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Carbon losses by tillage under semi-arid Mediterranean rainfed agriculture (SW Spain)

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Abstract

Conservation tillage has been promoted as a solution to counteract constraints caused by intensive agriculture. In this work the effects of two conservation tillage systems, reduced tillage (RT) and no-tillage (NT) were compared to the traditional tillage (TT) in a long- (15 years, RT) and short-term experiment (3 years, NT). Both experiments were carried out under semi-arid, rainfed agriculture of Mediterranean SW Spain. Tillage caused a sharp increase in soil CO_2 emissions immediately after tillage implementation, with a maximum value of 6.24 g CO_2 m^{-2} h^{-1} under long-term TT treatment. Along the year, losses of carbon through CO_2 emission were higher (905 and 801 g C m^{-2} $year^{-1}$ for the long- and short-term TT treatments respectively), than those estimated for conservation systems (764 and 718 g C m^{-2} $year^{-1}$ for RT and NT respectively). Conservation tillage systems accumulated more soil organic carbon (SOC) in surface than the corresponding TT treatments (1.24 and 1.17 times greater for RT and NT, respectively, at 0-10 cm depth). Despite SOC accumulation would be moderate other variables related to soil quality, such as dehydrogenase activity, can be consistently increased in soil surface in conservation tillage, as the stratification ratio values indicated. Crop yields in conservation tillage were similar to or even greater than those obtained in TT. The agricultural (soil quality) and environmental (less CO_2 emission to the atmosphere) benefits derived from conservation tillage make this system recommendable for semi-arid Mediterranean rainfed agriculture.

Additional key words: CO_2 fluxes, conservation tillage, crop yields, soil quality.

Resumen

Pérdidas de carbono debidas a laboreo bajo agricultura mediterránea de secano (SE España)

El laboreo de conservación representa una solución para contrarrestar las limitaciones de la agricultura intensiva. En este trabajo se comparó el efecto de dos sistemas de laboreo de conservación, laboreo reducido (RT) y no-laboreo (NT), con laboreo tradicional (TT) en un experimento de larga duración (15 años, RT) y otro de corta duración (3 años, NT), bajo condiciones semi-áridas mediterráneas de secano (SE España). El laboreo aumentó las emisiones de CO_2 en el momento de las labores, con un valor máximo de 6,24 g CO_2 m^{-2} h^{-1} bajo el tratamiento TT del experimento de larga duración. A lo largo del año, las pérdidas de carbono CO_2 fueron mayores (905 y 801 g C m^{-2} $año^{-1}$ para los tratamientos TT de larga y corta duración, respectivamente) que las estimadas bajo laboreo de conservación (764 y 718 g C m^{-2} $año^{-1}$ para RT y NT, respectivamente). Los sistemas de laboreo de conservación acumularon más carbono orgánico total (SOC) en superficie que sus correspondientes tratamientos TT (1,24 y 1,17 veces mayor para RT y NT, respectivamente, profundidad 0-10 cm). A pesar de la moderada acumulación de SOC, otras variables de calidad de suelo, como la actividad deshidrogenasa, pueden aumentar considerablemente en superficie bajo laboreo de conservación, así como valores de razón de estratificación. La producción del cultivo en laboreo de conservación fue similar o mayor que en TT. Los beneficios agrícolas del laboreo de conservación (calidad del suelo) y medioambientales (menores emisiones de CO_2 a la atmósfera), hacen a este sistema recomendable para condiciones mediterráneas semi-áridas de secano.

Palabras clave adicionales: calidad del suelo, flujo de CO_2, laboreo de conservación; rendimiento de cultivo.

Abbreviations used: CT (conservation tillage), MBC (microbial biomass carbon), NT (no tillage), RT (reduced tillage), SOC (soil organic carbon), SR (stratification ratio), TT (traditional tillage), T (temperature), W (water content).

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Introduction

Intensive agriculture frequently causes important losses of soil carbon. Losses in soil organic carbon (SOC) are associated with reductions in soil productivity and with increases in CO_2 emissions from soil to the atmosphere (Lal *et al*., 1989; Bauer *et al*., 2006; Ventera *et al*., 2006; Conant *et al*., 2007). Gas exchange between soils and the atmosphere may be an important contributing factor to global change due to increasing release of greenhouse gases (Ball *et al*., 1999).

Reduced tillage agriculture (conservation tillage, CT) has been promoted since approximately 1960 as a means of counteract all these constraints (Gajri *et al*., 2002); apart from the benefits on soil quality and crop performance, especially under semi-arid conditions (Moreno *et al*., 1997; Franzluebbers, 2004, Muñoz *et al*., 2007), there are studies that suggest that the greenhouse gases contribution of agriculture can be mitigated by widespread adoption of conservation tillage (Lal, 1997, 2000). To be considering CT, any tillage and planting system must maintain at least 30% of the soil surface covered by residue after planting to reduce soil erosion by water. Where soil erosion by wind is a primary concern, the system must maintain a 1.1 Mg ha^{-1} flat small grain residue equivalent on the surface during the critical wind erosion period (Gajri *et al*., 2002). Numerous competing uses of crop residues under arid and semi-arid conditions (Bationo *et al*., 2007) can be a constraint for CT establishment.

