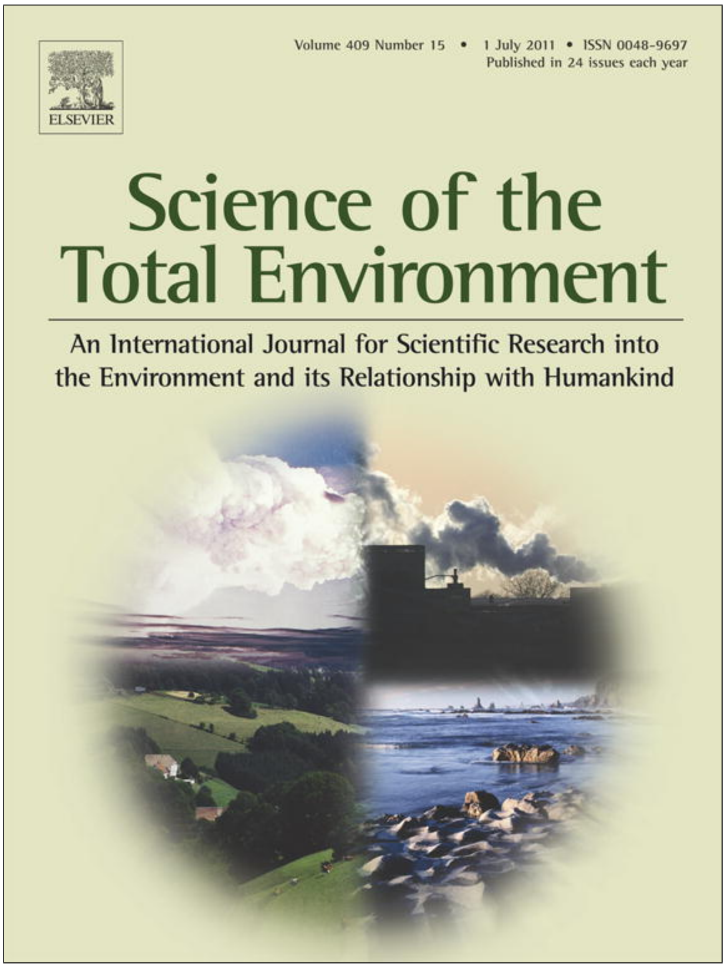

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Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain

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ABSTRACT

The soil in general and that destined for agricultural use, more specifically, can act as a source or sink of carbon, hence its direct involvement in strategies for mitigating climate change. A large proportion of this mitigation potential is produced by the sequestration of carbon by soils and, to a lesser extent, by a reduction in emissions from the soil.

The most effective practices for increasing the organic carbon in the soils are generally those linked to conservation agriculture, which includes practices of no tillage or minimum tillage and the use of cover crops. During the farming seasons of 2006/07, 2007/08, 2008/09 and 2009/10, a trial was conducted in which the carbon dioxide emissions in soil with a high percentage of clay in the Vega de Carmona (Seville) were estimated, and it was determined how climate conditions and the adoption of conservation agriculture practices vs. the use of traditional tillage influenced the flux of gas into the atmosphere.

1. Introduction

Organic matter (OM) is involved in the enhancement of soil quality because it acts on soil structure, nutrient storage and biological activity. It is a key soil component, as it affects the chemical, physical and biological properties of soil, and it is essential for obtaining crops with stable, high yield levels (Franzluebbers, 2002). The intensification of tillage to which European agricultural soils have been subjected since the second half of the 20th century has caused a notable diminution in soil OM content (Maljean et al., 2004). The soil organic C (SOC) present in agricultural soils represents approximately 10% of the total organic C stored in all the soils on the earth's surface (Paustian et al., 1997a). Despite this low proportion, the SOC stored in agricultural soils has had important repercussions on increases in greenhouse gas (GHG) concentrations for decades. The typically Mediterranean climate of the south of Spain promotes low crops yields and low organic carbon content in the soil.

Crops capture CO_2 from the atmosphere during photosynthesis, converting carbon into forms associated with organic matter in the soil during microbial decomposition processes (Johnson et al., 2007). Although agriculture is usually excluded from environmental regulations, its capacity to compensate for the GHG emissions coming from diverse emission sources makes it possible for agriculture to play an important role in climate policies (Claassen and Morehart, 2009).

The CO_2 concentration in the atmosphere has increased by approximately 25% in the past century. Carbon dioxide has a great heating potential, as this type of GHG presents the shortest life cycle and shows a lower infrared radiation absorption potential compared to other GHGs (U.S. Environmental Protection Agency., 2010).

Since the 17th century, the factors most responsible for the increase in CO_2 in the atmosphere have been first the decomposition of organic matter in the soil and the burning of large plant masses associated with the conversion of large areas of fields and forests into agricultural soils and second the burning of fossil fuels (Greenhouse Gas Working Group, 2010).

Throughout the 21st century, it is expected that the increased GHG concentration in the atmosphere and its consequences for the climate change will have greater impacts. These measures are included in articles 3.3 and 3.4 (IPCC, 2000). It is forecast that the increase in NO_2 emissions will reach between 35 and 60% in 2030 due to increased use of nitrogenous fertilizers (FAO, 2003). Similarly, Mosier and Kroeze (2000) and the US-EPA (2006) estimate that NO_2 emissions will be increased by 50% for the year 2020 (with respect to 1990). Additionally, CH_4 emissions are expected to increase by up to 60% by 2030 (FAO., 2003). The data related to CO_2 emissions increases for 2030 are more uncertain, but according to the US-EPA (2006), it has been estimated that during the decades 2000–2010 and 2010–2020, there will be an increase of 13%, and a similar increase (10–15%) is assumed for 2020–2030.

