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Tillage Effects on Soil Organic Carbon Fractions in Mediterranean Dryland Agroecosystems

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ABSTRACT

Under semiarid conditions, soil quality and productivity can be improved by enhancing soil organic matter (SOM) content by means of alternative management practices. In this study we evaluated the feasibility of no-tillage (NT) and cropping intensification as alternative soil practices to increase soil organic carbon (SOC). At the same time, we studied the influence of these management practices on two SOC fractions (particulate organic matter carbon, POM-C, and the mineral associated carbon, Min-C), in semiarid agroecosystems of the Ebro river valley. Soil samples were collected at five soil layers (0-5, 5-10, 10-20, 20-30, 30-40 cm depth) during July 2005 at three long-term tillage experiments located at different sites of the Ebro valley river (NE Spain). Soil bulk density, SOC concentration and content, SOC stratification ration, POM-C and Min-C were measured. Higher soil bulk density was observed under NT than under reduced tillage (RT), subsoil tillage (ST) and conventional tillage (CT). At soil surface (0-5 cm depth), the highest total SOC concentration, POM-C and Min-C was measured under NT, followed by RT, ST and CT, respectively. However, in the whole soil profile (0-40 cm) similar o slightly greater SOC content was measured under NT than under CT with the exception of the SV site where deep subsoil tillage compared with moldboard plowing accumulated more SOC than NT. In semiarid Mediterranean agroecosystems where CT consisted in moldboard plowing, NT is a viable management practices to increase SOC.

Abbreviations: AG, Agramunt site; CF, cereal-fallow rotation at the Peñaflor site; CT, conventional tillage; Min-C, Mineral Associated Carbon; NT, no-tillage; PN-CC, continuous cropping system at the Peñaflor site; POM, Particulate Organic Matter; POM-C, Particulate Organic Matter Carbon; RT, reduced tillage; SOC, Soil Organic Carbon; SOM, Soil Organic Matter; ST, subsoil tillage; SV, selvanera site.

The soil organic matter (SOM) is a key factor on semiarid agroecosystems productivity. Soils of semiarid regions are characterised by low SOC content, low water and nutrient retention and, thus, low inherent soil fertility (Lal, 2004a). In these regions, low and erratic rainfall together with high evapotranspiration rates leads to a low crop biomass production and, thus, to a limited residue input into the soil. Bauer and Black (1994) quantified the contribution of SOM to productivity and observed that 1 Mg ha^{-1} of SOM increased wheat grain yield up to nearly 16 kg ha^{-1}. These authors concluded that a loss of fertility explained the loss of productivity due to a depletion of SOM.

Reeves (1997), after compiling information from several long-term studies, concluded that cropping resulted in a general loss of soil organic carbon (SOC) that can be reduced through rational soil management practices. The influence of different agricultural management practices on soil C storage or C sequestration has been reviewed by several authors (Freibauer et al., 2004; Lal, 2004b). Enhancing SOC by soil management may be mainly achieved by means of reducing SOC decomposition and/or increasing residue inputs (Paustian et al., 2000).

A reduction in the intensity of tillage has been widely recognized as a successful strategy to reduce SOC losses (Halvorson et al., 2002; West and Post, 2002; McConkey et al., 2003). West and Post (2002) analysed the results from 67 long-term agricultural experiments and concluded that, on average, a shift from conventional tillage (CT) to no-tillage (NT) can sequester nearly 60 g C m^{-2} yr^{-1}. Moldboard plowing, in CT systems, accelerates SOM decomposition and C loss from soil to the atmosphere as CO_2. Plowing creates residue and soil mixing, favouring physical contact between soil microorganisms and crop residues, and more optimal soil microclimatic conditions for crop residue decomposition (e.g., higher soil moisture content, temperature and aeration) (Paustian et al., 1998; Bruce et al., 1999). In contrast, under NT systems, the absence of soil disturbance produces a modification of surface soil conditions reducing microbial activity and, therefore, SOM decomposition (Mielke et al., 1986). Several studies have measured greater soil bulk density values after the adoption of NT (Kay and VandenBygaart et al., 2002). Increments of bulk density under NT are associated with reductions in soil porosity that may lead to a more limited oxygen supply for heterotrophic decomposition. On the other hand, the intensification of cropping systems by means of a reduction of the long fallow period is associated with a greater residue production and, therefore, with an increase in SOC content (Potter et al., 1997; Halvorson et al., 2002).

