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Reduced tillage as an alternative to no-tillage under Mediterranean conditions: A case study

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ABSTRACT

Most farmers in SW Spain usually apply traditional tillage (TT) with soil inversion to avoid potential problems of soil compaction after repeated application of no tillage (NT). NT might cause some difficulties for soil workability and crop development derived from the original soil conditions, and, consequently, other tillage options are evaluated. However, less aggressive tillage practices, such as reduced tillage (RT), could solve the problem without losing the advantages of conservation agriculture. We show that despite the chemical (slight increases of soil organic carbon, N, P and K at soil surface) and biochemical (increases of dehydrogenase and β-glucosidase activities) improvements derived from NT, this treatment greatly worsened physical soil conditions after five years of establishment on a Xerofluvent soil cropped with a wheat-sunflower-fodder pea crop rotation. This deterioration was mainly reflected by the penetration resistance at the time of seedling emergence (6.04 MPa under NT versus 0.65 in RT and 0.40 in TT at surface), which contributed to an extreme reduction of the seeds yield of the sunflower crop (about 100 Mg ha^{-1} in NT versus more than 3000 Mg ha^{-1} in RT and TT) and seed quality (33.6% of oil in NT versus 48.0% in TT and 49.6% in RT). In general, the best seed quality related to lipid composition was recorded under RT with a slight, but significant, increase of the oil content, the oleic acid and the unsaturated/saturated fatty acid ratio; very positive features considering their dietary and industrial importance.

1. Introduction

Inadequate agricultural practices may negatively affect soil quality, contributing to soil erosion and degradation. This may include excessive deep ploughing in intensive agriculture, which has caused huge losses of soil organic carbon (SOC) (Lal, 2004) accompanied by soil erosion and degradation in many cases. Although the historic loss of the SOC pool, caused by conversion from natural to agricultural ecosystems, is difficult to estimate, it could be close to 80 Pg C (Lal, 1999). In order to prevent such eventualities, there is a growing trend worldwide for the adoption of conservation tillage (CT) systems, which do not use mouldboard ploughing and leave an adequate amount of residues covering the soil after harvesting (Bradford and Peterson, 2000; Gajri et al., 2002; Lahmar, 2010; Lal and Pimentel, 2007). CT has numerous advantages related to soil quality and biodiversity, such as SOC increase at the surface (with the benefits this entails), gas efflux decrease, reduction of soil erosion and less costs because of the lower fuel and labour inputs (Álvaro-Fuentes et al., 2007; Franzluebbers, 2002; Jemai et al., 2012; Kladivko, 2001; López et al., 2012; Madejón et al., 2007).

Among the different modalities of CT, NT is frequently preferred by many farmers as saving operations and fuel. However, there can be some biophysical constraints which indicate that NT is not a panacea, and does not always produce equivalent crop yields in climates with cold springs, sub-optimal soil temperatures, and poorly drained and heavy-textured soils (Lal, 2007). These constraints are frequent in humid temperate regions, where excessive crop residues and wet soils lead to difficulties in soil workability, soil compaction, cooler soil temperatures at seeding and adverse effects on plant growth from residues (Gajri et al., 2002; Hammel, 1995). These constraints, frequently based on inadequate physical properties, can also arise in less humid climates under particular conditions (rainy years, excess of residues, extreme texture), such as that of many Mediterranean areas.

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It has frequently been suggested that biological and biochemical variables are the most appropriate indices for detecting soil quality deterioration or improvement (Visser and Parkinson, 1992). In fact, in a long-term experiment conducted by López-Garrido et al. (2012) it was shown that the improvement of the SOC management proxies in a modality of CT (RT) compared to TT over 16 years had very little impact on soil physical properties. The impact of SOC management was better correlated with soil microbial than with the physical properties at the surface. However, when inadequately controlled by a particular management practice, physical properties are absolutely decisive for plant growth and yield, their influence being much more pronounced than that exerted by chemical and biochemical properties.

Thus, the effects of CT systems, NT in particular, can vary consistently over a wide range of soils and climatic conditions (Franzluebbers, 2002; Lal, 1989; Moreno et al., 1997). The dependence of CT on the soil and climatic conditions makes the study of its effects on soil and crop responses necessary for different sites, considering climatic variations between years for a particular scenario (Wilhelm et al., 2004). This is a very important topic from an agronomic point of view where the adoption of NT has led to difficulties in soil workability, forcing farmers to switch to other systems. Taking into account the negative consequences that could result from a very aggressive tillage, in these cases it would be desirable that farmers opt for other modalities of CT that are different from NT, such as ridge tillage or RT (López-Garrido et al., 2011; Melero et al., 2009b; Panettieri et al., 2013). The suitability of some tillage in arable lands under particular conditions has been considered recently by Kirkegaard et al. (2013).

In the present work we have compared crop development and physical, chemical, and biochemical properties in soils under different tillage systems: TT, RT and NT, in a mid-term experiment (over five years) after a period of continuous rains. Under this condition, NT might cause some difficulties for soil workability and crop development derived from the original soil conditions, and, consequently, other tillage options are evaluated.