Conservation agriculture has introduced important changes in the dynamics of C in the soil and favors its sequestration. The combination of leaving crop residues on the soil surface and not disturbing the soil directly results in a reduction in the decomposition rate of the crop

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Table 1
Physico-chemical characteristics of the upper 0.2 m of the soil studied under the two tillage treatments investigated.

	Texture (%)					Chemical properties				
	Sand %	Silt %	Clay %	pH	OC (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	CEC (mol$_c$kg^{-1})
Traditional tillage	6.3	31.4	62.2	7.6	9.5	12.7	649.0	605.0	28.7	0.5
No tillage	7.8	36.5	56.4	7.5	12.0	24.6	858.0	499.0	28.5	0.5

remains; a diminution in the mineralization of the soil organic matter due to less aeration and a lower accessibility of microorganisms to it; and an increase in soil carbon (Balota et al., 2004., Ordóñez Fernández et al., 2008).

It is frequently observed that the major differences in OM content between no-tillage (NT) and traditional tillage (TT) soils are found in the upper few centimeters of soil (Dick et al., 1991). Paustian et al. (1997b) compared 39 paired tillage experiments ranging in duration from 5 to 20 years and estimated that NT resulted in an average soil C increase of 285 g m^{-2} compared to TT. Using an average experiment duration of 13 years implies an approximate C sequestration rate of 22 g^{-2} year^{-1}.

When soil is subjected to a type of operation that results in the alteration of its profile, such as soil disturbance or inversion, the flux of the CO_2 emissions into the atmosphere is increased. This increase begins immediately after conducting the operation and lasts for a certain period of time. This response may be due to the breaking up of aggregates, which leaves organic matter unprotected and exposed to the decomposing action of microorganisms (La Scala et al., 2008).

SOC concentrations and soil texture most likely influence aggregate stability. The magnitude of soil disturbance and the amount of residue incorporated into the soil impact aggregates and the associated C pool (Blanco-Canqui and Lal, 2004).

Thus, the type of tilling operation modifies the trend of CO_2 emissions from the soil (Sánchez et al., 2003).

Recently, studies validating this conclusion have been appearing. Based on a study on CO_2 sinks, Figueroa and Redondo (2007) indicated that according to the climatological characteristics of an area, it can be estimated that fields dedicated to agricultural crops are capable of capturing between 0.1 and 1.0 ton of carbon per ha and per year. In Spain, a number of investigations have supplied information on short-term emissions due to different types of tillage (Álvaro-Fuentes et al., 2007, López-Garrido et al., 2009).

Land use management of agricultural systems is known to change the storage of soil organic carbon through variations in land use, tillage, cropping practices and other activities. Consequently management and land use can be used to mitigate greenhouse gas emissions by encouraging practices that sequester carbon in the soil, thus creating a carbon sink for atmospheric CO_2 (Paustian et al., 1997b). Reviewing the scant literature available on this theme, it can be deduced that the effects of agricultural operations on CO_2 emissions are strongly influenced by the type of operation, soil type, and climate conditions in the area. The objective of this study was to evaluate the influence of the management system used on a vertisol in the south of Spain under a Mediterranean climate on the flux of CO_2 into the atmosphere.

2. Materials and methods

2.1. Localization of the field trial and climate conditions in the area

Our experiments were conducted in a long-term field trial established in 1982 in the Experiment Station of Tomejil in the Campiña de Carmona, Seville, Spain, with coordinates of 37° 24′ 07″N and 05° 35′ 10″W.

Data were collected in a plot of 3.5 ha in which a long-term soil management field trial has been conducted since 1982. In this plot, an evaluation was made of the effects produced by different soil management systems, including Traditional tillage (TT) and No tillage (NT), on the physical, chemical, and biological qualities of the soil, as well as the crop yields in a wheat–sunflower–legume rotation.

The soil in the study area is classified as very fine Montmorillonite, Chromic Haploxeret (Soil Survey Staff., 1999). It presents good natural fertility, with high concentrations of potassium and calcium, medium levels of phosphorus, low organic matter content and a pH tending towards neutrality. The principal component of its textural composition is clay, with values of over 60% distributed in 70% of expandable Montmorillonite type clay, 20% of illite and 10% of kaolinite (Perea, 2000). Table 1 shows the physicochemical characteristics of the soil.

The area presents a Mediterranean-type climate, characterized by long summer droughts with a great inter-annual and intra-annual irregularity in rainfall. This variability, together with the high temperatures recorded during the summer, hinders agricultural activity to a great extent.

The mean annual rainfall ranges around 475 mm and is concentrated in the autumn and the beginning of spring, whereas a smaller amount is observed in the winter. The highest temperatures are recorded in July and August and sometimes exceed 35 °C, whereas the minimum temperatures are usually recorded in February and rarely fall below 0 °C (Perea, 2000).

The weather conditions during the trial period can be seen in Fig. 1.