The SOM is formed by various components with different structural complexities that differ in their chemical stability and, consequently, in their turnover rates (Christensen, 1996; Krull et al., 2003). Several SOC models have been developed in the last 30 years (Jenkinson and Rayner, 1977; van Veen and Paul, 1981; Parton et al., 1987). One of the major limitations of these models is that they are composed by conceptual C pools that do not correspond to experimentally verifiable fractions (Christensen, 1996). Accordingly, several attempts have been made to set up measurable C fractions that closely match to the SOC pools described in those models (Cambardella and Elliot, 1992; Paul et al., 1999; Six et al., 2002). Cambardella and Elliot (1992) isolated a SOM pool named particulate organic matter (POM), which is more sensitive to soil management than the total SOM. This fraction is mainly composed of fine root fragments and other organic debris (Cambardella and Elliot, 1992) and serves as a readily decomposable substrate for soil microorganisms (Mrabet et al., 2001). Wander et al. (1998) observed a 25% greater SOC under NT than under CT. However, when POM-C was analysed this difference between tillage systems achieved a 70%. Another measurable C fraction is the mineral associated-C, which is the SOM chemically stabilised on the silt and clay surfaces (Hassink, 1997). However, this is a more stabilized SOM than the POM and, therefore, less sensitive to soil management.

In semiarid Spain, several studies have been focussed on the effect of soil management on SOM content (López-Fandos and Almendros, 1995; López-Bellido et al., 1997; Hernanz et al., 2002; Moreno et al., 2006). The most part of these studies concluded that a reduction in tillage intensity increases SOM content, especially at soil surface. However, in these studies, no attempt was made to estimate the effect of soil management on different SOM fractions.

In this study we present SOM data from three different long-term tillage experiments located in semiarid Ebro valley (NE Spain). In this region, intensive soil tillage, with moldboard plowing as the main tillage implementation and the cereal-fallow rotation have been traditional agricultural practices during decades. We hypothesised that a shift from intensive tillage to more conservative tillage operations may lead to an increase in SOM as it has been previously observed in other semiarid areas of Spain. At the same time, the removal of the fallow period in the rotation may help to rise the levels of SOM and, thus, to increase soil quality and productivity in the study area. In this respect, we consider a major issue to quantify the different SOM fractions and to study the role that these fractions play on SOM dynamics. Therefore, our objectives were to investigate the influence of different soil tillage and cropping systems on SOC content and distribution of C between SOM fractions (particulate organic matter and mineral-associated C).

MATERIALS AND METHODS

Cropping systems and Locations

This experiment was conducted at three different long-term tillage experiments located across the semiarid Ebro river valley (NE Spain). The Selvanera and Agramunt experimental sites, established in 1987 and 1990, respectively, were located in the Lleida province at dryland farms managed by the Agronomy Group of the University of Lleida. The third experimental site, Peñaflor, was established in 1989 at the dryland research farm of the Estación Experimental Aula Dei (Consejo Superior de Investigaciones Científicas) in the Zaragoza province. In the three sites, prior land-use consisted in conventionally-managed agriculture with intensive soil implementation. Selected site and Ap soil horizon characteristics are presented in Table 1.

In Selvanera (SV) the cropping system consisted of a wheat (*Triticum aestivum* L.)-barley (*Hordeum vulgare* L.)-wheat-rapeseed (*Brassica napus* L.) rotation with four tillage treatments: conventional tillage (CT), subsoil tillage (ST), reduced tillage (RT) and no-tillage (NT). The CT and ST treatments consisted of a subsoiler tilling respectively at 50 cm and 25 cm depth in August followed in both cases by a pass with a field cultivator to a depth of 15 cm in October before sowing. The RT treatment was implemented every October with only one pass of cultivator to a depth of 15 cm. In Agramunt (AG), the cropping system consisted of a barley-wheat rotation with four tillage treatments: conventional tillage (CT), subsoil tillage (ST), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of a pass of moldboard plowing to a depth of 25-30 cm depth every October followed by a pass with a field cultivator to a depth of 15 cm. The ST treatment consisted of a subsoiler tilling at 25 cm depth every October followed by a field cultivator to 15 cm depth. The RT treatment was implemented with one or two passes of cultivator to 15 cm depth every October. In Peñaflor (PN), two cropping systems were compared, a continuous barley cropping system (PN-CC) and a barley-fallow rotation (PN-CF). Three tillage systems were compared in both cropping systems: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of a pass with a moldboard plow to a depth of 30 to 35 cm plus a pass with a tractor-mounted scrubber as a traditional practice to break down large clods. The RT plots were chisel plowed to a depth of 25 to 30 cm. In the CT and RT plots of the PN-CC system, primary tillage was implemented every season in October followed by a pass of a sweep cultivator to a depth of 10-15 cm as secondary tillage. However, in the PN-CF rotation, primary tillage was implemented in March every two seasons, during the fallow phase of the rotation, while secondary tillage consisted of a cultivator pass to a depth of 15-20 cm in May. At the three experimental sites, in the NT treatment no tillage operations were done and for sowing a direct drill planter was used. In this treatment, the soil was kept free of weeds by spraying total herbicide (glyphosate).

