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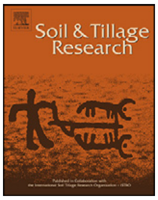

Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain

Aurora Sombrero *, Avelino de Benito

Agrarian and Technological Institute of Castile - Leon (ITACyL), Ctra. Burgos, Km. 119, 47071 Valladolid, Spain

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ABSTRACT

Minimum (MT) or no tillage (NT) and increased cropping intensity can enhance soil structure and raise carbon sequestration in agricultural soils. The effectiveness of these procedures depends on soil type, crops, and tillage management systems. Increases in the organic carbon content may be affected by crop type, crop rotation and the quality and quantity of crop residues left on the soil surface. Soil organic carbon (SOC) is a good indicator of soil quality and conservation. The present study was conducted from 1994 to 2004 at Torrepadierne, Burgos, a cereal farming area in Spain, on Typic Calcixerolls soil with a 1.8% soil organic matter (SOM) content. The average annual rainfall in the area is 448 mm. A split-plot experimental design was used, in which the main factor was the tillage system – conventional (CT), minimum (MT) or no-till (NT) – and the sub-factor crop rotation – cereal/cereal (C–C), cereal/fallow (C–F) and cereal/legume (C–L). Fallow/cereal and legume/cereal were added to these sequences to have the same crops every year. The present study was conducted to determine the effect of tillage systems and cropping sequences on SOC patterns after 10 years of soil management. At a depth of 0–10 cm, the SOC content was significantly higher with NT than CT or MT, by 58% and 11%, respectively. SOC values were 41% higher with MT, in turn, than with CT. At a depth of 10–20 cm, the SOC content was 30% higher with NT than with CT and 7% higher than with MT. And at 20–30 cm, it was 7% higher with MT than with CT, 12% higher with NT than CT and 9% higher with no-till than minimum-till. In 2004, at the end of the 10 years period, SOC was 25% greater with NT than CT, 16% greater with NT than MT, and 17% higher with MT than CT. Crop rotation was not observed to have any significant effect on the SOC content in 2004, however. These findings suggest that carbon sequestration in the 30 cm layer can be improved if NT or MT are used in lieu of conventional practice. The total crop residue returning to the soil was significantly greater in plots sown with legume after cereal harvest than in plots left fallow. It also enhanced SOC sequestration in non- or minimally tilled soils.

1. Introduction

In semi-arid Castile-Leon, a region with a yearly precipitation of 400–450 mm, climate is the chief constraint on agricultural production. Rainfall, the primary production factor for rainfed crops, is irregularly distributed, limiting crop choice and production in most of the region. Since most of the rain falls in spring and autumn, rainfed crop yields are low and unstable. As a rule, the soils have a low organic matter content and weak structure. The texture of most of the soils supporting rainfed herbaceous crops is from loam to sandy-loam, although all the intermediate stages can also be found. While the usual rainfed crop rotation sequence is cereal–legume or cereal–fallow, continuous cereal cropping prevails. The most common cereal crops are barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.), while vetch (*Vicia sativa* L.) and field pea (*Pisum sativum* L.) are the predominant legumes.

Conservation tillage, particularly no tillage (García Calleja and González Sánchez-Diezma, 1985), was pioneered in Spain in the Castile-Leon region in 1980–1985, but these techniques were not implemented by farmers until the latter half of that decade. Conservation tillage systems and the chisel plough have become increasingly popular in the region over the last 10 years because they enhance profitability by lowering machinery and other costs, and are more environmentally fit than the moldboard plough.

Soil carbon dynamics play a crucial role in sustaining soil quality, promoting crop production and protecting the environment (Bauer and Black, 1994; Doran and Parkin, 1994; Robinson et al., 1996). The soil organic carbon (SOC) pool, a significant indicator of soil quality, has many direct and indirect effects on such quality. Increases in the SOC pool improve soil structure and tilth, counter soil erosion, raise water capacity and plant nutrient

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* Corresponding author. Tel.: +34 983317351; fax: +34 983414780.
E-mail address: somsacau@itacyl.es (A. Sombrero).