2.2. Experimental design

The tillage systems compared in the trial were traditional tillage and no tillage. TT consists of a disk plow pass after stubble is burnt and successive cultivator passes to decrease soil clod size. In the NT treatment, we used a tine seeder. The speed of seeding is very important. If it is high, the bars exert much pressure on the soil and alter its surface profile, so the soils in this treatment were seeded at a low speed of 0.6 m/s, which ensures a good distribution of seeds and causes no alteration due to pressure on the soil surface. The residue is left on the soil surface until it decays.

The depth reached in the tillage operations is a very important factor in determining the dynamics of CO_2 emissions, so we proceeded to make a comparison between a disk plow reading down to 20 cm of the profile, which has been the normal procedure in the study plots devoted to traditional tillage, and a moldboard plow, which reached depths up to 40 cm, in some plots adjacent to the experimental plots.

The plots were 15 m wide and 180 m long and were replicated three times in a randomized complete block design. To evaluate the temporal

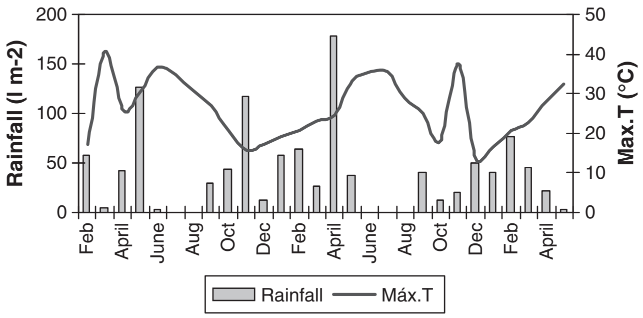


Fig. 1. Distribution of rainfall and maximum temperatures recorded during the period of the Carmona study.

evolution of the flow of CO_2 into the atmosphere in each plot, 9 points were chosen. In addition to these, a tenth point was chosen within each plot around the central random within a radius of 1 m to take into account the spatial variability of emissions (Fig. 2).

This study was conducted in three consecutive farming seasons, 2006/07, 2007/08, 2008/09 and 2009/10, in which pea, wheat, sunflower and pea were grown, respectively.

2.3. Emission measurements

To evaluate the temporal evolution of CO_2 emissions, in each of the plots, 9 points were chosen in which measurements of the CO_2 emissions into the atmosphere were made. In addition to these, a tenth point was selected in each random plot around the central one at a radius of approximately 1 m (Fig. 2).

Gas flow was estimated by means of a portable IR absolute and differential PP-Systems EGM-4 gas analyzer. This consists of a battery, integrated data recorder and soil temperature sensor and is coupled with a respiration camera. This suction or respiration camera is approximately 15 cm high and 10 cm in diameter.

The machine is calibrated automatically using the surrounding air before each measurement as a reference, and it automatically transfers the obtained data to a computer. The camera is placed on the surface of the soil for 2.5 min, during which time data are collected every 4 s, giving as a final value the average value of the whole period. It is capable of measuring CO_2 flows at a range of 0 to 9.99 g CO_2 m^{-2} h^{-1}, with a precision of ± 1 SD and a resolution of 1 ppm. The principle on which the analyzer is based is a closed system in which the increases in the aerial CO_2 concentration found on the soil surface are calculated, for which quadratic equation fits are used.

To observe the effects of the tillage operations used for the soil's preparation and sowing on gas emissions, measurements were made before these operations took place, immediately after them and at 2, 4, 6, 24 and 48 h after carrying them out in the two management systems considered in the study. Specific measurements were also made after the most important rain events to observe the effects of the increase in moisture in the soil on biological activity and the acceleration of decomposition of the residue.

2.4. Data analysis

Analyses of variance (ANOVA) were used to detect the significance of the effect of the main factor: the tillage system. The separation of means was determined by a Tukey test, where the effects were statistically significant ($p<0.05$).

The fit of the regression models was made with the linear regression module in the program Statistix 8.

3. Results

Fig. 3a and b depicts the hourly evolution of the CO_2 emissions in both types of soil preparatory tillage operations for the farming season of 2006/07, in which pea was sown; Fig. 3c and d shows the emissions corresponding to the season of 2007/08, during which wheat was sown; Fig. 3e presents values for the season 2008/09, in which sunflower was sown; and Fig. 3f gives results for the season of 2009/10, in which pea was again sown. From these results, it can be observed that there were no notable differences in the gas emissions in areas subjected to the two management systems for the measurements taken prior to carrying out the preparatory work. However, immediately after performing the preparatory operations, the CO_2 emissions exhibited an important increase in the tilled soils compared to the measurements obtained in the non-tilled soils.

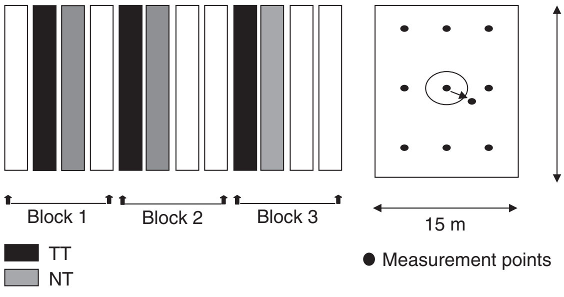


Fig. 2. Diagram of the distribution in the Tomejil farm of the plots used for the field trials and of an experimental unit, with the measurement points indicated.

As can be observed in Fig. 3, the maximum CO_2 emission value for the different measurements corresponds to the period between 2 h and the 4 h following the tillage operations, and this is a common trend for both treatments as a result of the higher ambient temperature recorded at this time and the displacement of gas to non-tilled plots, which were very close to those of the traditional system. In the first measurement made on 14/11/06, it was noted that at 24 h, there was still a notable difference between the gas measured in both systems of cultivation, which led us to increase the measurement time in successive measurements until there were no significant differences in the emission values of either management system, fixing 48 h after the work in the soil was done as a measurement limit.