At all sites, tillage treatments were arranged in a randomized complete block design with three replicates in SV, PN-CC and PN-CF and with four replicates in AG. The size of each plot was 7x50 m at SV, 9x50 m at AG and 10x33 m at PN-CC and PN-CF.

Soil sampling and analyses

Soil samples were collected at five different depths (0-5, 5-10, 10-20, 20-30, 30-40 cm) in July 2005 after crop harvest. For C analyses, a composite sample was prepared from two samples taken from each plot and depth. Once in the laboratory, the soil was air-dried and ground to pass a 2-mm sieve. For soil dry bulk density determination, by the core method (Grossman and Reinsch, 2002), stainless steel cylinders (height 51 mm, diameter 50 mm, volume 100 cm^3) were used for undisturbed soil sampling. Four soil cores were taken per plot and soil depth.

A 5 g subsample was used to determine total SOC content by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). The carbon content of the particulate organic matter (POM-C) and the mineral associated organic matter (Min-C) were separated using a physical fractionation method adapted from Cambardella and Elliot (1992). Twenty-gram subsamples of soil from each depth, plot and site were dispersed in 100 ml of 5 g L^{-1} of sodium hexametaphosphate during 15 h on a reciprocal shaker. Then, the samples were passed through a 53-µm sieve to separate the POM-C and the Min-C. The material passing through the sieve (Min-C) was collected in aluminium pans and oven dried at 50 ºC overnight. The wet oxidation method of Walkley and Black was then used to measure the C concentration in the Min-C fraction. The total SOC and Min-C contents were expressed on a mass per unit area basis by multiplying the C concentration values obtained from the oxidation method by the corresponding soil bulk density values. The POM-C content was determined as:

POM–C content = Total SOC content – Mineral associated-C content [1]

Data were analyzed using the SAS statistical package (SAS Institute, 1990). To compare the effects of tillage treatments, analysis of variance (ANOVA) for a randomized block design was made. Differences between means were tested with Duncan's multiple range test.

RESULTS AND DISCUSSION

Soil bulk density

Soil bulk density ranged from 1.28 to 1.55 Mg m^{-3}, from 1.25 to 1.67 Mg m^{-3}, from 1.15 to 1.48 Mg m^{-3} and from 1.19 to 1.40 at AG, SV, PN-CC and PN-CF, respectively (Fig. 1). At all four fields, it was observed a general increase in soil bulk density from the 0-5 cm layer to the 5-10 cm soil layer, especially under NT (Fig. 1).

At AG, PN-CC and PN-CF the highest soil bulk density corresponded to the NT treatment, especially in the first 20 cm. However, at SV differences among tillage treatments were only found in the 5-10 cm soil layer, where greater soil bulk density was measured under NT and RT than under CT and ST (Fig. 1). Several studies have observed greater soil bulk density under NT systems (Rhoton et al., 1993; Wander and Bollero, 1999; Lampurlanés and Cantero-Martínez, 2003).