2. Materials and methods

2.1. Localisation of the experimental area and description of tillage systems

The experiment was carried out under different tillage treatments on a sandy clay loam soil, Entisol (Xerofluvent, Soil Survey Staff, 1999) at the experimental farm "La Hampa" of the "Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC)" (37°17′ N, 6°3′ W), 13 km southwest of the city of Seville (Spain). Some characteristics of the soil are: pH of around 7.8 (calcareous), alkaline-earth carbonates 280 g kg^{-1}, particle fractions of about 540 g kg^{-1} sand, 210 g kg^{-1} silt, and 250 g kg^{-1} clay, 10 g kg^{-1} SOC and 950 mg kg^{-1} Kjeldahl Nitrogen.

The climate is typically Mediterranean, with mild rainy winters (484 mm mean annual rainfall) and very hot, dry summers. The mean annual daily temperature is 17 °C, with maximum and minimum temperatures of 33.5 °C in July and 5.2 °C in January. The site has an annual average of around 2900 h of sunshine with maximum values of solar radiation exceeding 1000 W/m^2. Environmental data were obtained from the weather station at the experimental farm.

The experiment was established in 2008. Three different tillage treatments were established in a completely randomised experimental design. Three replicates per treatment were established (6 m × 33.5 m, 200 m^2 plots): traditional tillage (TT), reduced tillage (RT) and no-tillage (NT). A tractor with 1.17 m of wheel internal separation was used for field operations in all the treatments. The seed drill had a wheel internal separation of 2.73 m. Traditional tillage consisted of mouldboard ploughing (ca. 25–30 cm deep) and two chisel operations at 25 cm depth (0.57 m separation between chisels) followed by a disc harrowing of 12 cm depth; RT was characterised by a lack of mouldboard ploughing, a reduction in the number of tillage operations (only one chisel operation at 25 cm depth followed by a disc harrowing of 5 cm depth), spraying the plot with pre-emergence herbicides and leaving the crop residues on the surface. NT was characterised by the absence of tillage (only direct drilling), spraying also the plot with pre-emergence herbicides and leaving the crop residues on the surface (Moreno et al., 1997).

CT has been defined as any tillage system that maintains >30% of the soil surface covered with residues from the preceding crops (Gajri et al., 2002). The soil surface area covered by residues in the CT treatments was determined by placing a 10 m cord (marked every 10 cm) diagonally across several rows (Plaster, 1992) and counting the number of marks coincident with some crop residue. This percentage (calculated by the method of Plaster, 1992) was always >30% (in most cases, it was >60%).

All the plots were cultivated under a *Triticum aestivum* L. – *Helianthus annuus* L. – *Pisum arvense* L. crop rotation. Sunflower and pea crops were not fertilised, as is traditional in this area, while wheat received 200 kg ha^{-1} of a compound fertiliser (15N–15P_2O_5–15 K_2O: 60 kg N ha^{-1}, 26.4 P kg ha^{-1}, 49.8 kg K ha^{-1}). NT and RT practices involved leaving crop residues on the surface and spraying the plots with preemergence herbicide (glyphosate at a rate of 4 L ha^{-1}).

The results of this work correspond to the years 2012 and 2013. Sunflower was cropped in 2013. The period from September 2012–April 2013 was very rainy, 526 mm, with a lower total potential evapotranspiration (PET: 455 mm) (Table 1) forcing substantially delayed sunflower planting (early May; the normal period in this area is late February). A hybrid sunflower (cv. Es Topic) was sown in early May with a density of ca. 50,000 seeds ha^{-1}, and harvested in early September 2013.

2.2. Soil sampling

The first soil sampling was conducted in October 2012, five months after the wheat harvest (sown in late 2011). Soil samples were taken at three sites of each individual plot at three depths 0–5, 5–10 and 10–25 cm (a total of three composite samples per treatment and depth). The moist field soil was sieved (2 mm) and divided into two subsamples. One was immediately stored at 4 °C in plastic bags loosely tied to ensure sufficient aeration and to prevent moisture loss before assaying for enzymatic activities. The other was air-dried for chemical analysis.

2.3. Plant sampling

Seedling emergence and plant height were periodically monitored in each treatment. To estimate yields, 16 sunflower heads per treatment were covered with a plastic mesh (5 mm light) to prevent the action of birds. The heads were threshed by hand at 9% seed moisture and the total seeds per head weighed. The seeds were then dried at 70 °C for 24 h to calculate the 1000 seed weight and the oil, fatty acid and nutrient contents.

2.4. Soil chemical and biochemical analysis

The SOC was analysed by dichromate oxidation and titration with ferrous ammonium sulphate (Walkley and Black, 1934). The permanganate oxidisable C (POC), also known as active C (AC), was determined by oxidation with 0.2 M $KMnO_4$ in 1 M $CaCl_2$ (pH 7.2), and non-reduced Mn^{7+} was colorimetrically determined at 550 nm

Table 1
Total monthly rainfall, potential evapotranspiration values (PET), mean values of minimum and maximum temperatures (T) and relative humidity (RH). Period January 2012–September 2013.