However, a comprehensive view of the behavior of the gas in the different measurements permits us to indicate that starting from the peak of the maximum emissions, the flux begins to decrease, until reaching similar values in both treatments at 24 h. The significant increase in CO_2 emissions that takes place immediately after tilling responds to the physical release of this gas trapped in the porous space of the soil.

Table 2 summarizes the daily emissions accumulated in both soil management systems and the moment at which the greatest differences in the gas flux that were recorded.

At the points of maximum difference, higher carbon dioxide values on the order of between 39 and 90% were measured in the tilled soils compared to soils in which the profile had not been altered. Specifically, considering a period of 24 h, the soils under traditional management emitted 30.1 and 11.8 kg ha^{-1} more CO_2 than those managed under conservation agriculture conditions for the first and second tillage performed in the season of 2006/07, 2.5 and 4.6 kg ha^{-1} more for the tillage operations conducted in the second season, and 16 and 22 kg ha^{-1} for the seasons of 2008/09 and 2009/10, respectively.

Independent of the management system used, the highest CO_2 emission values were seen in the measurements made on 14/11/06 and 14/10/2009 due to the greater amount of moisture in the soil as a result of the rain accumulated in the month prior to the measurements being made; the lowest emissions were found in the measurement made on 20/09/07 due to the high temperatures recorded at that time, which conditioned the activity of the microorganisms in the soil that is responsible for decomposing organic remains.

In the case of sowing (Fig. 4), the trend observed in the CO_2 flux was similar to that described for tillage, i.e., a maximum peak was noted between 2 and 4 h of the beginning the operations, and the highest values were estimated in the soils managed under the traditional system. However, due to the lesser depth of the alteration of the profile with sowing, at 6 h, the emission levels were similar in both management systems.

Table 3 summarizes the daily emissions accumulated on the sowing date and the moment at which the greatest differences in the CO_2 flux that were recorded between the management systems.

With the aim of introducing a new variable that is of great importance in studying emissions, i.e., the depth of tillage, we proceeded to use a disk plow pass to till down to 20 cm of the profile, which has been the normal procedure used in the study plots devoted to traditional tillage. At the same time, a pass was made with a moldboard plow in some plots adjacent to the experimental plots, which reached up to a depth of 40 cm.