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stores, provide energy for soil fauna, purify water, denature pollutants, enhance soil biodiversity, improve the crop/crop residue ratio and mitigate the effects of climate (Lal, 2007). Conservation tillage systems (such as minimum and no-till) have been observed to contribute to the role of soil as a carbon sink. By minimizing soil disturbance, reduced tillage decreases the mineralization of organic matter. The result is a larger store of soil organic carbon than with conventional tillage (West and Post, 2002; Al-Kaisi and Yin, 2005). The latter is used to mix topsoil to recover lost nutrients, prepare the seedbed and control weeds, but has been associated with losses in soil organic carbon, which lead to a significant decline in soil quality (Hernanz et al., 2002). Due soil management, including conservation tillage and annual cropping practices, can increase total soil organic carbon storage (Franzluebbers et al., 1995; Halvorson et al., 2002a). The effects of tillage on soil carbon dynamics are complex and often variable, however. Franzluebbers and Arshad (1996) reported that there may be little to no increase in SOC in the first 2–5 years after changing to conservation management, but a large increase in total carbon in the following 5–10. Diuker and Lal (1999), in turn, found that after 7 years the application rate of residue had a positive linear effect on soil organic carbon in all the tillage systems they studied.

Carbon sequestration and other conservation benefits require a detailed knowledge of crop residue production and management. SOC can be increased by raising biomass production and crop residue retention with the adoption of crop rotation and conservation tillage (especially no-till) procedures that retain crop residue near the surface of the soil (Lal et al., 1998; Allmaras et al., 2000; Reicosky and Allmaras, 2003). Little information is available about the effect of cropping and tillage systems on SOC in the semi-arid plateau in Castile-Leon, a region in northern Spain. While such information is available for central Spain (López-Fandó and Almendros, 1995; Hernanz et al., 2002), it may not be applicable due to differences in temperature, rainfall, and growing degree days. The adoption of reduced tillage practices and the cultivation of crops with a high potential for contributing to C-biomass are further prerequisites for SOC accumulation (Sisti et al., 2004). Increases in soil organic carbon may also depend on the type of crop, crop rotation and the quality and quantity of crop residues (Wright and Hons, 2005). Bayer et al. (2006) and Diekow et al. (2005) observed that under long-term management based on NT and low-addition cropping systems, soils failed to accumulate SOC, while NT in conjunction with legume-based cropping systems yielded SOC accumulation rates of around 0.8 mg ha^{-1} year^{-1}. The relative contribution of these two factors is heavily dependent on both soil and climate conditions.

The present study aimed to: (i) examine the effect of tillage systems and crop rotation on the amount of cereal biomass returned to the soil, as well as on crop residue and soil organic carbon (SOC) at a depth of 0–30 cm; (ii) determine the effects of tillage systems and cropping sequences on soil organic carbon (SOC) patterns; (iii) show that with local practice, i.e., conventional tillage and straw removal, less carbon is sequestered in dryland soils than when conservation tillage is deployed and crop residue is left on the soil surface.

2. Materials and methods

This study was conducted from 1994 to 2004 on the Torrepadierne farm (42°13′17″N, 4°22′45″W), located on a flat limy moor typical of the Duero Valley cereal belt in the Spanish province of Burgos. The soil, classified as Typic Calcixerolls, is characterized by a loamy-clay texture in the upper surface horizon, gradually changing to clay with depth. Its mean pH is 8.3, its bulk density 1.13 g cm^3 and its organic matter content 1.8%.

The area has a continental climate (Groczynski index) with a frost-free period running from 3 May to 22 October, a yearly water deficit of over 180 mm and mild Mediterranean weather (Papadakis classification). These climatic conditions are suitable for cereal grain production in winter and irrigated maize in summer. The mean rainfall in the area from 1963 to 1993 was 448 mm (Table 1). Distribution of precipitation across the season is an important consideration. The heaviest rainfall recorded in the period studied was in the 2000–2001 growing season, although cumulative precipitation from April to June 2001 was only 50.6 mm. The 1998–1999 and 2001–2002 seasons were extremely dry (330 and 333 mm).

In the four-replicated split-plot experiment designed, tillage system was the variable in the main plot and crop rotation in the sub-plot. The study covered a total of sixty 450-m^2 elementary plots. The tillage systems used were: conventional tillage (CT), minimum tillage (MT) and zero or no-till (NT).

Preparatory work was conducted in keeping with the respective tillage system: CT (moldboard plough (25–30 cm deep), cultivator, harrow, roller and sowing), MT (chisel plough (10 cm deep), harrow, roller and sowing) and NT (herbicide and sowing) in early November.