Year	Month	Rainfall (mm)	*T* (°C)		RH (%)	PET (mm)
			Minimum	Maximum		
2012	January	17.0	3.2	16.9	87.8	57.3
	February	0.4	0.0	17.0	62.6	72.3
	March	24.2	6.9	22.3	60.9	94.1
	April	37.6	8.8	21.3	67.9	104
	May	32.1	14.1	30.6	54.1	160
Wheat harvesting	June	0.0	16.8	33.3	51.0	184
	July	0.0	16.8	34.3	52.5	197
	August	0.4	18.0	35.5	56.7	171
	September	72.3	16.3	30.4	67.2	115
	October	87.9	9.4	18.8	84.8	35.5
	November	89.9	9.4	18.8	84.8	35.5
	December	21.5	6.1	16.7	90.1	27.4
2013	January	39.8	5.5	16.6	86.4	35.3
	February	52.4	4.1	16.4	80.0	44.8
	March	124	8.9	18.2	86.9	59.0
	April	38.5	9.5	23.1	76.4	103
Seeding sunflower	May	6.7	10.3	26.0	64.5	140
	June	1.0	14.6	31.0	52.7	173
	July	0	18.4	34.1	58.0	190
	August	0	18.3	35.5	55.3	174
Harvesting	September	22.4	17.5	31.5	63.8	109

(Weil et al., 2003). Soil nitrogen was determined by Kjeldahl digestion, phosphorus by extraction with sodium bicarbonate at pH 8.5 (Olsen et al., 1954), and potassium after extraction with ammonium acetate at pH 7.5 (Dewis and Freitas, 1970). The cation exchange capacity (CEC) was determined according to Coger et al., at pH 8.2. Sodium was analysed by atomic absorption spectrophotometry.

Dehydrogenase activity (DHA) was determined according to Trevors (1984) after soil incubation with p-iodo nitrotetrazolium chloride, (INT) and measurement of the p-iodo-nitrotetrazidin formazan (INTF) absorbance at 490 nm. ?-Glucosidase activity (β-Glu) was measured as indicated by Eivazi and Tabatabai (1988), after soil incubation with p-nitrophenyl-β-D-glucopyranoside and measurement of the p-nitrophenol absorbance at 400 nm.

2.5. Soil physical analysis

In May 2013 (during sunflower emergence) several physical properties were determined. Water content at surface (0–10 cm) was measured using a field operated meter for moisture/temperature/salinity of soils (time-domain-reflectometry probes, TDR FOM/mts, Institute of Agrophysics, Lubin, Poland). A subsequent soil moisture determination was performed gravimetrically. Bulk density was determined from the ratio mass/volume of soil cores taken with stainless-steel cylinders of 8 cm diameter and 4 cm height, taken at different depths in the three treatments. The resistance to penetration was determined by using a hand penetrometer Eijkelkamp Model 06.01 to different depths with five replicates per treatment, recording the maximum value for each depth.

2.6. Plant analysis

Sunflower achenes (seed + pericarp) were analysed for oil and nutrient contents. However, we use the terms seed and seed quality throughout the paper as usual in topics related to oilseeds (these are the terms used in the literature instead of achenes). The dried seeds were ground in a mill for the oil, fatty acids, sterols and nutrient contents. Oil was extracted in a Soxhlet glass using petroleum ether as a solvent (IUPAC, 1987a). The extracted oil was filtered at 40 °C through filter paper and stored in a freezer at −25 °C until analysis. fatty acid methyl esters (FAME) were analysed by gas chromatography (GC). FAMEs were extracted with n-hexane after cold methylation with 2 N KOH in methanol, following the official method (IUPAC, 1987b). Oleic acid was used as a reference to calculate the relative retention times. GC was performed with a Varian 3900 apparatus (Varian Co, Palo Alto, CA, USA) using a fused silica capillary HP 88 column (100 m × 0.25 mm, 0.25 mm film thickness). The oven temperature was kept at 175 °C for 13 min and was then raised to 205 °C at a rate of 3.0 °C min^{-1} and held isothermally for 5.0 min. The injector temperature was kept at 240 °C, while the detector temperature was 250 °C. Hydrogen (131 kPa inlet pressure) was used as a carrier gas, while the make-up gas was nitrogen.

Seeds were analysed for N by Kjeldahl digestion and crude protein estimated as N × 6.10. Mineral nutrients (P, K, S, Ca Mg, Cu, Fe, Mn, Ni and Zn) were extracted by wet oxidation with concentrated HNO_3 under pressure in a microwave digester. Three consecutive steps (5 min each) of power (250 W, 450 W and 600 W) were applied, and then these extracts were diluted with water of 18 mΩ deionised quality. The analysis of mineral nutrients in the digests was performed by inductively coupled plasma-optical emission spectrophotometry (ICP-OES; Thermo Jarrel Ash Corporation). The quality of the analytical method was assessed by routine analyses of a reference sample (BCR-62: olive tree leaves, European Community Bureau of Reference). Our experimental values showed recoveries of 95 and 110%.

2.7. Statistical analysis

Statistical analyses were performed using SPSS 11.5 for Windows. Mean and standard errors were determined for all variables. The data was analysed by ANOVA, considering the tillage system as the independent variable. The means were separated by the Tukey's test, using a significance level of $p < 0.05$.