The effectiveness of CT in mitigating the greenhouse gas impact of individual agro-ecosystems can vary substantially. Studies under different conditions are required to assess the broader of the greenhouse gases impacts of CT (Ventera *et al*., 2006). Tillage often increases short-term CO_2 flux from the soil due to a rapid physical release of CO_2 trapped in the soil air spaces (Bauer *et al*., 2006; Reicosky and Archer, 2007; Álvaro-Fuentes *et al*., 2008). This rapid flux of CO_2 is influenced by the tillage system and the amount of soil disturbance (Reicosky and Archer, 2007).

Microbial and root activity together constitute soil respiration. Root/rhizosphere respiration can account for as little as 10% to greater than 90% of total "in situ" soil respiration depending on vegetation type and season of the year (Hanson *et al*., 2000). However, with regard to the greenhouse effect, only soil organic matter (SOM)-derived CO_2 contributes to changes in atmospheric CO_2 concentration. Long residence time of SOM results in very slow turnover rates relative to other less-recalcitrant respiratory substrates and implies that SOM is the only C pool that can be a real, long-term sink for C in soils. Despite long residence times in steady state, this very large reservoir of carbon in SOM makes this pool a very large potential source of CO_2 if decomposition exceeds humification (Kuzyakov, 2006).

These processes are very influenced by the local conditions and management. Franzluebbers (2004) reported that low benefit of no tillage on SOC storage could be expected in dry, cold regions, in which low precipitation would limit C fixation by plants and decomposition even when crop residues are mixed with soil by tillage. Carbon storage under CT might also be limited in wet, hot regions, where abundant precipitation combined with warm temperature would lead to a rapid decomposition of surface-placed residues. Thus, long-term tillage studies under different soil and climatic conditions are needed to understand the dynamic of soil organic matter under the wide diversity of environments in the world (Franzluebbers, 2004).

For most soils, the potential of C sequestration upon conversion of plow tillage to no-tillage farming with the use of crop residue mulch and other recommended practices is 0.6 - 1.2 Pg C $year^{-1}$ (Lal, 2004). The important ecological and agronomic benefits that can derive from these practices could be limited not only by plowing but also by using crop residues for biofuel production (Lal and Pimentel, 2007). There is at present an imperious necessity of using cellulosic biomass instead of crop grain for producing biofuel (mainly ethanol) and, currently, few sources are supposed to be available in sufficient quantity and quality to support development of an economically sized processing facility, except crop residues (Wilhelm *et al*., 2004).

The objective of this work was to study the effect of tillage practices on the short- and long-term CO_2 emissions and SOC accumulation under Mediterranean, semi-arid conditions. As pointed out by Franzluebbers (2004), soils with low inherent levels of organic matter, frequent under semi-arid conditions, could be the most functionally improved with CT, despite modest or no change in total standing stock of SOC within the rooting zone. Two experiments, comparing traditional and reduced tillage in a long-term experiment (15 year old) and traditional and no-tillage in a short-term experiment (3 years old) were conducted. Flux of CO_2, total SOC contents and selected biochemical soil properties at different soil depths are compared in the different tillage systems in both experiments.

Material and methods

Study area: climatological characteristics and tillage treatments

Field experiments were carried out on a sandy clay loam soil (Xerofluvent, USDA, 1996) at the experimental farm of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC) located 13 km southwest of the city of Seville (Spain). Soil pH is around 8 (Table 1) and the water retention (g g^{-1}) 0.23 at -33 kPa and 0.12 at -1500 kPa. Climate of the zone is typically Mediterranean, with mild rainy winters (484 mm mean rainfall, average of 1971-2004) and very hot, dry summers (average annual evapotranspiration is 1139 mm). Rainfall in the hydrological year September 2006 - August 2007 was 649 mm, greater than the mean and well distributed for crops. The mean annual daily temperature is around 17ºC, with maximum and minimum temperatures in July (33.5ºC) and in January (5.2ºC), respectively. This zone has an annual average of around 2900 hours of sunshine with maximum values of solar radiation exceeding 1,000 W m^{-2}. Environmental data were obtained from the weather station located at the experimental farm (200 m far from the experimental plots).