From 1994 to 2001 the following crop rotations were defined: R1, cereal–fallow (C–F); R2, fallow–cereal (F–C); R3, continuous cereal (C–C); R4, legume–cereal (L–C); and R5, cereal–legume (C–L). The fallow/cereal and legume/cereal sequences were included to have all the same crops each year. From 2001 to 2004, plots with conservation tillage (minimum and no-till) in monoculture cereal crop were infested by *Bromus sterilis* L. In order to control this weed, crop rotations were changed and defined as: R1: cereal–legume-cereal; R2: cereal–legume–cereal; R3: legume–cereal–cereal; R4: cereal–cereal–cereal and R5: legume–cereal–cereal. In 2004, to allow for chemical control of *Bromus sterilis* L., only wheat was grown in the final year of the series.

The crops were sown with a (Sola Super 395-sd) driller on the same day in November in all tillage systems, which were managed in accordance with local practice. In CT, the soil was ploughed to a depth of 25–30 cm and crop residue was packed into bales. In MT

Table 1

Monthly rainfall (mm) at Torrepadierne, Spain, in growing seasons 1994–2004 and historic mean values, 1963–1993.

Year	October	November	December	January	February	March	April	May	June	July	August	September	Total
1994/1995	58.9	57.4	39.3	23.3	38.9	3.8	18.1	28.9	39.3	13.1	3.0	23.6	347.6
1995/1996	16.8	78.6	104.2	108.9	20.7	64.4	35.1	49.2	16.5	9.9	34.9	20.6	559.8
1996/1997	8.8	42.6	126.7	59.8	7.9	0.0	9.7	66.1	56.8	108.9	48.4	21.2	556.9
1997/1998	49.1	130.7	115.1	33.8	9.8	11.1	51.5	49.3	33.5	21.2	19.0	70.6	594.7
1998/1999	7.1	19.8	45.5	43.5	2.4	16.6	37.4	52.4	4.7	34.2	26.3	39.8	329.7
1999/2000	79.5	34.7	23.1	16.8	4.9	35.8	117.4	25.9	25.3	33.7	14.3	24.7	436.1
2000/2001	48.1	109.9	83.2	86.5	16.9	111.0	12.8	36.7	1.1	57.4	14.1	24.5	602.2
2001/2002	40.7	21.6	11.3	35.3	14.9	19.8	53.8	32.8	20.5	17.5	13.5	50.9	332.6
2002/2003	84.7	62.0	69.8	90.8	53.0	25.9	56.5	34.1	20.7	25.2	38.9	23.8	585.4
2003/2004	102.5	59.6	35.3	31.9	22.3	48.2	32.3	43.3	26.5	1.00	41.0	8.8	452.7
Historic mean	43.1	40.7	37.1	42.5	41.3	24.5	51.7	54.5	43.3	21.6	17.3	30.0	447.6

Table 2
Effects of tillage and crop rotation on crop residue (stems + leaves) of cereals from 1995 to 2004.

Treatment	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Crop residue (Mg ha^{-1})										
Tillage										
CT	4.47a	5.87a	4.72a	6.06a	5.89a	6.42b	3.33b	3.82a	3.46a	7.81a
MT	3.86b	6.06a	4.72a	6.97a	6.89a	6.05a	3.25b	3.48a	2.06b	6.70b
NT	3.67b	5.86a	4.92a	6.65a	7.16a	6.05a	3.87a	3.67a	2.37b	6.61b
Crop rotation										
R1	3.95a	5.25c	4.79a		7.24a		3.16b	3.81a		8.11a
R2		6.57a		6.92a		6.60a		4.02a		6.85b
R3	3.94a		4.76a	5.96a	5.48b	5.88b	3.47ab		1.73b	6.70b
R4		5.96b		6.67a		6.11a		3.19b	1.80b	6.24b
R5	3.85a		4.82a		7.23a		3.82a		4.30a	7.13b
T × R	N.S	N.S	N.S	N.S	N.S	N.S	**	N.S	**	N.S

CT, conventional tillage; MT, minimum tillage; NT, no tillage.

From 1994 to 2001: R1: cereal–fallow, R2: fallow–cereal, R3: cereal–cereal, R4: cereal–legume, R5: legume–cereal. From 2001 to 2004: R1: cereal–legume–cereal. R2: R2: cereal–legume–cereal. R3: legume–cereal–cereal. R4: cereal–cereal–cereal. R5: legume–cereal–cereal.

Numbers followed by same letter within tillage and crop rotations treatments are not significantly different at $p < 0.05$ by Duncan test. T × R, tillage × rotations, NS, no significant.