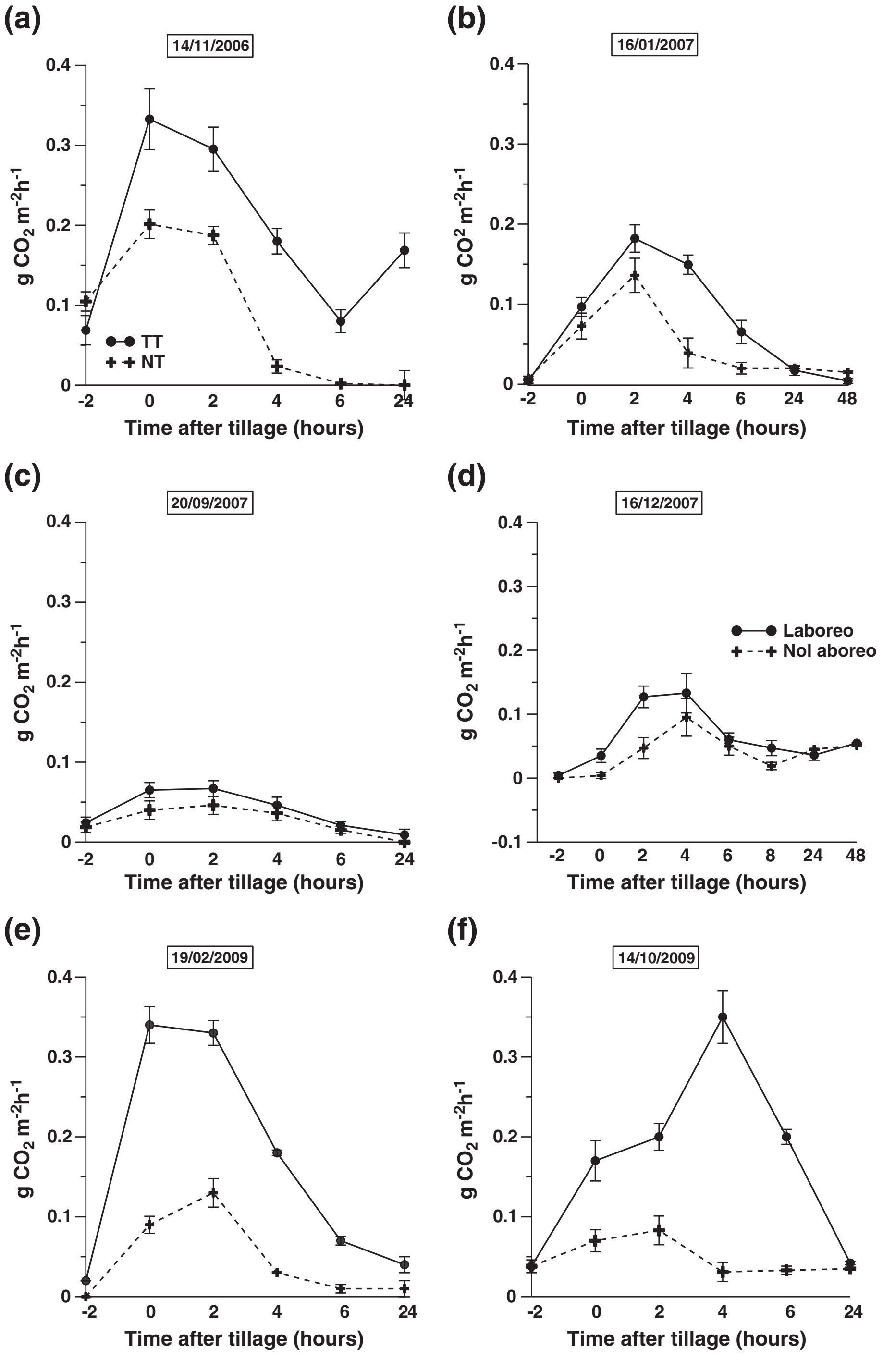


Fig. 3. Hourly evolution of the CO_2 emissions during the preparatory tillage operations in the soil in both cultivation systems.

After the passes of the different machinery in the corresponding plots, the CO_2 emissions were measured in the same way as had been done throughout the field trials. The first reading was made before tillage, the following reading just after the pass, and the subsequent readings at 2, 4, 6, and 24 h, both in the plots in which the machinery passes were made and in those destined for no tillage, with the aim of comparing the three systems.

Fig. 5 shows the emission values at the different time points at which the CO_2 flux was measured and the difference between the values measured in the tilled soils compared to the no tillage sites.

As can be seen in the figure, the trend in the hourly gas emission is the same for the three cultivation systems and is dictated by the daily evolution of the temperature, which affects microbial activity.

Table 4 shows the increase in the emissions recorded in the plots subjected to any of the individual tillage systems expressed as the ratio of emissions in the tillage plots to those presented by the plots under no tillage.

As can be observed in Table 4, the ratio value in all of the tillage cases over the no-tillage cases was fairly high. In the cases of both the disk plow and the moldboard plow, the greatest difference was produced at

Table 2
Daily CO_2 emission values when performing tillage operations in soil and maximum differences in them between the two management systems.

Date	Daily CO_2 emission kg ha^{-1}		Max. difference in emissions TT − NT	Max. t	Accumulated rainfall in the last month (mm)	Soil moisture (%)
	TT	NT				
14/11/06	38.5	8.4	87% (4 h)	21.2	127.8	20.5
16/01/06	20.3	8.5	74% (4 h)	17.7	38.8	10.1
20/09/07	6.3	3.8	38.7% (opening)	34.2	11.0	2.9
16/12/07	13.7	9.1	63% (2 h)	16.0	66	11.36
19/02/09	22	6	73% (opening)	18.7	95.2	18.3
14/10/09	30	8	90% (4 h)	31.3	44.6	10.6

the moment of the tillage pass, and the values were 6.7 and 10.5, higher than under no tillage, respectively.

Fig. 6 presents the CO_2 concentration in the air immediately after tillage was performed as a function of the amount of gas measured before the soil was tilled for both management systems and operations performed in the soil.

In Fig. 6, it can be seen how the increase observed after the tilling operations is linearly related to the flux measured before carrying out these operation, both for the preparatory work in the soil and the sowing operations. This indicates to us that the content of CO_2 in the soil conditions the emissions caused when any type of tillage is performed. As can be seen in Table 3, in the case of conducting sowing where tillage operations had been conducted previously, the CO_2 levels retained in the soil were lower, so the emissions subsequent to the sowing operations presented lower emission fluxes, as they are linearly related.

4. Discussion

Reduced tillage is one of the most effective agricultural practices for reducing CO_2 emissions and for increasing the sequestration of atmospheric carbon in the soil (Sainju et al., 2008). Similarly, it has been observed that managing soil under a no-tillage system with residues left on the soil surface can further diminish the amount of emissions produced in comparison with the same type of system with bare soil (Al-Kaisi and Yin, 2008).

In the present study, the hourly emission values obtained (Fig. 3) are somewhat lower than those estimated by Álvaro et al. (2004) and by Morell et al. (2010) in the provinces of Zaragoza and Lleida, respectively, in northeastern Spain. The magnitude of the response of the conservation agriculture systems to the sequestration of carbon and to the reduction in emissions varied considerably depending on the depth of the work performed in the soil and the edaphic and climatic conditions of the area.

Climate notably modifies the nature and rapidity of the decomposition of plant remains and, thus, the carbon dioxide emitted into the atmosphere. Moisture and the temperature are among the most determinative variables (Brinson., 1977) because they influence both the