A homogeneous area of about 2500 m^2 was selected in 1991 to establish the experimental plots, which were cropped with wheat under rainfed conditions. After harvesting wheat (*Triticum aestivum* L.) (June 1992), two treatments were established: i) traditional tillage, TT_{15}, consisted of mouldboard ploughing (25-30 cm depth), after burning the straw of the preceding crop (straw burning was suppressed since 2003), and ii) conservation tillage (reduced tillage), RT_{15}, characterized by not using mouldboard ploughing, by reduction of the number of tillage operations (only chisel at 25 cm depth), spraying the plot with pre-emergence herbicides and leaving the crop residues on the surface (for more details see Moreno *et al*., 1997). Wheat-sunflower (*Helianthus annuus* L.) crop rotation was established for both treatments. In 2005 a fodder pea crop (*Pisum arvense* L.) was included in the rotation, when two additional tillage treatments were established: traditional tillage, TT_3, as described above, and conservation tillage (no-tillage, NT_3). These additional treatments were established in an adjacent area. This zone had been cultivated using traditional tillage (mouldboard ploughing) and alternating wheat, barley and cotton the last 10 years.

No-tillage involved not using mouldboard ploughing, leaving the crop residues on the surface, spraying the plots with pre-emergence herbicides and drilling with a single-disc drill which created seeding slits about 5 cm deep. Three replicates per treatment were distributed in a completely randomised design for each experiment. Main results in this study correspond to the period September 2006 (after harvesting the wheat crop) to November 2007. Data of other years were included when convenient.

As pointed out before, CT has been defined as any tillage system that maintains at least 30% of the soil surface covered by residues of the preceding crops. The percentage of soil surface covered by residue in the RT and NT treatments were determined by stretching a 10 m cord (marked every 10 cm) diagonally across several rows (Plaster, 1992) and counting the number of marks touching a piece of crop residue. This percentage was always greater than 30 (in most cases it was greater than 50%).

Soil CO_2 flux measurements

Soil CO_2 fluxes were measured by attaching a 6400-09 chamber with an area of 71.6 cm^2 to a 6400 LICOR gas-exchange system (LI-COR, Environmental Division, Lincoln, NE, USA). The system was provided

Table 1. General characteristics of the soils used for the long- and short-term experiments

	Depth (cm)	pH	SOC[a] (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
Long-term	0-10	8.0	8.3	566	186	248
	10-30	7.9	7.1	582	176	242
Short-term	0-10	8.0	8.5	490	240	270
	10-30	7.6	6.9	510	235	255

[a] Soil organic carbon

with a thermocouple probe to measure soil temperature. To minimise soil surface disturbances, the chamber was mounted on PVC soil collars sharpened at the bottom and inserted into the soil to about 3.8 cm. To prevent an overestimation of soil fluxes, typically observed immediately after the collars have been installed, the latter were inserted some days before the measurements were made. Furthermore, 6 collars were placed at random locations in each treatment in order to describe statistically the spatial variability. Only one measurement was made on each collar on each observation day. The sampling time in each collar varied in accordance with the CO_2 concentrations inside the chamber, ranging from 3 to 8 min. All the observations were performed during daylight hours, beginning at variable times ranging from 10:30 to 13:00 h. Measurements made at this time of the day were assumed to represent the average flux of the day (Kessavalou *et al.*, 1998; Álvaro-Fuentes *et al.*, 2007). Two sets of measurements were carried out: i) monthly during the hydrological year 2006-2007 (from October 2006, after the wheat crop, until June 2007, at the end of the sunflower crop), and ii) short-term measurements following the agricultural practices for sunflower sowing in both experiments, which involved: mouldboard ploughing in both TT_{15} and TT_3 treatments, chiselling at 25 cm deep in RT_{15} and drilling in NT_3. Measurements of CO_2 were performed on previous day (-24 h, all treatments), immediately after (0 h), and 3, 6 and 24 h after these practices.

For the short-term measures following the agricultural practices (-24, 0, 3, 6 and 24 h) each flux reading was taken 3 min after the PVC cylinder was inserted into the soil in order to avoid possible unrealistic values caused by the disturbance produced after placing it into the soil (Álvaro-Fuentes *et al.*, 2007). In this case, three replicates per treatment were taken.

Cumulative soil CO_2 emissions during the whole period were calculated using a numerical integration (trapezoid rule), assuming that this procedure may be subject to error because long time between sampling dates (Reicosky, 1997; Álvaro-Fuentes *et al.*, 2007). However, the method allows the comparison between tillage treatments providing a single value of CO_2 emitted during a particular period of time.

Soil temperature was measured with a hand-held probe inserted 10 cm into the soil 10 cm away from the chamber. The volumetric soil water content was also recorded monthly in those samples taken for the dehydrogenase activity determination.

Soil sampling and chemical analysis

Soil sampling for chemical and biological properties was carried out monthly in all treatments at the depths of 0-5, 5-10 and 10-25 cm (six samples per each depth and treatment). For the experiment following the agricultural practices, three samples per treatment were taken at 0-25 cm depth. Field moist soil was sieved (2 mm) and divided into two subsamples. One was immediately stored at 4ºC in plastic bags loosely tied to ensure sufficient aeration and to prevent moisture loss until assaying of microbiological and enzymatic activities. The other was air-dried for chemical analysis, after the determination of the gravimetric soil water content in a soil sub-sample.