** Significant at $p < 0.001$.

and NT, crop residue was not removed. Plots were sown with 180 kg ha^{-1} of winter barley (cv. Tipper), 200 kg ha^{-1} of winter wheat (cv. Marius) and 160 kg ha^{-1} of vetch (cv. Buza). Based on the results of the soil analysis and crop needs, only cereal was fertilized, at a rate of 400 kg ha^{-1} (8-24-8 NPK). A topdressing was applied in the subsequent tillering-stem elongation phase, consisting in 300 kg ha^{-1} of ammonium sulphate. Thirty six per cent glyophosate (1l ha^{-1} + 1 kg ha^{-1} of ammonium sulphate) was applied preplant on minimal and zero-till plots; all the other herbicide treatments were the same in all cereal (2.5 l ha^{-1} of oxytril (7.5% ioxynil + 37.5% mecoprop + 7.5% bromoxynil) + 1.25 l ha^{-1} of esplendor (25% tralkoxydim)) and vetch (1.1 l ha^{-1} of Agil + 0.5 l ha^{-1} of extravon (humectant)) plots. In 2003–2004, 25 g ha^{-1} of sulfosuron was applied to combat *Bromus sterilis* L.

Four cereal grain and four straw samples were taken per 1.36-m^2 plot. Crop production components were determined for all samples. Biomass was calculated by weighing the oven-dried samples (65 °C for 48 h). Vetch, a legume used for forage, was cut at flowering.

Soil properties were determined at the outset. Soil samples were taken before the preparatory work in October 1994, 1997 and 2000 at three sites on each elementary plot to obtain a composite sample per plot (total 60 samples) at a depth of 0–30 cm, because none of the tillage treatments exceeded that depth. In 2004, in the same time frame, soil samples were taken at depths of 0–10, 10–20 and 20–30 cm (total 180 samples). The samples were air dried and sieved through a 2 mm mesh. The organic matter content in the soil was determined with the Walkley and Black method (1934). In 1994, 1997 and 2000, bulk density at a depth of 0–30 cm was measured by hand with a 67.44 cm^3 steel cylinder driven into the soil twice per tillage system. In 2004, bulk density was evaluated by taking two samples by tillage systems at three different depths (18 samples). After removal, cores were dried at 105 °C and weighed. The SOC element mass per unit area was calculated from horizon thickness and bulk density. Bulk density used was the mean by depth of the two samples taken in each treatment.

Data were statistically analyzed using the ANOVA or the general linear model (GLM) procedure (SAS Institute, 1990) for a split-plot design, applying Duncan's or the LSMeans test with $p < 0.05$.

3. Results and discussion

3.1. Crop residue

The amount of cereal crop residue returned to the soil between 1995 and 2004 was significantly impacted by tillage system and crop rotation (Table 2) and differed from year to year over the 10-year period. In 1998 to 2000, for instance, the amount was higher than in any other year except 2004, when crop residue was highest because cereal was grown on all plots. Total rainfall during the February to June growing season was 155, 113 and 209 mm in 1998, 1999 and 2000, respectively. The larger amount of crop residue in these years was due to the greater rainfall. The mean crop residue in 2001 was very small because of the very atypical rainfall distribution that year: 111 mm in March and a total of 178 mm in the growing season. Moreover, since daily low temperatures in December and January were below zero (the mean low temperature for these two months was −3 °C), all crops, but the legumes in particular, had irregularly and very late stand establishment. As a result, weeds, primarily *Bromus sterilis* L., were a major problem in 2002 and 2003, when crop residue was very low in all systems. Wheat was grown on all plots in 2004 to be able to apply chemical treatment to combat this weed, which would explain the larger amounts of crop residue than in the previous years.

The amount of cereal crop residue was significantly higher with conventional (CT) than minimum (MT) or no tillage (NT) in four of the 10 years, due most likely to greater total rainfall during the growing season: with very abundant rainfall from April to June, significantly more crop residue was produced with CT than NT or MT, notwithstanding, in CT the residue was baled and removed. On the contrary, when the second quarter was dry or rainfall was irregularly distributed, the amount of crop residue was similar in the three systems, or lower with CT. Soil water content has been reported to rise with conservation tillage under the semi-arid conditions prevailing in northern Spain (Lampurlanés and Cantero-Martínez, 2006).