Total SOC

In the 0 to 40 cm soil depth, total SOC concentration values ranged from 5.3 to 22.5 g kg $^{-1}$ at SV, from 3.7 to 18.8 g kg $^{-1}$ at AG, from 8.0 to 13.7 g kg $^{-1}$ at PN-CC and from 7.3 to 11.6 g kg $^{-1}$ at PN-CF (Fig. 2). At the soil surface (0-5 cm depth), a significantly greater SOC concentration was measured under NT in all the experimental sites. On the contrary, below 10 cm depth, the SOC concentration under this tillage treatment was similar (PN) or lower (SV and AG) than the measured in the other tillage treatments. Thus, at SV and AG, from the 0-5 to the 10-20 soil depth SOC concentration under NT decreased more than a 60%. At PN-CC and PN-CF, this reduction was close to a 40% (Fig. 2). In general, in the first 10 cm depth, the lowest SOC concentration corresponded to CT but at deeper soil layers CT had the greatest SOC concentration in all the sites (Fig. 2). Several studies have reported greater SOC at the soil surface under NT than under other tillage systems (Potter et al., 1997; Deen and Kataki, 2003; Puget and Lal, 2005). In other similar experiments carried out in semiarid Spain, SOC accumulation at the soil surface has also been observed when soil management shifted from conventional tillage to conservation tillage (Hernanz et al., 2002; Moreno et al., 2006). In NT systems, crop residues are left on the soil surface implying a much slower crop residue incorporation and decomposition when compared with tilled systems in which crop residues are mechanically incorporated into the soil. This slower decomposition of crop residues under NT leads to the accumulation of SOC in the upper soil layers (Reicosky et al., 1995).

The accumulation of SOC at the soil surface has been observed as a promising soil quality indicator (Franzluebbers, 2002). This author developed the so-called stratification ratio, defined as, the proportion of SOC at the soil surface in relation with the SOC at deeper soil layers. This ratio permits an easy comparison between tillage treatments. Franzluebbers (2002) concluded that SOC stratification ratios higher than 2 would be an indication that soil quality might be improving. In our experiment, NT showed the highest stratification ratio in all the experimental sites. The greatest stratification ratios were measured at SV, with values equal or greater than 2 in all the tillage treatments (Table 2). In contrast, at Peñaflor (PN-CC and PN-CF), there were observed the smallest ratios with values lower than 2 in all the tillage treatments. At AG, the CT treatment showed a SOC stratification ratio lower than 2 whereas NT showed a ratio greater than 5 (Table 2). Greater SOC stratification ratios imply better soil conditions for crop growth due to the positive effects of SOM on soil surface processes such as erosion control, water infiltration and nutrient conservation (Franzluebbers, 2002).

When the whole soil profile (0-40 cm) was considered, at AG and PN-CF similar SOC content was measured among tillage treatments (Table 3). At PN-CC a significantly greater SOC content was measured under NT than under CT and RT over the whole soil profile (Table 3). On the contrary, the SOC value at SV was significant greater under the tilled treatments (CT, RT and ST) than under NT (Table 3). Therefore, in sites where the CT treatment consisted of moldboard plowing (AG and PN) similar or greater SOC content in the whole soil profile was measured in NT compared with CT. However, at SV, where CT consisted of subsoil plowing (without soil profile inversion), the SOC content was significantly higher in CT compared with NT. This fact would indicate that intensive tillage with moldboard plowing induces a greater disturbance than subsoil tillage leading to greater SOM decomposition. Moldboard plowing compared with subsoil tillage caused deeper distribution of SOM along the soil profile, greater soil microclimate conditions modification (e.g. soil temperature, aeration and water content) and aggregate breakage releasing aggregate-protected SOM susceptible to microbial attack (Paustian et al., 1997; Peterson et al., 1998).

Since no differences in crop biomass existed among tillage treatments, differences in SOC were only the result of the effect of tillage on SOC decomposition. In the SV and AG sites, Cantero-Martínez et al. (2007) compiled crop biomass values since the beginning of the experiments. These authors observed similar averages among tillage treatments with values ranging from 9034 to 10681 kg ha^{-1} and from 19568 to 22657 kg ha^{-1} at AG and SV, respectively.

In our study, the intensification of the cropping systems did not significantly increase SOC content (Table 3). Moret et al. (2007) in the same experimental plots and during three cropping seasons (2000-2001-2002) only measured less than 10% more above-ground crop biomass in the continuous cropping system than in the barley-fallow rotation. Therefore, low biomass production among cropping systems led to similar SOC contents

Soil organic matter fractions

The SOM fractions (POM-C and Min-C) were only determined at SV, AG and PN-CC. Following the same trend observed with the total SOC concentration, the greatest POM-C was measured under NT at the soil surface (0-5 cm) (Table 4). At this depth, POM-C ranged from 0.8 (in CT at PN-CC) to 6.4 Mg C ha^{-1} (in NT at AG) (Table 4). These findings are in agreement with other studies measuring greater POM-C under NT than under CT at soil surface (Wander et al., 1998; Hussain et al., 1999; Bayer et al., 2006; Sainju et al., 2006). However, below 10 cm depth, in general, significantly greater POM-C was observed under CT (Table 4). Mrabet et al. (2001), in semiarid Morocco, measured slightly greater POM-C under CT than under NT at 7-20 cm soil depth.