The total soil organic carbon content (SOC) was determined according to Walkley and Black (1934). The microbial biomass carbon (MBC) content was determined by the chloroform fumigation-extraction method modified by Gregorich *et al.* (1990). Dehydrogenase activity was determined by the method of Trevors (1984) and β-glucosidase activity as indicated by Tabatabai (1982).

Statistical analyses

The differences between each set values of each paired treatments RT_{15} / TT_{15}, and NT_3 / TT_3 were assessed by the Student t-test. When temporal variation was found to be significant, post hoc multiple comparison of mean values by Tukey´s test was used. Data normality was tested prior to analysis; and when necessary, variables were transformed logarithmically. If after transformation, the data did not have a normal distribution, we used the non-parametric Mann-Whitney U test for comparison of mean values. All statistical analyses were carried out with the program SPSS 11.5 for Windows.

Results

Soil respiration

Data from short-term CO_2 fluxes reveal significant increases of CO_2 immediately after tillage in both TT treatments, respect to the corresponding RT_{15} and NT_3 treatments (Fig. 1). The difference between TT_3 treatment (4.38 g CO_2 m^{-2} h^{-1}) and NT_3 (0.27 g CO_2 m^{-2} h^{-1}) was greater (x 16) than that between TT_{15} (6.21 g CO_2

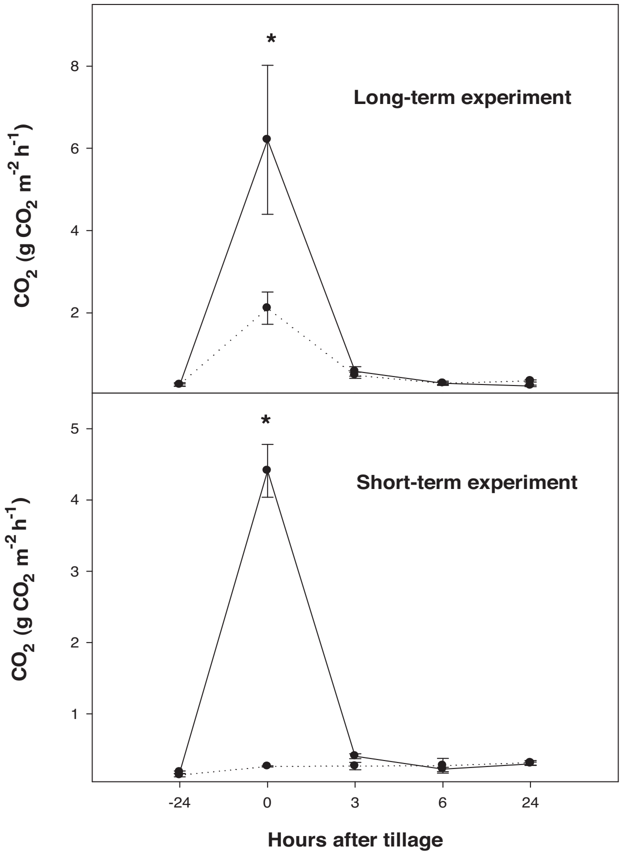

Figure 1. Short-term soil CO_2 fluxes following tillage operations in the long- and the short-term experiments. Mean values ± standard errors (N=3; for each experiment, dotted lines represent the conservation tillage treatment: RT_{15} (reduced tillage), long-term experiment and NT_3 (no-tillage), short-term experiment. Solid lines are used for TT_{15} and TT_3 (traditional tillage treatments), February 2007. For paired means significant differences are indicated by an asterisk (p < 0.05).

m^{-2} h^{-1}) and RT_{15} (2.11 g CO_2 m^{-2} h^{-1}) (x 3), due to absence of any tillage in NT_3. In general only a slightly, not significant increase in the values of dehydrogenase and β-glucosidase activities under TT (TT_{15} and TT_3) was recorded after 24h (Table 2).

Differences between conservation and traditional tillage treatments were not always significant due to the frequent high variability that characterizes the CO_2 fluxes measurements, although the CO_2 fluxes along the 10 month-period tended to be greater in both TT treatments respect to RT_{15} and NT_3 (Fig. 2). In the long-term experiment, the cumulative value was 1.2 fold greater in TT_{15} (34 Mg CO_2 ha^{-1} $year^{-1}$) than in RT_{15} (28 Mg ha^{-1} $year^{-1}$), which imply a flux of 6 Mg ha^{-1} $year^{-1}$ more in TT than in RT. In the short-term experiment the difference (3 Mg ha^{-1} $year^{-1}$) was 1.1 times greater in TT_3 than in NT_3. The greater difference in the first case could be due to long-term character of that experiment. The measured CO_2 fluxes would imply C losses of about 905 g C m^{-2} $year^{-1}$ (TT_{15}), 801 g C m^{-2} $year^{-1}$ (TT_3), 764 g C m^{-2} $year^{-1}$ (RT_{15}), and 718 g C m^{-2} $year^{-1}$ (NT_3). These values may be considered as conservative estimations of the true values for this variable, as it has been assumed that the measurements represent the average CO_2 flux of the day, as reported by Kessavalou *et al*. (1998).