From 1995 to 2001, crop residue varied significantly with the crop rotation system. Intra-year biomass was highest with cereal–fallow (C–F), followed by cereal–legume (C–L) and continuous cereal (CC) in that order. Since the fallow and forage legume regimes were alternated every 2 years, crop residue returned to the soil only once every 2 years under these arrangements. As a result, the mean biomass was significantly higher in continuous winter cereal than in other sequences. In plots left fallow, the rise in crop residue was probably due to the differences in the amount of soil moisture during inter-rotational sowing. Soil moisture storage has been reported to be higher following fallow than continuous cereal regimes (Sombrero et al., 1996). While in 2002 significantly more crop residue was recorded under the continuous cereal than C–F or C–L sequences, in 2003 the highest volume was observed in C–L

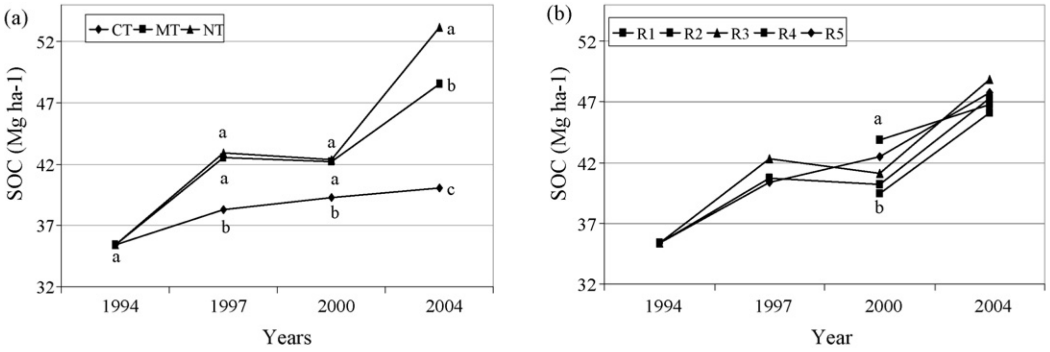

Fig. 1. Soil organic carbon (SOC) levels in the 0–30 cm layer, 1994–2004, by: (a) tillage system and (b) crop rotation sequence. Points lettered differently in a given year mark significant differences at $p < 0.05$ (Duncan's test). (a) CT, conventional tillage; MT, minimum tillage; NT, no tillage. (b) From 1994 to 2001: R1: cereal–fallow, R2: fallow–cereal, R3: cereal–cereal, R4: cereal–legume, R5: legume–cereal. From 2001 to 2004: R1: cereal–cereal–legume–cereal. R2: fallow–cereal–legume–cereal. R3: cereal–legume–cereal–cereal. R4: legume–cereal–cereal–cereal. R5: cereal–legume–cereal–cereal.

plots. The plots were weed-infested in these 2 years, the legumes by *Gallium aparine* L., and the continuous cereal by *Bromus sterilis* L. The crop residue values were smaller in 2003 than in any other year. Winter wheat was planted on all the plots in 2003, with more residues recorded in the legume-cereal than the continuous cereal sequence. In 2001 and 2003, crop residue patterns in terms of rotation sequence varied with the tillage system (Table 2). In 2001, the highest values were found for C–L under CT and NT, whereas under MT the C-C rotation yielded most crop residue, an indication that both factors impacted the results. Further evidence of this interaction was observed in 2003, when the amount of residue found after the C–L sequence was greater with CT than NT or MT.

The mean total crop residue for all tillage systems for the entire period was highest in plots continuously growing cereal in 8 of the 10 years, followed by cereal–legume and cereal–fallow rotation plots, in that order. Further to findings reported by other authors (Halvorson et al., 2002a,b), cropping intensity may raise the amount of crop residue returned to the soil.

3.2. Soil organic carbon patterns

While organic carbon in the 0–30 cm layer rose more in conservatively than conventionally tilled (CT) soils, the difference was statistically significant after the third year of soil management only (Fig. 1). In 1997, SOC was 11% higher in non-tilled (NT), and 10% higher in minimally tilled (MT) than in conventionally tilled soils. In 2000, it was 7% higher under both NT and MT than under CT. At the end of the 10-year period, soil organic carbon was 25% higher in no-till than conventionally tilled and 16% higher than minimally tilled plots. In that same year, SOC was 17% higher with MT than CT. Clearly then, conservation tillage raised soil organic carbon content.

Chemical analyses of the 0–30 cm layer soil samples conducted in 1997 showed that SOC content was not significantly affected by crop rotation. Nonetheless, SOC content was higher with MT and NT than conventional tillage in all three sequences. Under cereal–cereal (C–C) arrangements, SOC content was 24% lower in CT than MT and 21% lower than in NT. With the cereal–falow (C–F) sequence, SOC values were 9% and 6% lower under CT than MT and NT, respectively. Lastly, when cereal and legume (C–L) crops were alternated, SOC was 3% lower with CT than MT and 13% lower than with NT. The cereal crop residues accounted for these cross-tillage system patterns.