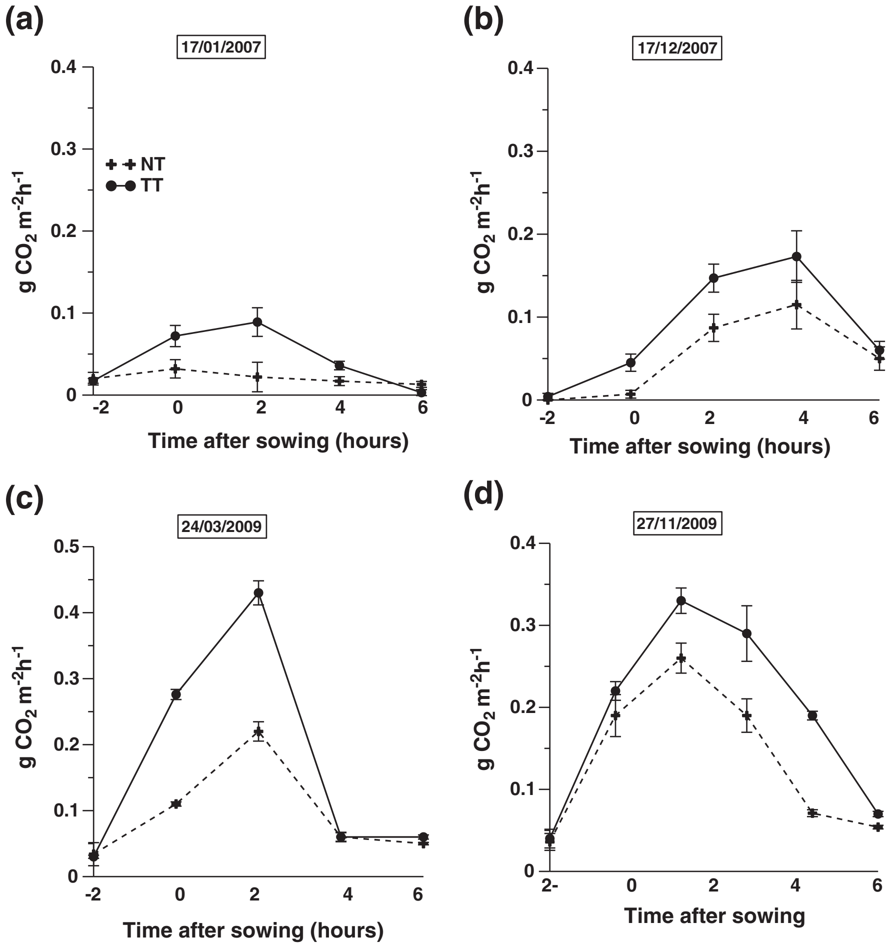


Fig. 4. Hourly evolution of the CO2 emissions during the sowing operations for the different farming seasons in both cultivation systems.

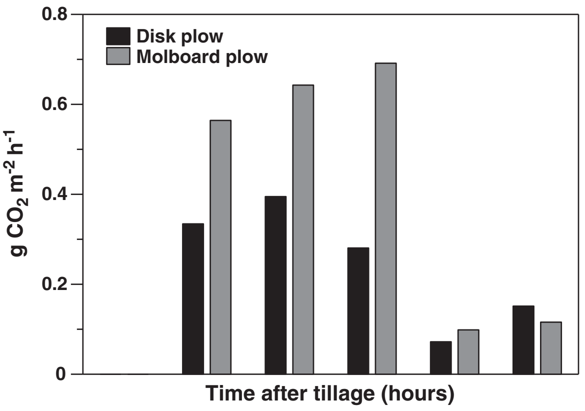
Table 3
Daily CO_2 emission values on the sowing dates and maximum differences in these values between the two management systems.

Date of sowing	Daily emission of CO_2 kg ha^{-1}		Max. difference in emissions TT-NT	Max temp.	Rain accumulated in the last month (mm)	Soil moisture (%)	Days since preparatory tasks
	TT	NT					
17/01/07	8	3	75% (4 h)	17	38.8	10.1	1
17/12/07	14.6	10	41% (4 h)	15	66	11.36	1
24/03/09	23	5	49% (4 h)	17	41.8	12.27	33
27/11/09	33	21	34.5% (4 h)	16	6	3.4	44

growth of vegetation and microorganism activity, which are extremely vital factors in the formation of soils (see Table 2). Citing several publications, Kononova (1975) reached the conclusion that the maximum intensity of the decomposition of organic matter is observed under moderate temperature conditions (around 20 °C) and with a moisture content of approximately 60–80% of the maximum capacity to retain water. Increasing or reducing temperature and moisture simultaneously, beyond optimal levels, causes a decreased decomposition of organic matter, which results in an important reduction in the CO_2 emitted.

In our case (Table 3), the points of maximum difference all occurred at 4 h of sowing, and CO_2 values between 34 and 75% higher were measured in the tilled soils. The differences recorded throughout the investigated 24 hour period were that 5, 4.6, 18 and 12 kg ha^{-1} more emissions occurred in the soils that traditionally tilled compared to those subjected to conservation agriculture practices.

If these data (Table 3) are compared to those shown in Table 1, which correspond to the work done before sowing, it can be observed that the volumes of emissions for both management systems were somewhat lower in the latter. As mentioned previously, this was due to the lesser depth reached with sowing in comparison to the other type of operation. It should also be taken into account that sowing is often performed a short time after having conducted the previous operation in the soil to prepare the bed for sowing. This means that the volume of gas trapped in the soil is released with the first operation, and the short space of time remaining before sowing, in some cases only 1 day, does not permit large amounts of gas to be stored again. In Table 3, the lowest emission values are given for the sowing corresponding to 17/01/07 and 17/12/07, and they coincide in that in the two cases, a day had passed since the previous cultivator pass. In the other two cases, the period was increased to over 30 days, and the emission volumes were greater.