Figure 3 shows the evolution of the CO_2 fluxes and the values of soil temperature (T) and water content (W) for each month along the study (all treatments). Increases of CO_2 fluxes were observed as T increased whereas no a clear relationship between W and CO_2 fluxes were detected (Table 3). However, the sudden decrease observed in CO_2 fluxes in June could be related to a decrease in the root activity.

Soil organic carbon and variables related to soil biology

Data of SOC at 0-5 cm and 5-10 cm depths are shown in Table 4. The accumulation of SOC at 0-10 cm depth was slightly higher for conservation tillage after 5 and 15 years of establishment.

Data of SOC, microbial soil carbon (MBC), dehydrogenase activity, and the corresponding stratification ratio (SR) values for the three soil depths analysed are shown in Fig. 4. Stratification ratios were calculated by dividing values at 0-5 cm by those at 10-25 cm. Values of SOC were greater under RT_{15} than under TT_{15} at the three soil depths, especially at surface ($p < 0.05$). The stratification ratio for SOC was close to 1.8 in RT_{15} and only 1.4 in TT_{15}, although the difference was not significant. In general, under any condition of soil and climate, high stratification ratios for this variable indicate a good quality of the soil, because ratios higher than 2 are not frequent in degraded soils (Franzluebbers, 2002). In general, greater values of MBC and dehydrogenase activity were obtained for the conservation tillage treatments (RT_{15} and NT_3), although the differences were not always significant. As a rule, values of SR for these variables were also higher for conservation tillage treatments, although dehydrogenase activity was the biochemical property that showed greater increases in conservation tillage treatments compared to traditional tillage treatments, significant ($p < 0.05$) for the short-term experiment.

Table 2. Dehydrogenase and β-glucosydase activities (25 cm depth) at different times after tillage (mean ± standard errors, N=3). Values followed by the same setter in the same column, for each enzymatic activity, do not differ significantly ($p < 0.05$)

	Time	TT_{15}	RT_{15}	NT_3	TT_3
Dehydrogenase	0 h	0.89 ± 0.36 a	1.04 ± 0.25 a	1.12 ± 0.18 a	0.91 ± 0.10 ab
(µg INTF [a] /g dry soil h^{-1})	6 h	0.94 ± 0.27 a	0.91 ± 0.11 a	0.94 ± 0.21 a	0.67 ± 0.06 a
	24 h	1.05 ± 0.15 a	1.20 ± 0.36 a	1.03 ± 0.04 a	1.11 ± 0.21 b
β-glucosidase	0 h	84.3 ± 10.5 a	90.8 ± 20.8 a	70.2 ± 2.66 a	60.6 ± 12.0 a
(mg PNF [b] /kg dry soil h^{-1})	6 h	97.6 ± 8.91 a	85.4 ± 4.79 a	49.5 ± 7.27 a	35.1 ± 3.90 a
	24 h	112 ± 20.6 a	82.1 ± 23.9 a	69.1 ± 9.41 a	64.6 ± 14.4 a

[a] INTF: iodonitrotetrazolium violet formazan. [b] PNF: *p*-nitrophenol.