The POM fraction has been defined as a labile SOM pool mainly consisting of plant residues partially decomposed and not associated with soil minerals (Cambardella and Elliot, 1992; Six et al., 2002). In our study, as we suggested with the total SOC, the lack of soil disturbance under NT produced an accumulation of POM at the surface soil. However, when intensive tillage was applied (e.g., CT) two effects could have taken place: firstly, a redistribution of POM along the soil profile, which explains the increase in POM under CT compared with NT and, secondly, a faster mineralization of POM at the topsoil due to better soil microclimatic conditions for microbial activity.

Over the whole soil profile (0-40 cm depth), similar POM-C was measured among tillage treatments in all the three sites (Table 4). At SV the greatest POM-C was measured under the CT treatment and the lowest under NT. However, at AG and PN-CC, where the CT treatment consisted of moldboard plowing, it was observed the opposite trend. Therefore, as suggested before, in the sites where CT consisted in moulboard plowing, soil profile inversion accelerated POM decomposition. However, in the SV site, the pass of a subsoil tillage as CT implied lower tillage disturbance compared with moldboard plowing and also lower bulk density in soil depth compared with NT. We hypothesized that this fact resulted in better conditions for root development compared with NT leading to greater root biomass in deep soil layers and thus greater POM-C accumulation in CT compared with NT in the SV site.

Regarding the mineral-associated C (Min-C) content, this carbon fraction was significantly greater under NT than under the other tillage treatments at the soil surface (0-5 cm depth) (Table 5). The Min-C resulted from the decomposition of the POM and the subsequent protection by silt and clay particles (Denef et al., 2004). Beare et al. (1994) found greater Min-C in soil aggregates of NT compared with CT in soil surface (0-5 cm). They concluded that besides POM other soil C fractions were lost under CT compared to NT. Also, Cambardella and Elliot (1992) found greater Min-C under NT compared with a bare fallow treatment tilled with moldboard plowing from 0- to 20-cm depth. Therefore, in our experiment, in soil surface (0-5 cm) NT compared with CT is not only sequestering SOC as POM-C but also as Min-C. Due to the more humified and recalcitrance nature of the Min-C fraction, greater SOC accumulation as Min-C implies the stabilization of SOC in the long-term in NT compared with CT.

SUMMARY AND CONCLUSIONS

The NT system increased the SOC content only at the soil surface (0-10 cm depth) due to the accumulation of crop residues. However, when deeper soil layers were considered the amount of SOC accumulated was greater under CT than under NT due to the placement of crop residues all along the soil profile. When the whole soil profile (0-40 cm depth) was considered similar o slightly greater SOC content was measured under NT than under CT with the exception of the SV site where CT consisted in a subsoil tillage instead of moldboard plowing. Therefore, deep vertical subsoiling accumulated greater SOC in the whole soil profile as compared with NT.

The POM pool, formed mainly by crop residues under different decomposition stages increased on the soil surface under NT due to the accumulation of crop residues. At the same time, on soil surface the Min-C fraction formed from the decomposition of the POM-C was also greater under NT compared with CT.

In semiarid agroecosystems of the Ebro valley, enhancing soil organic carbon contents is a key factor to improve soil quality and productivity. The adoption of conservation tillage, especially NT, has a potential effect to sequester SOC in the dryland soils of this Mediterranean region. Nevertheless, after more than 15 years of tillage testing, this beneficial effect of NT on SOC sequestration has been only observed in the first 10 cm of soil.

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Table 1. Site and soil (Ap horizon) characteristics.

Climate and soil characteristics	Study sites		
	Selvanera	Agramunt	Peñaflor
Latitude	41º 50’N	41º 48’N	41º 44’N
Longitude	1º 17’E	1º 07’E	0º 46’W
Elevation (m)	475	330	270
Mean annual air temperature (ºC)	13.9	14.2	14.5
Mean annual precipitation (mm)	475	430	390
Soil classification †	Xerocrept Fluventic	Xerofluvent Typic	Xerollic Calciorthid
Ap horizon depth (cm)	37	28	30
pH (H_2O, 1:2.5)	8.3	8.5	8.23
$EC_{1:5}$ (dS m^{-1})	0.16	0.15	0.29
Water retention (g g^{-1})			
-33 kPa	0.16	0.16	0.20
-1500 kPa	0.04	0.05	0.11
Particle size distribution (%)			
Sand (2000-50 µm)	36.5	30.1	32.4
Silt (50-2 µm)	46.4	51.9	45.5
Clay (< 2 µm)	17.1	17.9	22.2
	Loam	Silt loam	Loam

† USDA classification (Soil Survey Staff, 1975).