In 2000, soil organic carbon amount varied significantly with the crop rotation system. The overall mean SOC content with C–L was higher than with C–F and C–C by 8% and 5%, respectively. With conventional till, the SOC content was 15% higher under cereal–legume than cereal–fallow alternation and 7% higher with the former than with continuous cereal arrangements. With no-till, the C–L values were 8% and 10% higher than for C–F and C–C, respectively. SOC content did not vary significantly by crop rotation with minimum tillage, although the C–C values were 5% higher than the C–F and 4% higher than the C–L figures.

SOC content at the end of the 10-year period did not vary significantly by crop sequence (Fig. 1b). No significant differences were observed in NT and MT, although SOC content was highest in both systems under the L–C–C sequence. In six of the 10 years, the SOC content in conventionally tilled plots was significantly higher in plots where legumes were planted than where they were not, for the roots of legumes remained in the soil. In NT and MT plots, in turn, these roots reinforced the cereal residues, accounting for the higher SOC content under L–C–C rotation.

3.3. Soil organic carbon distribution and accumulation over 10 years

As a rule, after 10 years of soil management, the tillage system had a greater effect on soil organic carbon than crop rotation (Fig. 2). SOC was significantly impacted by the type of tillage in all three 10 cm layers in the depth studied (0–30 cm). SOC declined with greater depth under the no- (NT) and minimum-till (MT) systems and was significantly higher in the 0–10 and 10–20 cm layers than in the bottom layer in both NT and MT. Moreover, at depths of over 20 cm significantly higher levels of soil organic carbon were recorded in NT than MT or CT (conventional tillage).

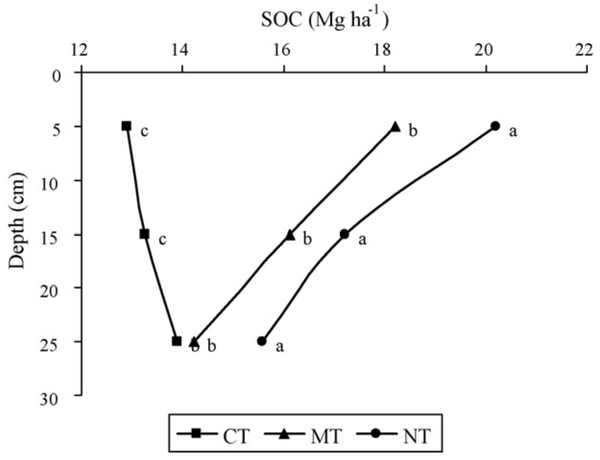

Fig. 2. Vertical distribution of the soil organic carbon (SOC) content in 2004 by tillage system. Lettered values mark significant differences at $p < 0.05$ (Duncan's test). CT, conventional tillage; MT, minimum tillage; NT, no tillage.

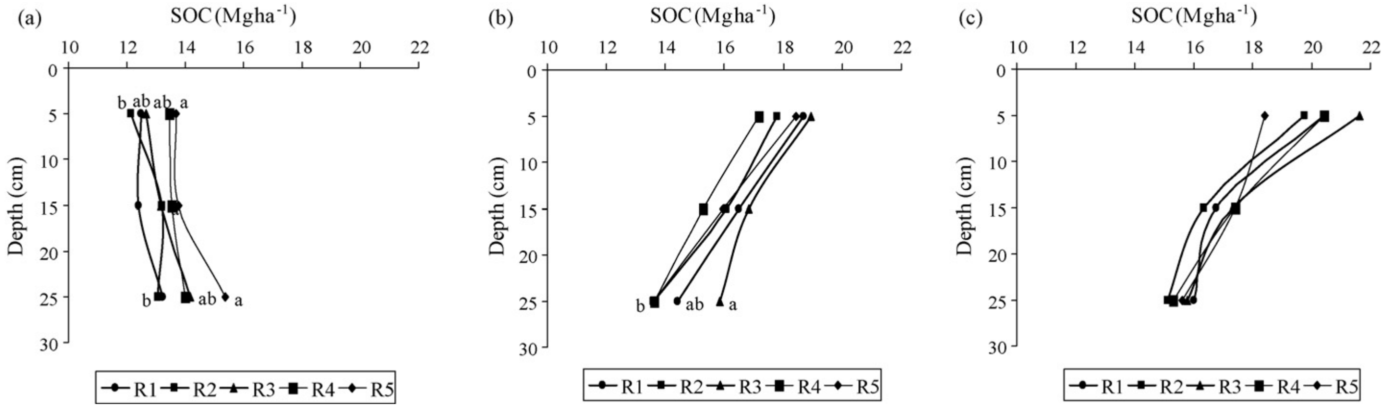

Fig. 3. Vertical distribution of the soil organic carbon (SOC) content for different crop rotation sequences in 2004 under: (a) conventional tillage; (b) minimum tillage; (c) no tillage. Lettered values mark significant differences at $p < 0.05$ (Duncan's test). R1: cereal–cereal–legume–cereal. R2: fallow–cereal–legume–cereal. R3: cereal–legume–cereal–cereal. R4: legume–cereal–cereal–cereal. R5: cereal–legume–cereal–cereal.