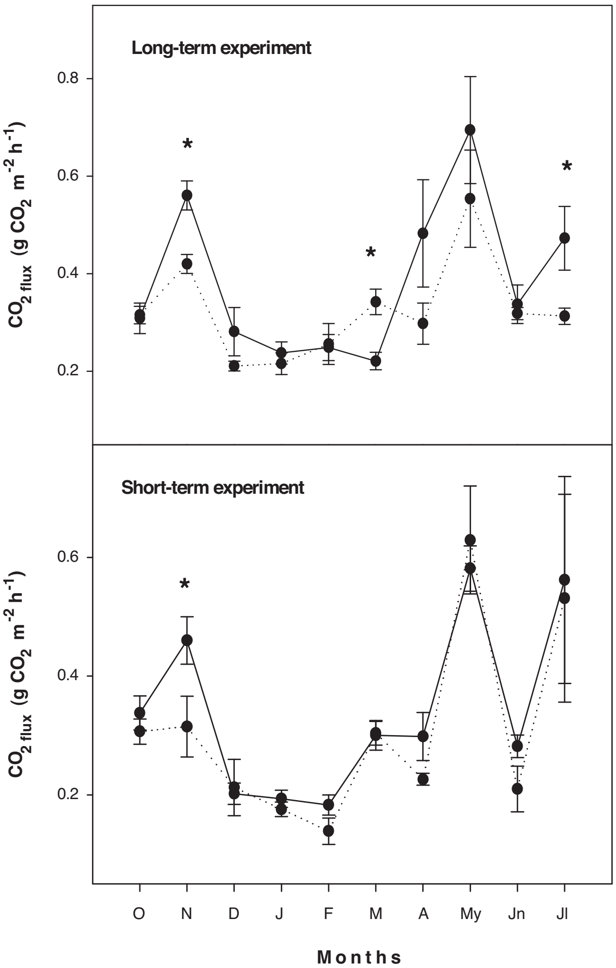

Figure 2. Monthly soil CO_2 fluxes (October 2006 - July 2007) in the long- and the short-term experiments as influenced by tillage. Mean values ± standard errors (N=6; for each experiment, dotted lines represent the conservation tillage treatment: RT_{15} (reduced tillage), long-term experiment, and NT_3 (no-tillage), short-term experiment. Solid lines are used for TT_{15} and TT_3 (traditional tillage treatments). For paired means significant differences are indicated by an asterisk ($p < 0.05$).

Crop yields

Despite soil data in this paper correspond mainly to the years 2006 and 2007, data of the crop yield in 2005 have also been reported (Table 5) attending the importance of this variable for the CT establishment under semi-arid, Mediterranean rainfed agriculture. Data show there were no significant differences between TT and CT, except in 2006 for wheat.

Discussion

Maximum fluxes following tillage in TT reflect the importance of these physical emissions when considering global landscape under conventional tillage. The duration of these immediate passive losses of CO_2 are related to different soil roughness and tillage intensity, and not to an increase of microbial activity that can start

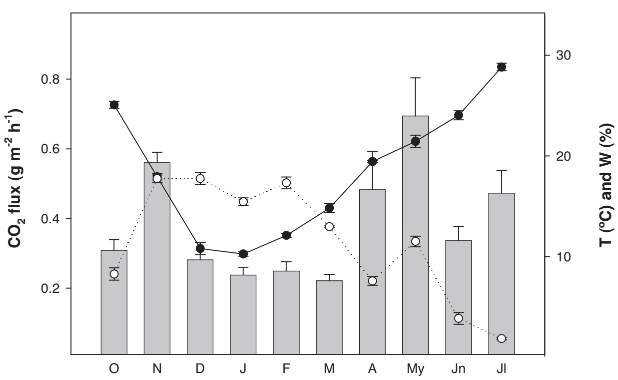

Figure 3. Soil CO_2 fluxes (columns), soil temperature (T, filled circles) and soil water content (W, open circles). All treatments; mean values ± standard errors (N=24). October 2006 - July 2007.

Table 3. Pearson' correlations between soil CO_2 fluxes and soil temperature (T) and gravimetric water content (W) per each treatment (N = 60) and all treatments (N = 240) along the sampling period (10 months).

Variables	TT_{15}	RT_{15}	TT_3	NT_3	All treatments
T	0.386**	0.305*	0.531**	0.437**	0.437**
W	- 0.190	- 0.234	- 0.319*	- 0.362**	- 0.272**

*, ** : *r* significant at 0.05 and 0.01 level of probability respectively.

further. Reicosky *et al*. (1997) did not find a clear relationship between high CO_2 fluxes after tillage and the increase of inorganic N, concluding that the increase in CO_2 fluxes after tillage was not due to the changes in microbial activity. Data of dehydrogenase and β-glucosidase activities following tillage in this study corroborate this hypothesis (Table 2).

Literature holds evidence that intensive tillage decreases SOC enhancing carbon dioxide (CO_2) losses. Studies involving various tillage methods and associated incorporation of residue in the field indicated major C losses immediately following tillage (Reicosky and Lindstrom, 1993; Reicosky *et al*., 1995; Reicosky *et al*., 1997; Álvaro-Fuentes *et al*., 2007). There are comparatively fewer studies in semi-arid, Mediterranean conditions. Results in this study agree with most data in literature, although with notable differences in the magnitude of the fluxes. Reicosky and Archer (2007) reported a rapid decline in the flux during the first few minutes with the break at 0.22 h after tillage, although the maximum initial flux for a conventional mouldboard ploughing depth of 28 cm (similar to that used in our experiments) ranged from 60 g CO_2 m^{-2} h^{-1} to 85 g CO_2 m^{-2} h^{-1}. Differences could arise, not only from the CO_2 measuring techniques, but also from the complex interaction of several physical, chemical and biological factors that control the CO_2 flux (Reicosky and Archer, 2007), which can introduce notable variations in different scenarios.