Table 2. Soil organic carbon (SOC) stratification ratio (0-5:30-40) at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) and in a barley-fallow rotation (PN-CF) for different tillage treatments (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage).

Sites	Tillage treatments			
	NT	RT	ST	CT
SV	4.2a†	3.1b	2.7b	2.0c
AG	5.1a	3.0b	2.6bc	1.3c
PN-CC	1.7a‡	1.2b	-	1.0b
PN-CF	1.6a	1.3b	-	1.0c

†Within each site and depth values followed by a different letter are significantly different at *P* <0.05.

‡* indicate significant differences between PN-CC and PN-CF within the same tillage treatment and soil depth (*P*<0.05).

Table 3. Cumulative soil organic carbon (SOC) content at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) and in a barley-fallow rotation (PN-CF) under different tillage treatments (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage).

Soil depth (cm)	Cumulative SOC (Mg ha^{-1})							
	AG				SV			
	NT	RT	ST	CT	NT	RT	ST	CT
0-5	12.8a†	9.1b	7.7c	5.6d	14.5a	13.6a	11.4b	10.3b
0-10	22.4a	18.0b	15.2c	11.6d	23.9ab	25.7a	21.8b	20.8b
0-20	33.2a	30.5ab	28.0b	23.7c	36.9a	39.9a	38.3a	37.4a
0-30	41.1a	39.5a	37.4a	36.7a	46.6b	50.6a	50.7a	51.1a
0-40	46.8a	46.2a	44.1a	46.5a	55.4b	61.0a	61.6a	63.1a
	PN-CC				PN-CF			
	NT	RT	CT		NT	RT	CT	
0-5	9.2a‡	6.0b	5.4b		7.5a	5.6b	4.9b	
0-10	16.6a	12.4b	11.2b		13.9a	11.5b	10.0c	
0-20	28.6a	24.7b	23.0b		24.4a	21.9b	20.9b	
0-30	39.5a	35.9ab	34.9b		34.5a	32.2b	32.0b	
0-40	50.5a	47.4b	47.5b		44.4a	42.0a	43.6a	

†Within each site and depth values followed by a different letter are significantly different at *P* <0.05.

‡* indicate significant differences between PN-CC and PN-CF within the same tillage treatment and soil depth (*P*<0.05).

Table 4. Distribution of particulate organic matter C (POM-C) content in the plow layer (0-40 cm depth) at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) as affected by tillage (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage).

Soil depth (cm)	POM-C (Mg ha^{-1})										
	AG				SV				PN-CC		
	NT	RT	ST	CT	NT	RT	ST	CT	NT	RT	CT
0-5	6.4a†	3.5b	4.0b	1.7c	5.8a	5.1a	4.3a	4.1a	2.9a	1.0b	0.8b
5-10	4.0a	3.5ab	2.7bc	1.9c	1.7b	3.6a	3.5a	3.3a	1.2a	1.0a	0.5a
10-20	3.0b	3.9a	4.0a	4.1a	1.3c	1.1c	2.9b	3.7a	0.8b	1.3ab	1.8a
20-30	2.8ab	1.8b	2.1b	5.0a	1.5b	1.8b	2.4b	3.5a	2.5a	2.3a	1.1b
30-40	1.6ab	1.0b	1.2b	2.7a	1.2b	0.8b	1.9a	2.3a	0.7b	0.5b	1.5a
0-40	17.9a	13.8a	14.0a	15.4a	11.5a	12.5a	14.9a	17.0a	8.2a	6.0a	5.7a

†Within each site and depth values followed by a different letter are significantly different at *P* <0.05.

Table 5. Distribution of mineral-associated C (min-C) content in the plow layer (0-40 cm depth) at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) as affected by tillage (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage).