Intra-tillage system differences in the SOC content were highly significant in the 0–10 cm layer, with NT levels 58% higher than CT and 11% higher than MT values. SOC values were 41% higher with MT, in turn, than with CT. These results are consistent with findings reported by Hernanz et al. (2002) and Moreno et al. (2006), who observed a higher SOC content at 10 cm in non-tilled than conventionally tilled soils in semi-arid climates. A number of authors have observed more surface SOC with NT than other tillage systems (Sainju et al., 2006; Martin-Rueda et al., 2007; Álvaro-Fuentes et al., 2008). No tillage also yielded significantly higher SOC in the 10–20 cm depth, with values 30% higher than in CT and 7% than in MT. The soil organic carbon content in this layer was 7% higher with minimum than conventional tillage. SOC also tended to be significantly greater under no-till in the 20–30 cm layer: 12% and 19% higher than with CT and MT, respectively. These results differ from earlier reports, according to which SOC did not vary at depths of under 10 cm (Moreno et al., 2006; Álvaro-Fuentes et al., 2008). Baker et al. (2007) observed no correlation between tillage system and differences in the SOC content at soil depths of over 30 cm. Dolan et al. (2006), in turn, found that more SOC was stored below 20 cm in conventionally tilled soils and stressed the importance of obtaining SOC values for the entire profile.

As the vertical distribution of SOC by crop rotation and tillage system in Fig. 3 shows, patterns varied by tillage system. SOC content was higher with conservation than conventional tillage at all three depths. Nonetheless, while SOC values declined at the 20–30 cm layer under conservation tillage, with conventional tillage they rose. The slight decrease with conservation tillage at this depth might be explained by the fact that crop residues would remain on the surface in NT and MT but penetrate to depths of 25–30 cm with moldboard ploughing.

With conventional tillage, SOC amount varied significantly between crop rotation sequences (Fig. 3a). Soil organic carbon was lower in fallow plots (5 of 10 years) than in plots growing legumes (5 of 10 years) at depths of 0–10 and 20–30 cm. In minimum tillage, the SOC content varied significantly by crop rotation in the 20–30 cm layer only (Fig. 3b). The highest SOC values were obtained where cereal was planted in 8 of 10 years and the lowest in plots left fallow in 5 of 10 years. In the no-till system, the SOC content did not vary by crop rotation sequence at any depth interval (Fig. 3c). Martin-Rueda et al. (2007) reported no significant differences in SOC by crop rotation at any depth. Similarly, Sainju et al. (2006) found that crop rotation had no effect on SOC. Other authors (Collins et al., 1992) observed that differences in SOC were attributable to the type and amount of residue incorporated in the soil. Finally, according to Sherrod et al. (2003), greater cropping intensity raised crop residue and SOC only after 12 years of soil management. In this study, tillage system was found to have a greater effect on SOC than crop rotation.

Table 3 gives the effect of tillage and crop sequence on cumulative SOC at depths of 0–10, 10–20 and 20–30 cm, measured in November 2004. In the 0–30 cm profile as a whole, the mean SOC, considering all crop rotations, differed statistically across the three tillage systems. After this 10-year experiment, the mean SOC values found in the 0–30 cm layer were 17.8 mg ha^{-1} in NT, 13.3 mg ha^{-1} in MT and 4.6 mg ha^{-1} in CT. These results were consistent with West and Post's (2002) reports to the effect that minimizing mechanical soil treatment enhanced carbon storage. In the present study, the large additional amounts of crop residues accumulating over 10 years raised the SOC content in NT and MT as compared to CT soils, in the 0–30 cm layer. Soil was sampled only to a depth of 30 cm, for none of the tillage treatments exceeded that depth. Nonetheless, as tillage systems may change the SOC content patterns beneath the tilled layers, these findings may be overestimating the positive effects of conservation tillage on SOC. Gál et al. (2007) proved the need for deep sampling to ensure the accuracy of carbon sequestration assessments with no-till and conventional tillage.