Data of this study (Fig. 1) are similar to those reported by Álvaro-Fuentes *et al*. (2007) for semiarid areas of NE Spain. These authors reported fluxes ranged from 0.17 g under reduced tillage to 6 g CO_2 m^{-2} h^{-1} under conventional tillage immediately after tillage; these data were 3 to 15 times greater than fluxes before tillage, except in no tillage in which CO_2 fluxes were low and

Table 4. Total soil organic carbon (SOC) at different depths and dates. For paired means significant differences (p<0.05) are indicated by an asterisk (November 2007). N=6.

Year	Depth (cm)	Treatment	SOC (g kg^{-1})	SOC (0-10 cm) (kg ha^{-1})
1997	0-5	RT[a]	10.7	14308
		TT[b]	8.90	11985
	5-10	RT	8.90	
		TT	8.10	
2007	0-5	RT_{15}	13.2*	15678
		TT_{15}	9.26	12646
		NT_3[c]	10.0	14020
		TT_3	9.10	11994
	5-10	RT_{15}	9.80	
		TT_{15}	7.62	
		NT_3	9.04	
		TT_3	7.60	

[a] RT: reduced tillage. [b] TT: traditional tillage. [c] NT: no-tillage.

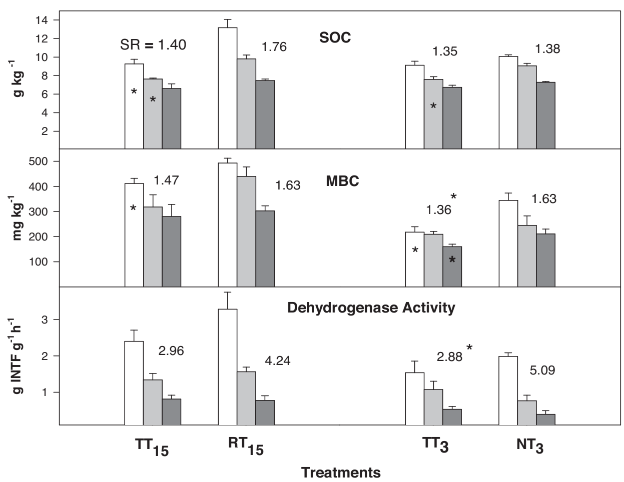

Figure 4. Values of soil organic carbon (SOC), microbial biomass carbon (MBC) and dehydrogenase activity at 0-5 cm (white bars) and 5-10 and 10-25 cm (increased grey scale) depths of each treatment (TT: traditional tillage, RT: reduced tillage, NT: no-tillage). The stratification ratio values (SR) for each variable are also indicated (November 2007). Mean values ± standard errors (N=6). For paired means significant differences are indicated by an asterisk (p < 0.05).

Table 5. Crop yields in the years 2005, 2006 and 2007 (mean values ± standard errors, N=3) for the long- and the short-term experiments.

Year	Crop	Treatments	Yield ($Mg\ ha^{-1}$)
2005	Fodder Pea	RT[a]	4.30 ± 0.32
		$TT_{long-term}$[b]	4.06 ± 0.54
		NT[c]	3.56 ± 0.03
		$TT_{short-term}$	3.69 ± 1.94
2006	Wheat	RT	10.2 ± 0.80*
		$TT_{long-term}$	8.00 ± 0.37
		NT	11.1 ± 2.50
		$TT_{short-term}$	9.20 ± 0.65
2007	Sunflower	RT_{15}	3.48 ± 0.86
		TT_{15}	3.23 ± 1.12
		NT_3	3.51 ± 0.96
		TT_3	3.32 ± 0.82

[a] RT: reduced tillage. [b] TT: traditional tillage. [c] NT: no-tillage. For paired means significant differences are indicated by an asterisk (p<0.05).

steady during the whole study period. In our study, the maximum flux after tillage in TT_{15} was 3 times greater than that of the RT_{15} treatment, and about 30 times greater than before tillage.

This study also proves that under semiarid Mediterranean conditions, conservation tillage (reduced and no-tillage) can lead to a consistent reduction in CO_2 fluxes to the atmosphere at more long-term, as compared to tillage using mouldboard ploughing (Fig. 2). Deep soil inversion causes a readily exposition to more oxygen, which contributes to enhance biological oxidation and long-term CO_2 losses. Besides the 'burst' effect on soil CO_2 fluxes, tillage also accelerates SOM decomposition, which led to a lesser accumulation of SOC at soil surface by greater C losses as CO_2 emissions. Agricultural systems nearly always cause less carbon to be added to the soil and more to be lost by microbial respiration and erosion (Weil and Magdoff, 2004). Type, frequency and intensity of tillage influence mineralization processes, with potentially greater CO_2 fluxes to the atmosphere. Higher intensity and frequency of tillage generally result in lower SOC, nutrient retention and nutrient cycling capacity (Seiter and Horwath, 2004; Dawson and Smith, 2007). Past losses of SOC from croplands are estimated to have contributed ca. a range of 50 Pg (Paustian *et al*., 2000) - 80 Pg (Lal, 2000) to the atmospheric CO_2 pool.