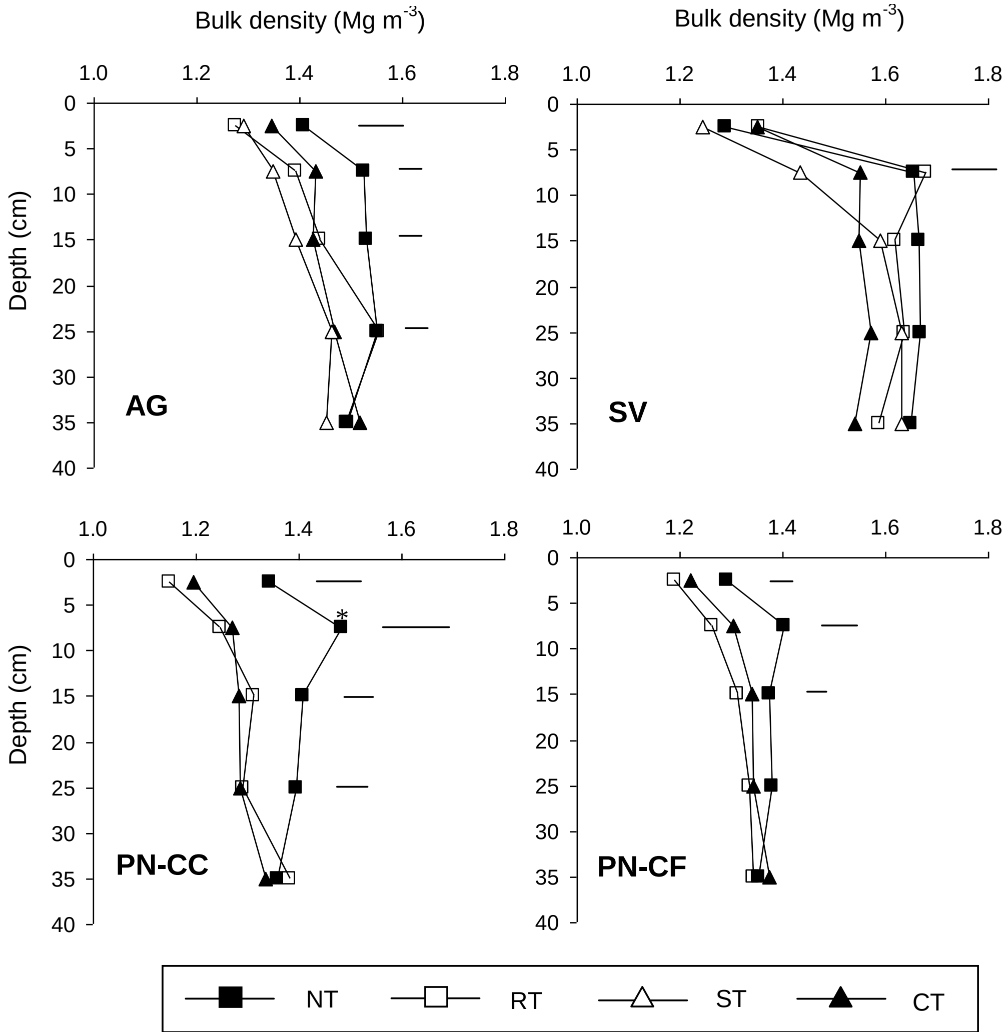
Soil depth (cm)	Min-C (Mg ha^{-1})										
	AG				SV				PN-CC		
	NT	RT	ST	CT	NT	RT	ST	CT	NT	RT	CT
0-5	6.3a†	5.6a	3.6b	3.9b	8.6a	8.5a	7.1b	6.3b	6.3a	5.0b	4.6b
5-10	5.6a	5.4a	4.8a	4.1a	7.7a	8.6a	6.9a	7.2a	6.1a	5.5b	5.3b
10-20	7.8a	8.6a	8.8a	8.1a	11.7a	12.9a	13.7a	12.3a	11.2a	11.0a	10.0a
20-30	5.1b	7.1ab	7.3ab	8.0a	8.8a	9.0a	11.0a	10.2a	8.3b	9.3b	10.8a
30-40	4.0b	5.8ab	5.5ab	7.1a	7.5b	9.6a	9.8a	9.7a	10.2b	11.3a	11.1a
0-40	28.8a	32.4a	30.0a	31.2a	44.5a	48.6a	48.4a	46.2a	42.2a	42.1a	41.8a

†Within each site and depth values followed by a different letter are significantly different at *P* <0.05.