3. Results and discussion

3.1. Soil organic carbon

After five years of establishment, NT treatment significantly increased the SOC content at surface (by ca. 20%) with an opposite tendency at depth (10–25 cm), with respect to TT, due perhaps to

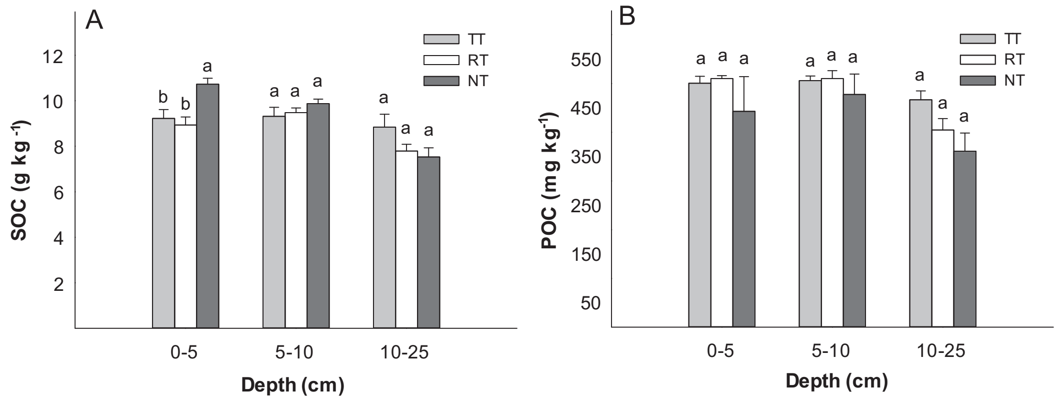

Fig. 1. (A) Soil organic carbon (SOC); and (B) permanganate oxidisable carbon (POC) concentrations (mean values ± standard error), at different depths in TT (traditional tillage), RT (reduced tillage) and NT (no tillage) treatments. For each variable and depth, columns with the same letter do not differ significantly ($p < 0.05$).

the soil inversion occasioned by this treatment (Fig. 1A). Nevertheless, SOC accumulation at 0–25 cm depth was greater under both conservation tillage systems (about 3.4 and 3.7 Mg ha^{-1} in RT and NT, respectively) compared with traditional tillage (3.3 Mg ha^{-1}). This was due to a noticeable SOC accumulation at the surface under conservation tillage.

However, no response was observed for the POC fraction (Fig. 1B), contradicting previous results showing the usefulness of this variable as an early index of increased soil quality (Culman et al., 2012; López-Garrido et al., 2011; Melero et al., 2009a, 2009b). The POC level can vary depending on the sampling period (season), although contrasting reports exist in the literature (Culman et al., 2012).

In this same soil, Melero et al. (2009b) reported a significant increase of POC under NT, with respect to TT, at 0–5 cm depth after only three years of experimentation, but in a warmer period. This fraction usually represents about 4% of the SOC, and is more closely related to smaller sized and occluded (heavy) particulate organic carbon fractions, suggesting this reflects a more processed, degraded fraction of soil C (Culman et al., 2012). These authors demonstrated the ability of POC to detect changes in management involving tillage and site differences. However, the sensitivity of different labile fractions of SOC, including POC, was not distinguishable regarding the effects of depth and time of sampling (Culman et al., 2012). Our results suggest the necessity of further research on the effect of sampling time on the POC dynamic under our conditions.

3.2. Cation exchange capacity and nutrients N, P and K

The influence of soil management on the CEC can vary depending on soil characteristics. For example, in soils with low clay content at surface, the CEC may be strongly dependent on the SOC content, consequently this parameter increased under tillage systems that add organic residues to soil, such as CT (Smettem et al., 1992). Conversely, in soils with high clay content this increase may be absent, as reported by Bravo et al. (2007) for a montmorillonitic soil: the CEC was high irrespective of the tillage (CT had been applied for 20 years) indicating a good fertility level of the soil used in that experiment.

In our case, using a Xerofluvent soil with a clay content of about 250 g kg^{-1} (of which 60% was montmorillonite), a greater increase of CEC at surface (0–5 cm) in both CT (RT and NT) systems was not expected; as shown in Table 2, this was only significant in NT compared to RT, but not compared to TT. It is possible that the differences between treatments would be slightly greater at long-term, although, in general, these values of CEC can be considered normal for this kind of soil (Entisols, typically 11.6 $cmol_c$ kg^{-1}), and, for mineral soils, intermediate among the lowest values of the Ultisols (typically 3.5) and the highest values of Vertisols (35.6) (Holmgren et al., 1993).

By contrast, the concentration of total N (mostly in the organic form) in surface soils usually ranges between 0.8 and 4 g kg^{-1} (Bremner, 1965) therefore, the values found in this study would be at the lower limit, consistent with the moderate level of SOC. However, NT begins to exert a positive effect on the accumulation of N in the surface, where the concentrations were greater than those in RT and TT, although only significant differences were found with respect to TT ($p < 0.05$, Table 2). It is possible that this positive effect may be greater over time. However, the concentration of N under NT shows a decrease with depth, much more marked than under RT and TT, in what may have influenced the tillage practices performed in these two treatments, absent in NT.