	-2	0	2	4	6	24
No-tillage	0 a	0.06 c***	0.19 c***	0.14 c***	0.04 b**	0.07 b**
Disk plow	0 a	0.40 b***	0.59 b***	0.42 b***	0.11 a**	0.22 a**
Molboard plow	0 a	0.63a***	0.83 a***	0.83a***	0.14 a**	0.18 a**

Fig. 5. Increase in the hourly CO_2 emissions during the tillage operations in the soil in the different cultivation systems above the emissions measured in the no-tillage sites. Each value represents the mean of 14 readings.

In research performed in the United States (Reicosky and Archer, 2007), the short-term effects of two management systems on CO_2 emissions, one of which used a moldboard plow, whereas the other used no tillage, were evaluated. These investigators detected higher emission rates, both at short and medium terms, for the tilled plots compared to those under no tillage. These emission values ranged from being 3.8 times higher than found under no tillage when the work was conducted closer to the surface (10 cm), up to emissions 10.3 times higher than those measured under no tillage in the case of deeper tillage (28 cm).

As can be observed in Fig. 5, in spite of the influence of temperature on the hourly gas emissions, highly significant differences can be seen among the three systems, with the highest emissions being produced in the plots tilled with the moldboard plow, followed by those tilled with the disk plow, and finally, as expected, in those with no tillage.

Based on a study in which different soil management systems were compared, Prior et al. (2000) suggested that the increase in CO_2 fluxes occurring after tillage passes was related to the depth of the operation and to the degree of the soil's alteration. This coincides with the results obtained given that, in the comparison of the two tillage systems, it was seen that the moldboard pass, which reached down to 40 cm, was associated with the highest emissions.

These results coincide with those obtained by Álvaro-Fuentes et al. (2007), who reached the conclusion that plots in which traditional tillage was performed with a moldboard plow presented the highest emission values. These authors also affirmed that the maximum emissions produced after tillage begin to diminish 3 h after the operation. In our case, this maximum was reached at 2, following which the emissions begin to progressively decrease.

The results obtained here show that managing soils using no tillage is an especially favorable technique to reduce the CO_2 fluxes emitted by these soils into the atmosphere compared to soils subjected to traditional management. This difference was seen to be increased in the emissions recorded after the work performed in the soil in the traditional tillage plots, which entails a breaking up of the aggregates in the soil and the release of the gas trapped in it. These increases were found to be over 80% higher in the tilled soils.

Climate conditions were observed to be of great importance in the flow of the emissions, with increases in the volume of emissions being detected when there was abundant rainfall in the month preceding the data taking being observed.

The depth of the tillage directly affected the amount of CO_2 emissions. Comparison between the disk plow and the moldboard plow permitted the quantification of a total of 18 kg ha^{-1} more gas emissions being produced from the soils tilled with the moldboard plow in the 6 h following carrying out tillage and 38 kg ha^{-1} more emissions if this operation is compared to no tillage.

It is also of interest to point out that by doubling the depth of the tillage, the amount of CO_2 emitted into the atmosphere is nearly doubled.

In Spain, where the emissions of greenhouse gasses (GHGs) greatly exceed the objectives fixed by the Kyoto protocol for the period 2008–2012, it is more necessary than ever to implement measures permitting us to fulfill those objectives. Therefore, in the agricultural sector, the adoption of Conservation Agriculture practices, especially no tillage management, could be a very important option for fixing atmospheric C in soils and reducing the emissions derived from agricultural operations.

Table 4
Increases of gas emissions in each tillage system taking as reference unit the emissions under no tillage.

	Tillage	2 h after tillage	4 h after tillage	6 h after tillage	24 h after tillage
Disk plow	6.7	3.1	3.0	2.7	3.1
Moldboard plow	10.5	4.4	6.0	3.5	2.6

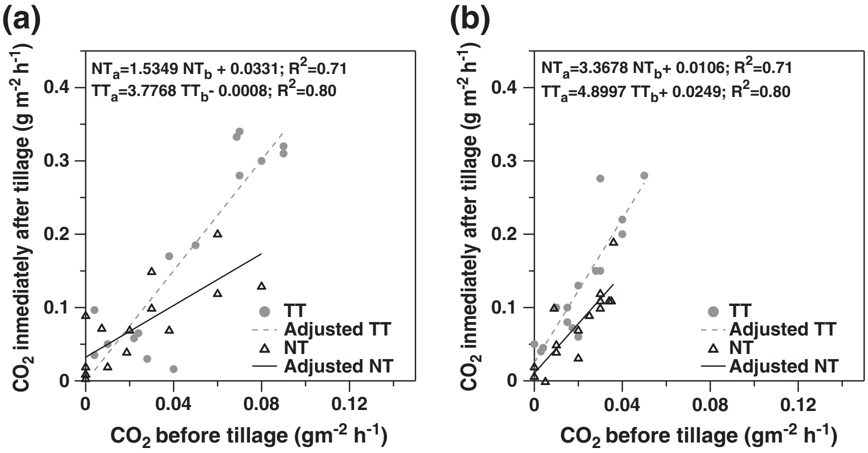


Fig. 6. Relation of CO_2 flux before tillage and immediately after tillage for both the traditional tillage (TT) and no-tillage (NT). (a) is for tillage operations and (b) is for sowing operations. Lines are linear adjustments for tillage and no-tillage systems. NT_a and NT_b are fluxes after and before tillage operations for the tillage system. TT_a and TT_b are fluxes after and before tillage operations in the no tillage system.

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References

Al-Kaisi MM, Yin X. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotation. J Environ Qual 2008;34:437–45.