FIGURE CAPTIONS

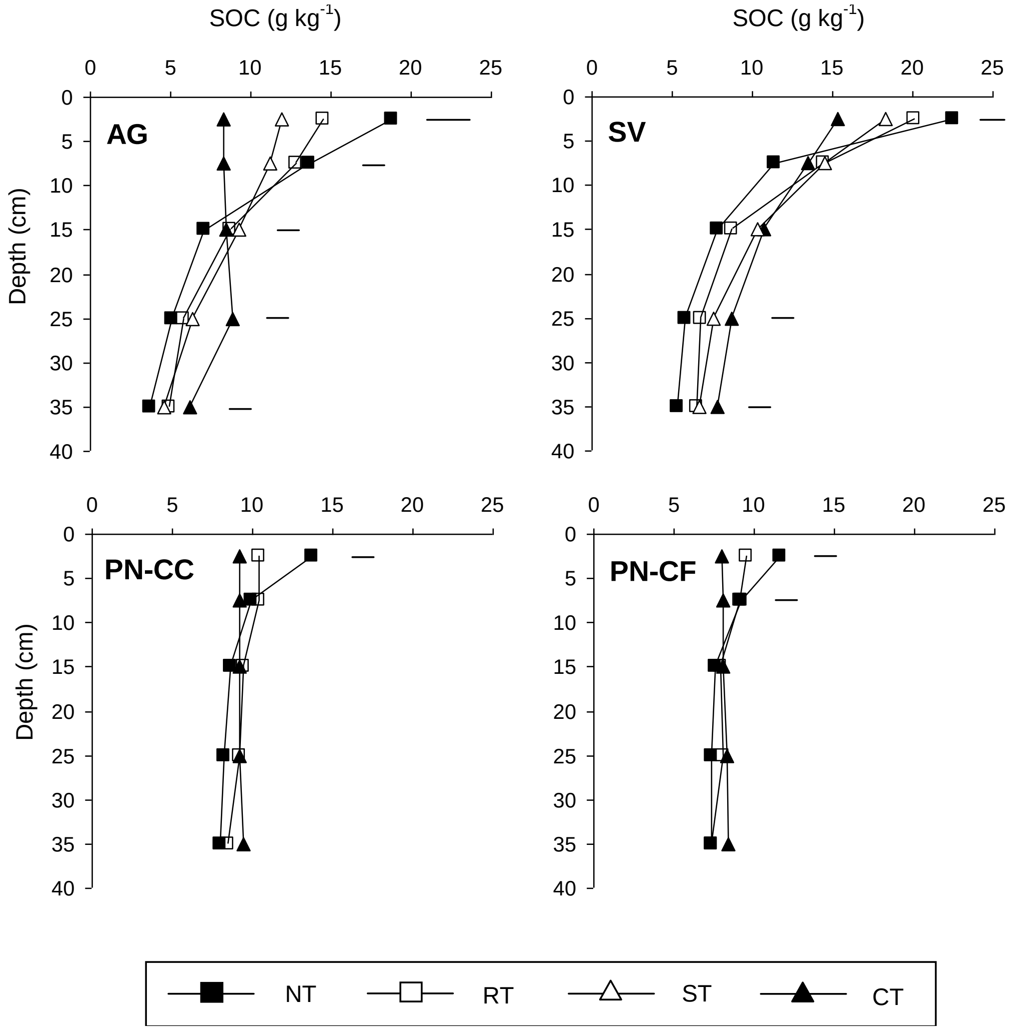
Fig. 1. Soil bulk density profile at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) and in a barley-fallow rotation (PN-CF) as affected by tillage (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage). Bars represent LSD (*P*<0.05) for comparison among tillage treatments at the same depth, where significant differences were found. * Indicate significant differences between PN-CC and PN-CF within the same tillage treatment and soil depth (*P*<0.05).

Fig. 2. Vertical distribution of the soil organic carbon (SOC) concentration at Agramunt (AG), Selvanera (SV) and Peñaflor in a continuous barley cropping system (PN-CC) and in a barley-fallow rotation (PN-CF) as affected by tillage (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage). Bars represent LSD (*P*<0.05) for comparison among tillage treatments at the same depth, where significant differences were found. * Indicate significant differences between PN-CC and PN-CF within the same tillage treatment and soil depth (*P*<0.05).



Bulk density (Mg m-3)
Bulk density (Mg m-3)
1.0
1.2
1.4
1.6
1.8
Depth (cm)
0
5
10
15
20
25
30
35
40
AG
SV
PN-CC
PN-CF
*
NT
RT
ST
CT

Fig.1.



SOC (g kg-1)
SOC (g kg-1)
0
5
10
15
20
25
Depth (cm)
0
5
10
15
20
25
30
35
40
AG
SV
PN-CC
PN-CF
NT
RT
ST
CT

Fig.2.