In general, CT frequently results in greater amounts, not only of N, but also of P and K in the upper soil layer as a consequence of

Table 2
Concentration values of the Cation Exchange Capacity (CEC, $cMol_c$ kg^{-1}) and nutrients (g kg^{-1}) in soils under different treatments (mean values ± standard error on a dry matter basis). For each depth and variable, values followed by the same letter do not differ significantly ($p < 0.05$).

Depth (cm)	Treatment	CEC	N	P	K
0–5	TT	11.2 ± 0.25b	0.91 ± 0.04b	26.1 ± 1.00a	428 ± 40.0a
	RT	12.2 ± 0.36ab	0.99 ± 0.02ab	25.7 ± 1.94a	419 ± 9.82a
	NT	12.8 ± 0.27a	1.06 ± 0.04a	25.6 ± 6.85a	508 ± 30.4a
5–10	TT	11.1 ± 0.23a	0.97 ± 0.03a	23.0 ± 1.85a	387 ± 37.0a
	RT	11.9 ± 0.30a	0.92 ± 0.01a	22.1 ± 2.30a	379 ± 5.03a
	NT	12.0 ± 0.28a	0.93 ± 0.05a	17.8 ± 3.81a	363 ± 26.6a
10–25	TT	–	0.91 ± 0.06a	22.2 ± 3.54a	367 ± 48.0a
	RT	–	0.95 ± 0.10a	17.8 ± 2.92a	307 ± 22.4a
	NT	–	0.76 ± 0.03a	14.5 ± 2.28a	290 ± 63.7a

TT, traditional tillage; RT, reduced tillage; NT, no-tillage.

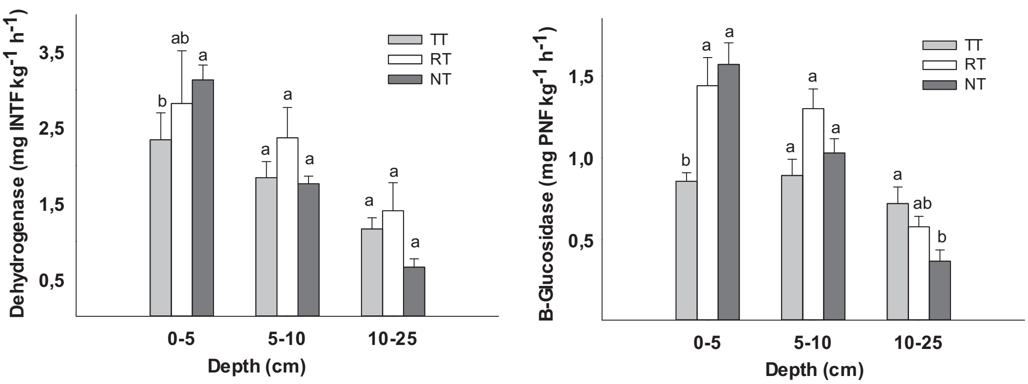

Fig. 2. (A) Dehydrogenase; and (B) β-glucosidase enzymatic activities (mean values ± standard error), at different depths in the soils of TT (traditional tillage), RT (reduced tillage) and NT (no tillage) treatments. For each variable and depth, columns with the same letter do not differ significantly ($p < 0.05$).

crop residues and fertiliser accumulation in the top soil (Franzluebbers and Hons, 1996; Houx et al., 2011; López-Garrido et al., 2011; Martin-Rueda et al., 2007). However, in this experiment no significant effect in P and K content was observed, although there was a tendency towards a greater accumulation of K in NT at the surface (Table 2). In other experiments carried out on this same soil (López-Garrido et al., 2011), the pattern of N, P and K also showed greater accumulation at the surface under CT, but only extractable K was significantly greater in the short- and long-term, which seemed to indicate that K could be a good indicator of the early changes caused by tillage.

At the 10–25 cm depth, the concentration of both nutrients tended to be smaller under NT, possibly due to the reasons mentioned for N (soil inversion), although, in general, P and K concentrations were higher than those considered "critical" for crop nutrition. According to the fertility index and soil-test ratings proposed by Cope and Evans (1985), for a soil with a CEC greater than 9 cmolc kg^{-1}, P and K concentrations into the ranges of 31–40 mg kg^{-1} (Mehlich 1 extractant, corresponding to 21–27 Olsen P) and 241–320 mg kg^{-1}, respectively, could be considered very high concentrations. In our case, the range was between 20–25 and 400–500 mg kg^{-1} at the surface for P and K respectively. The highest values were found under NT.

Nevertheless, the issue of nutrient concentrations at the surface under CT has been discussed in the literature from different approaches. According to some authors, P stratification in CT may be of concern because lower concentrations at depth in the rooting zone may reduce crop yields (Lupwayi et al., 2006) and high concentrations near the soil surface may increase the runoff of dissolved P and other nutrients (Duiker and Beegle, 2006; Sharpley and Smith, 1994). Occasional tillage could then be used to reallocate the P accumulated at the surface to lower depths in the rooting zone; even though this practice could inadvertently increase the loss of particulate P from the erosion derived from intensive tillage (Sharpley, 2003). In fact, this practice would be quite unwise in easily erodible soils (López-Garrido et al., 2011). An alternative for occasional tillage of long term P fertilised NT could be the cropping of shallow rooted plants for one or several years (Messiga et al., 2012), although the practice to be implemented will depend on the characteristics of each particular scenario. In our case, a more reasonable stratification of nutrients seems to be achieved under RT, possibly due to the less aggressive tillage (chisel) applied, which could also be a valid alternative in this context.

