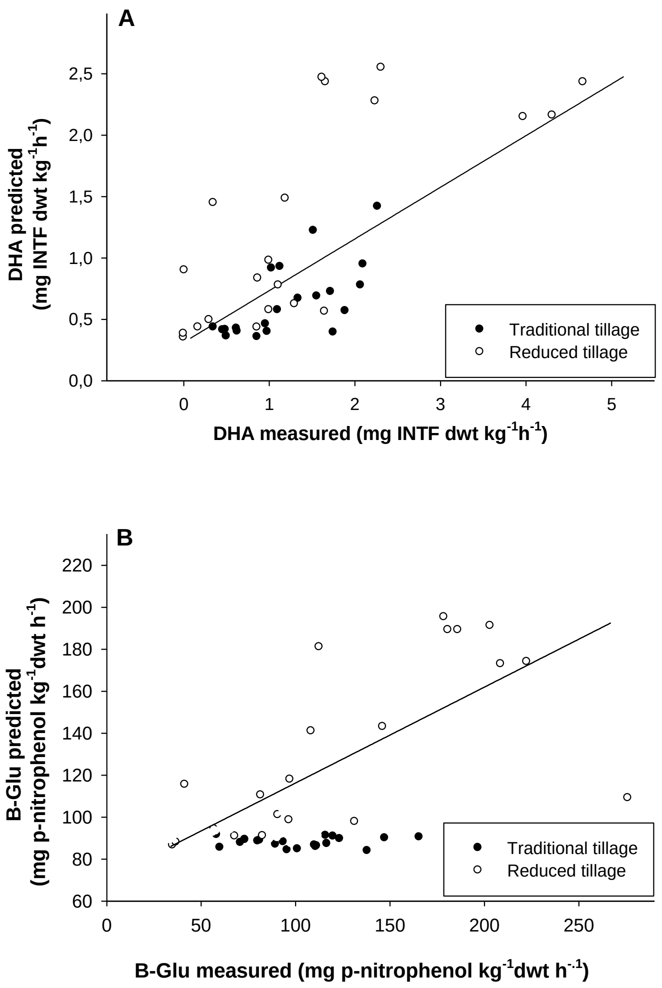
A
DHA predicted (mg INTF dwt kg-1h-1)
0,0
0,5
1,0
1,5
2,0
2,5
0
1
2
3
4
5
DHA measured (mg INTF dwt kg-1h-1)
● Traditional tillage
○ Reduced tillage
B
B-Glu predicted (mg p-nitrophenol kg-1dwt h-1)
60
80
100
120
140
160
180
200
220
0
50
100
150
200
250
B-Glu measured (mg p-nitrophenol kg-1dwt h-1)
● Traditional tillage
○ Reduced tillage

Fig. 3.

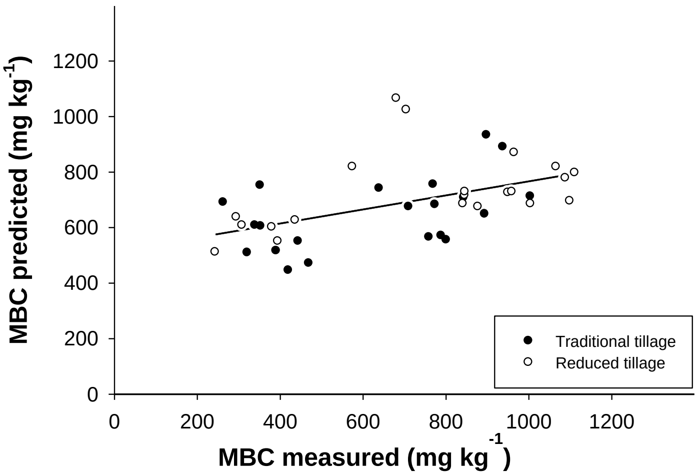
MBC predicted (mg kg^{-1})
0
200
400
600
800
1000
1200
0
200
400
600
800
1000
1200
MBC measured (mg kg^{-1})
● Traditional tillage
○ Reduced tillage

Fig. 4.