Values of C losses reported in this study, between 718 g C m^{-2} $year^{-1}$ (NT_3) and 905 g C m^{-2} $year^{-1}$ (TT_{15}), were roughly similar to those reported by Álvarez *et al*. (1995) and Amos *et al*. (2005) for crop field soils in Argentina and USA respectively. Due to fertilization and intensive cultivation, crop fields (1.7 billion hectares globally) release larger amounts of CO_2 compare to the amount of CO_2 release from natural ecosystems such as grasslands and forests (Luo and Zhou, 2006). For agricultural organic soils it has been reported CO_2 efflux up to ca. 26 g C m^{-2} d^{-1} (about 9500 g C m^{-2} $year^{-1}$) (Dawson and Smith, 2007). Results in this study, and data in literature, agree on the idea about the necessity of avoiding intensive tillage in order to reduce CO_2 fluxes to the atmosphere. High soil T in SW Spain, and similar areas, can enhance CO_2 fluxes. As pointed out before, positive correlations between CO_2 fluxes and T (and negative with W) (Table 3) were registered under our semi-arid conditions. This result was also recorded in experiments carried out in northern Spain (Sánchez *et al*., 2002; Álvaro-Fuentes *et al*., 2008) and confirms that soil T is the major factor in the regulation of SOM decomposition rate (Dawson and Smith, 2007).

The positive effect of conservation tillage-systems on SOC accumulation was observed only few years after the establishment of these techniques. Gallaher and Ferrer (1987) showed that untilled soil contained more N and SOC than conventional tillage soil at 0-5 cm depth only 3 years after of conservation tillage establishment. Results in this study agree with these findings. Under the semi-arid conditions of SW Spain, the NT_3 system seems to be effective for accumulating SOC. Total SOC accumulation in the first 10 cm was 1.17 times greater in NT than the corresponding layer of TT treatment in three years (Table 4). In arid areas the SOM content is frequently low in surface layers. Climatic conditions lead to continuous organic matter losses by oxidation. However, moderate SOC increases under conservation tillage systems can occasion parallel, and sometimes more pronounced increases of some biochemical properties (Fig. 4). The increase of SR for dehydrogenase activity under both conservation tillage systems was even greater than that for SOC, showing a positive influence of these techniques on this activity that is considered as an index of overall microbial activity (Nannipieri *et al*., 1997). Dehydrogenase activity occurs in all living microbial cells, and it is linked with microbial respiratory processes (Bolton *et al*., 1985).

For that reason it has been used mainly to assess the influence of management on soil quality (Gil Sotres *et al*., 2005).

This same pattern was not clearly observed for MBC at this sampling time, November 2007 (Fig. 4); biochemical properties are characterized by a high temporal variability, and in fact, significant increases in values of SR of MBC in RT have been observed in previous samplings (Madejón *et al*., 2007).

Despite the fact that conservation tillage is universally accepted to reduce soil erosion and facilitate water storage, which is especially important to achieve sustainable yields in semi-arid climate regions, its implementation has occasionally caused yield losses, especially in the no tillage system (Kirkegaard *et al*., 1995; Gajri *et al*., 2002). However, with correct management, the global experience with conservation tillage does not result in smaller harvests than traditional tillage (Warkentin, 2001; Gajri *et al*., 2002).

Yields obtained in this study in 2006 corroborate previous results for wheat under semi-arid SW Spain (Pelegrín *et al*., 1990). These authors showed that yield under no tillage was significantly greater than that with disc harrowing and similar to those with disc ploughing, mouldboard ploughing and cultivator; however sunflower yield under no-tillage was significantly lower due probably due to more deficient early plant growth (Pelegrín *et al*., 1990). This aspect has also been observed by Murillo *et al.* (1998) under RT, although further growth and yield was not affected. In general, soil quality and costs-reduction justify the establishment of NT in semi-arid conditions in Spain (Hernanz *et al*., 1995). The energy and production cost savings reached up to 15 and 24% under conservation tillage, in comparison to conventional tillage.

In this experiment, yield of fodder pea under NT was the lowest in the first year, although differences with the corresponding TT treatment were not significant (Table 5). In subsequent years, yield under NT were even slightly greater than those obtained in the other treatments. The high yield of wheat in 2006, especially under conservation tillage treatments derived from an optimal rainfall distribution along the cropping period, making the crop to grow under, practically, an irrigated system.

To summarize, despite in some scenarios reductions in yield after conservation tillage establishment may occur, especially under no-tillage, in this study no detrimental effect has been recorded. Attending the agronomical (soil quality) and environmental (CO_2 emissions) benefits, both conservation tillage treatments are highly recommended for semi-arid, Mediterranean rainfed agriculture.

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