3.3. Biochemical properties

Soil enzymatic activities have also been suggested as suitable indicators of soil quality because they are related to soil microbial activity, they response rapidly to changes in soil management and are easy to measure (Puglisi and Trevisan, 2012). Although the information given by a single enzymatic activity is limited, the copious database existing in literature can help to optimise sampling and analyses. The enzymatic activities arylsulphatase, β-Glu, phenoloxidase, catalase, phosphatase, urease, invertase, DHA and protease are usually increased by CT (Puglisi and Trevisan, 2012). Under our conditions of soil and climate, DHA and β-Glu have been proven to respond positively to CT (RT and NT) and have been checked again in this work (Madejón et al., 2007, 2009; Melero et al., 2009a,b; Panettieri et al., 2013). DHA, an oxidoreductase, is ubiquitous in viable microbial cells, and is thus widely used as an estimation of total soil microbial activity; β-Glu is one of the enzymatic activities involved in the C cycling in soils, giving indication of the activity of enzymes involved in cellulose degradation. It is thus frequently affected by CT managements, which maintain crop residues at the surface.

With respect to TT, NT significantly increased both enzymatic activities at surface, and also RT in the case of β-Glu (Fig. 2A and B), corroborating previous findings about β-Glu as a suitable index for soil quality in CT (different modalities) under Mediterranean conditions. At 10–25 cm depth, both activities tended to be higher under TT techniques, due to the crop residues inversion caused by TT.

The increase of β-Glu (Fig. 2B) was greater than that of DHA (Fig. 2A), which does not always respond as effectively to variations in C content induced by tillage, but to site factors, such as species composition, soil texture, and soil pH (Perez-Brandán et al., 2012). This variable may be a good predictor of the capacity to oxidise the first stages of soil OM, which can vary temporally and from one system to another. Nevertheless, in our case both enzymatic activities showed adequately the improvement derived from CT systems.

3.4. Soil physical properties and plant response

The results considered showed that CT establishment entails chemical and biochemical soil improvements. However, despite the improvement of soil quality at the surface, especially under NT, parameters related to plant performance were strongly affected under NT (Table 3). Emergence and plant height in NT were extremely low, which resulted in a much lower plant density and yield, prohibitive for the farmer (Table 3). The yield of the previous crop (wheat) also suffered a significant reduction under NT (ca. 25%). Table 4 shows grain yield data of the previous years (in 2008 the pea crop was attacked by a fungus and consequently no yield was recorded).

However, emergence, plant height and yield were similar in RT and TT or even slightly greater in RT, although significant

Table 3
Values of parameters related to crop performance. Mean values ± standard error. For each period values followed by the same letter do not differ significantly ($p < 0.05$).

Treatments	Emergence plants m^{-1} (30 DDS)	Height m (50 DDS)[a]	Plant density (plants ha^{-1} at harvest)	Grain yield Mg ha^{-1}
TT	6.22 ± 0.97a	92.4 ± 2.50a	44,400a	3520a
RT	7.89 ± 1.70a	106 ± 4.13a	45,000a	3839a
NT	0.10 ± 0.01b	36.1 ± 5.95b	2200b	105b

NT, no-tillage; RT, reduced tillage; TT, traditional tillage.
[a] DDS: days after sowing.

Table 4
Grain yield data by year and treatment (kg ha^{-1}).

Treatment	2009 (wheat)	2010 (sunflower)	2011 (pea)	2012 (wheat)
TT	3562a	6500a	1780a	3860a
RT	3792a	6800a	1930a	3985a
NT	4092a	6200a	1560a	2940b

differences, with respect to TT, were not observed. The low yield under NT was not only a consequence of the smaller plant density, but also the lower grain weight per plant (47.7 g compared to 79.3 g in TT and 85.3 g in RT, $p < 0.001$) and lower 1000 grain weight in NT (53 g in relation to 58 g in TT and 60 g in RT, $p < 0.001$).

Seed quality was also affected. In general, the seeds were rich in lipids with an oil content ranging into 33.6% (NT) and 49.6% (RT) (Table 5), values which were in agreement with previous findings reported by Pérez-Vicha et al. (1998): range of 23.7–51.6%. However, the crude fat content under NT (33.6%) was very low in comparison to the other treatments ($p < 0.00001$), a circumstance of extreme commercial importance. Even the slight, but significant ($p < 0.05$) increase in RT over TT was of commercial importance.