Table 3
Tillage and crop rotation treatment effects on soil organic carbon (SOC) accumulation at different depth intervals in 2004.

Crop rotations	CT, depth (cm)			MT, depth (cm)			NT, depth (cm)		
	0–10	0–20	0–30	0–10	0–20	0–30	0–10	0–20	0–30
SOC (Mg ha^{-1})									
R1	12.48ab	25.16bc	38.17c	18.69a	33.11a	49.58a	20.44a	36.64a	53.44a
R2	12.14b	24.66c	38.28c	17.78a	31.37a	47.43a	19.75a	35.05a	51.91a
R3	12.67ab	26.23bc	39.98bc	18.94a	34.79a	51.61a	21.65a	37.66a	55.02a
R4	13.46ab	26.89ab	41.01ab	17.17a	30.80a	46.07a	20.42a	35.94a	53.35a
R5	13.72a	28.36a	42.69a	18.43a	32.03a	47.96a	18.73a	34.49a	52.19a

Different letters indicate significant differences at $p < 0.05$, using Duncan's test. CT, conventional tillage; MT, minimum tillage; NT, no tillage. R1: cereal–cereal–legume–cereal. R2: fallow–cereal–legume–cereal. R3: cereal–legume–cereal–cereal. R4: legume–cereal–cereal–cereal. R5: cereal–legume–cereal–cereal.

In conventionally tilled soils, SOC was significantly affected by crop rotation. At depths of 0–10, 10–20 and 20–30 cm, SOC ranged from 12.1 to 13.7, 24.7 to 28.4 and 38.2 to 42.7 mg ha^{-1}, respectively. The lowest values were recorded for plots left fallow (5 of 10 years) and continuously planted with cereal (8 of 10 years), while the highest were for rotations involving vetch. These results concurred with other studies reporting the positive effect of vetch on the organic matter content in soil and consequently soil quality (Katsvairo and Cox, 2000; Masri and Ryan, 2006). C–L rotated plots had higher SOC contents than C–F plots (5 of 10 years). Higher cropping intensity often leads to greater SOC sequestration (Wright and Hons, 2005). As a rule, in the present study, SOC was unaffected by crop sequence in the 0–30 cm layer in NT and MT managed soils. In both these conservation tillage systems, SOC was lowest in plots left fallow in 5 of 10 years and the highest where cereal was continually planted in 8 of the 10 years. The SOC content was higher in NT than CT or MT in all rotation systems. The mean SOC values in the 0–30 cm profile ranged from 51.9 to 55.0 mg ha^{-1} with NT and from 46.1 to 51.6 mg ha^{-1} with MT.

4. Conclusions

Conservation tillage proved to be highly effective in enhancing SOC at a depth of 0–30 cm under the semi-arid conditions prevailing in Castile-Leon. The findings of this 10-year study showed that tillage type and crop rotation impacted crop biomass residue returning to the soil, as well as SOC. These findings may be applicable to many other areas with similar soils and climates. While biomass rose with cropping intensity, it varied from year to year as a result of differences in rainfall patterns.

Tillage systems were observed to lead to differences in SOC beginning in the third year after a change in management practice, followed by larger increases in subsequent years. In 1997, the SOC content was 11% higher under no-till (NT) than conventional tillage (CT), and 10% higher with minimal tillage (MT) than CT. By the end of the 10-year period, soil organic carbon was 25% higher with NT than CT and 16% higher with no- than minimum-till. In that same time frame, the SOC content was 17% higher with MT than CT. After 6 years, the mean SOC content for all three tillage systems in the 0 to 30 cm profile was affected by crop rotation. The overall mean SOC content with the cereal–legume (C–L) sequence was higher than with cereal–fallow (C–F) and cereal–cereal (C–C) arrangements by 8% and 5%, respectively. After 10 years of conventional tillage, cumulative SOC at a depth of 0–30 cm was significantly affected by crop rotation, whereas no such impact was observed under NT or MT.

The mean SOC store after 10 years for all the crop sequences was 17.8 mg ha^{-1} with NT, 13.3 mg ha^{-1} with MT and 4.6 mg ha^{-1} with CT in the 0–30 cm profile. Hence, carbon can be stored in soil in drylands of this area by no- and minimum-till with continuous cropping. Conventional tillage and fallow practices are not recommended as a sustainable system in a semi-arid condition.

Since the soil samples were taken to a depth of only 30 cm in the present study, however, the findings may overestimate the beneficial effects of conservation tillage on SOC sequestration. Soil samples covering the entire profile are needed to accurately evaluate and compare SOC storage in different tillage systems.

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