On the other hand, twelve fatty acids were identified in the sunflower oil. Qualitatively, fatty acid composition was identical for all treatments (Table 5). The unsaturated fatty acids were predominant with a mean of 92.1%. The most abundant fatty acid was oleic acid, with a mean value of 85.8% in TT, 90.5% in RT and 88.9% in NT. The highest and significant value in RT was a positive feature considering its nutritional implications and positive effects on the oxidative stability of oils (Aguilera et al., 2000). The unsaturated/saturated fatty acid ratio was also higher in RT (12.1) than in TT (10.9) and NT (10.8), a positive feature considering its dietary and industrial importance. It is known that unsaturated fatty acids can influence some physical properties of the cellular membranes, such as fluidity and permeability (Bruckert, 2001). Moreover, these compounds stimulate transcription of gene encoding for the LDL-cholesterol receptor (Al-Jassir et al., 1995).

In the case of N and mineral nutrients the differences were in general less noticeable than those observed for oil, one of the main constituents of the whole seed (including pericarp). They also showed adequate levels in RT, similar or even significantly greater than those in TT for N, K, Mg, P, and S (Fig. 3). In general, protein concentrations (about 152 in TT, 174 (RT) and 172 (NT) g kg^{-1}, values calculated from N × 6.10 as recommended by Robinson, 1975) were slightly lower than other results reported in the literature (e.g. Lofgren, 1997), due perhaps to the fact that the crop was not fertilised, as is usual in SW Spain. It has been reported in literature that sunflower has high N requirements that must be supplied throughout growth (Blamey et al., 1997). Nevertheless, sunflower cultivars can differ greatly in the protein composition of the seeds (Robinson, 1975).

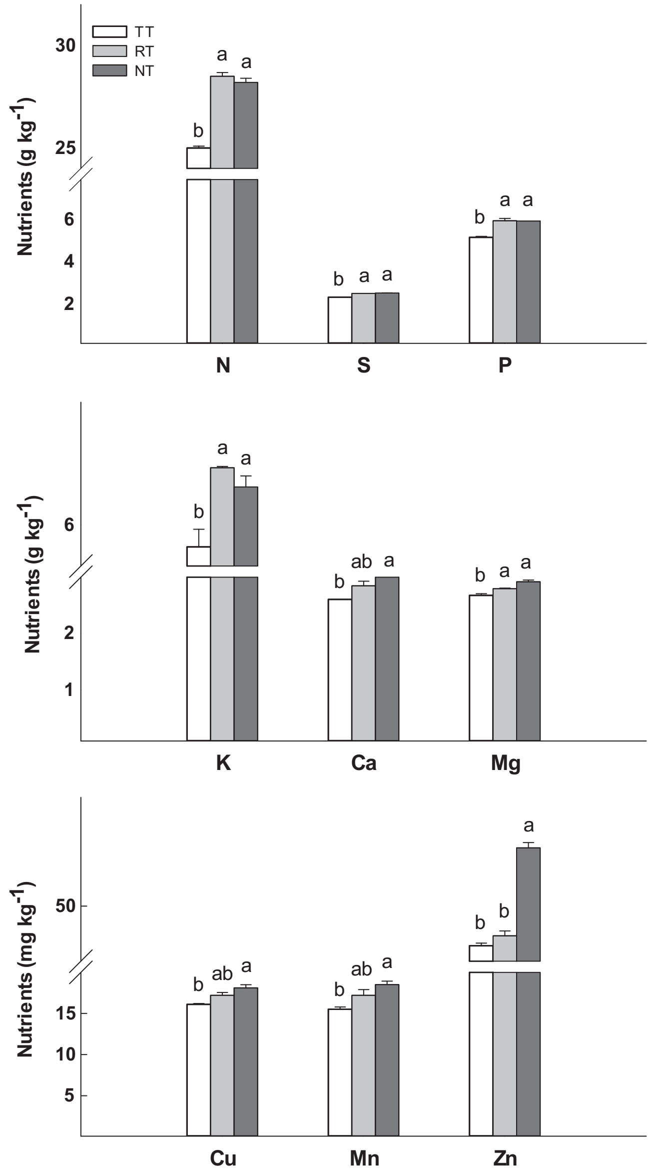

Fig. 3. Nutrient concentrations (mean values ± standard error) in mature sunflower seeds from TT (traditional tillage), RT (reduced tillage) and NT (no tillage) treatments. For each nutrient, columns with the same letter do not differ significantly ($p < 0.05$).

Differences between cultivars in mineral nutrients of the seeds have also been reported (Robinson, 1970, 1975). In general,

Table 5
Percentage of total oil, fatty acids, saturated fatty acids (SFA), monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) of the sunflower seeds. For each column, values followed by the same letter do not differ significantly ($p < 0.05$).

Treatment	Oil	C 14:0	C 16:0	C 16:1	C 17:0	C 17:1	C 18:0	C18:1	C 18:2	C 18:3	C 20:0	C 20:1	C 22:0	SFA	MUFA	PUFA
TT	48.0b	0.044a	4.58b	0.25b	0.030a	0.052b	2.23c	85.8c	5.65a	0.036b	0.24b	0.30c	0.81b	7.93b	86.4c	5.68a
RT	49.6a	0.040b	4.22c	0.24c	0.033a	0.058a	2.15b	90.5a	1.31c	0.036b	0.25b	0.33a	0.87a	7.55b	91.1a	1.35c
NT	33.6c	0.043a	4.68a	0.30a	0.033a	0.057a	2.41a	88.9b	2.11b	0.044a	0.29a	0.31b	0.85a	8.30a	89.5b	2.16b

Table 6
Soil moisture and density mean values ± standard error at different times and depths. For each depth values followed by the same letter do not differ significantly ($p < 0.05$).

Depth (cm)	Treatments	Moisture (%)	Moisture (%)	Density ($cm^3 cm^{-3}$)
		Early May[a]	Early June	Early June
0–5	TT	7.42 ± 0.91b	7.11 ± 0.71a	1.30 ± 0.04a
	RT	9.15 ± 0.52b	7.23 ± 0.80a	1.24 ± 0.08a
	NT	19.1 ± 0.73a	9.90 ± 2.12a	1.46 ± 0.08a
5–10	TT		14.0 ± 0.94a	1.52 ± 0.09b
	RT		13.4 ± 1.13a	1.74 ± 0.05ab
	NT		10.7 ± 1.91a	1.81 ± 0.08a

NT, no-tillage; RT, reduced tillage; TT, traditional tillage.
[a] Moisture at 0–10 cm measured by TDR

Table 7
Penetration resistance (MPa) ± standard error measured at early June at different depths. For each depth values followed by the same letter do not differ significantly ($p < 0.05$).

Treatment	Depth (cm)				
	0–5	5–10	10–15	15–20	20–25
TT	0.40 ± 0.02b	0.89 ± 0.17b	1.54 ± 0.88b	1.42 ± 0.22b	1.55 ± 0.25ab
RT	0.65 ± 0.11b	1.27 ± 0.16b	1.65 ± 0.18b	1.60 ± 0.17b	1.39 ± 0.15b
NT	6.04 ± 0.37a	4.45 ± 0.44a	4.50 ± 1.21a	2.80 ± 0.60a	2.60 ± 0.80a

NT, no-tillage; RT, reduced tillage; TT, traditional tillage.

concentrations in Fig. 3 are somewhat lower than values reported by other authors (Hocking and Steer, 1983; Robinson, 1975) for most nutrients, except for Ca; in our case twice the values found in literature, due to the soil richness in Ca. However, important ratios from a nutritional point of view such as N/S (around 11) and Ca/P (around 0.5) were adequately balanced in all treatments.

The negative results of crop development under NT were not due to pests, which were not observed at any time, or to a shortage of water in the soil at the time of germination, significantly greater under NT (more than double with respect to RT and TT) (first 10 cm, Table 6). However, the continuous rains during the period of September 2012–April 2013 forced the planting of sunflowers in early May (February is the normal time for this crop) with high temperatures. Thus, only one month later (early June) the water content of the soil become practically similar in all three treatments, even with a tendency to maintain slightly higher amounts of water at the sub-surface (5–10 cm) in RT and TT. At this time, these treatments (RT and TT) showed lower soil densities (at both depths) than NT (Table 6), which could be a favourable circumstance for root growth.

Penetration resistance was the variable that better reflected the negative conditions for root development under NT (Table 7). At the surface, the penetration resistance under NT was extremely high, ca. 10 and 15 times greater than those in RT and TT respectively. According to the classic work of Locher and De Bakker (1990), uninterrupted root growth can take place at penetration resistance values below 1.5 MPa. A value of approx. 3 MPa can be regarded as the upper limit for uninterrupted root growth. Interrupted root growth leads to reduced water and nutrient absorption, and ultimately to reduced crop production.

At deeper layers this variable continued to be greater in NT than in RT and TT, although the differences were not as pronounced as in the surface. Nevertheless, values in NT were always far greater than 2, a high level compared to those values registered in RT and TT. Penetration resistance values in RT were slightly greater than those in TT (without significant difference in either case), although without reaching levels that could be harmful for plant performance.

It is then not surprising that in these conditions farmers avoid agricultural practices such as NT, and in fact, the "Agricultural Association of Young Farmers" of Spain (ASAJA), with more than 200,000 associates, asked the Andalusia Government to till with soil inversion (TT) (without losing subsidy for conservation agriculture) due to weather conditions for much of the hydrological year 2012–2013, with very continuous rains, which facilitated the abundance of weeds and the compaction of many soils (ABC, http://hemeroteca.abc.es/nav/Navigate.exe/hemeroteca/sevilla/abc.sevilla/2013/05/13/079.html).

In our region farmers frequently only consider traditional tillage with soil inversion to eliminate weeds and avoid compaction. However, other CT practices, such as RT, could give good results (this work) without the necessity of soil inversion that inevitably leads to considerable losses of SOC.

4. Conclusion

We have found that in the same soil, cropped with the same crop rotation, two techniques of conservation agriculture, RT and NT (five years of establishment) yielded very different results. Although both treatments, NT in particular, improved soil quality in relation to chemical and biochemical properties, their impact on the soil physical properties was completely different, penetration resistance reaching prohibitive values for root growth under NT. Consequently, the crop performance and seed quality were greatly and negatively affected. On the contrary, the crop response under RT was very positive. Seed quality was even slightly, but significantly, better than under TT with soil inversion. It is therefore desirable to encourage farmers to use less invasive techniques in the environment, by introducing a judicious and flexible land management.

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