Álvaro J, López MV, Garcia R, Arrúe JL. Effect of tillage on short-term CO_2 emissions from a loam soil in semiarid Aragon (NE Spain). In: Arrue JL, Cantero-Martínez C, editors. Third Mediterranean meeting on no tillage, 60. Options Mediterranées; 2004. p. 51–4.

Álvaro-Fuentes J, Cantero-Martínez C, López MV, Arrúe JL. Soil carbon dioxide fluxes following tillage in semiarid Mediterranean agroecosystems. Soil Till Res 2007;96: 331–41.

Balota EL, Kanashiro M, Filho AC, Andrade DS, Dick RP. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agroecosystems. Braz J Microbiol 2004;35:300–6.

Blanco-Canqui H, Lal R. Mechanisms of carbon sequestration in soil aggregates. Crit Rev Plant Sci 2004;23:481–504.

Brinson MM. Decomposition and nutrient exchange of litter in an alluvial swamp forest. Ecol 1977;58:601–9.

Claassen R, Morehart M. Agricultural land tenure and carbon offsets. Economic Brief-14. Department of Agriculture, Economic Research Service; 2009.

Dick WA, McCoy EL, Edwards WM, Lal R. Continuous application of no-tillage to Ohio soils. Agron J 1991;83:65–73.

FAO. World agricultura: towards 2015/2030. An FAO perspectiva. Rome: FAO; 2003. 97 pp.

Figueroa MA, Redondo S. Los sumideros naturales de CO_2. Una estrategia sostenible entre el Cambio Climático y el Protocolo de Kyoto desde las perspectivas urbana y territorial. Universidad de Sevilla; 2007. 221 pp.

Franzluebbers AJ. Soil organic matter stratification as an indicator of soil quality. Soil Till Res 2002;66:95-106.

Greenhouse Gas working Group. Agriculture's role in greenhouse gas emissions & capture. Madison, Wi: Greenhouse Gas Working Group rep. ASA, CSSA and SSSA; 2010.

IPCC. Land use, land-use change and forestry special report. Cambridge University Press; 2000. p. 377.

Johnson JM, Franzluebbers AJ, Lachnicht-Weyers S, Reicosky DC. Agricultural opportunities to mitigate greenhouse gas emissions. Environ Pollut 2007;150:107–24.

Kononova MM. Humus of virgin and cultivated soils. In: Gieseking JE, editor. Soil components, I. Nueva York: Springer-Verlag; 1975. p. 475–526.

La Scala A, Lopes K, Bolonhezi D, Archer DW, Reicosky DC. Short-temporal changes of soil carbon losses after tillage described by a first-order decay model. Soil Till Res 2008;99:108–18.

López-Garrido R, Díaz-Espejo A, Madejón EW, Murillo JM, Moreno F. Carbon losses by tillage under semiarid Mediterranean rainfed agriculture (SW Spain). Span J Agric Res 2009;7:706–16.

Maljean JF, Amlinger F, Bannick CG, Favoino E, Feix I, Leifert I. Land use practises in Europe. In: Camp Van, et al, editor. Reports of the Technical Working Groups established under the Thematic Strategy for Soil Protection. Luxembourg: Office for Official Publications of the European Communities; 2004. EUR 21319 EN/3 872 pp.

Morell FJ, Álvaro-Fuentes J, Lampurlanés J, Cantero-Martínez C. Soil CO_2 fluxes following tillage and rainfall events in a semiarid Mediterranean agroecosystem: Effects of tillage systems and nitrogen fertilization. Agriculture, Ecosystems & Environment 2010;139:167–73.

Mosier AR, Kroeze C. Potential impact of the global atmospheric N_2O budget of the increased N input required to meet future global food demands. Chemosphere Global Change Acience 2000;2:465–73.

Ordóñez Fernández R, Carbonell Bojollo R, González Fernández P, Perea Torres F. Influencia de la climatología y el manejo del suelo en las emisiones de CO_2 en un suelo arcilloso de la Vega de Carmona. CAREL; 2008. p. 229–47. VI.

Paustian K, Collins HP, Paul EA. Management controls on soil carbon. In: Paul EA, Paustian K, Elliot ET, Cole CV, editors. Soil organic matter in temperate agroecosystems: long-term experiments in North America. Boca Raton, FL, USA: CRC Press; 1997a. p. 15–49.

Paustian K, Andren O, Janzen HH, Lal R, Smith P, Tian G, et al. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage 1997b;83:65–73.

Perea F. Agronomía del laboreo de conservación en los vertisoles de la campiña andaluza. Tesis Doctoral. Universidad de Córdoba. Departamento de Agronomía. Córdoba- España. 2000.

Prior SA, Reicosky DC, Reeves DW, Runion GB, Raper RL. Residue and tillage effects on planting implement-induced short-term CO_2 and water loss from a loamy sand soil in Alabama. Soil Till Res 2000;54:197–9.

Reicosky DC, Archer DW. Moldboard plow tillage depth and short-term carbon dioxide release. Soil Tillage Research 2007;94:109–21.

Sainju UM, Jabro JD, Stevens WB. Soil carbon dioxide emissions and carbon contents as affected by irrigation, tillage, cropping system and nitrogen fertilization. J Environ Qual 2008;37:98-106.

Sánchez ML, Ozores MI, López MJ, Collr R, De Torre B, García MA, et al. Soil CO_2 fluxes beneath barley on the central Spanish plateau. Agr Forest Meteorol 2003;118: 85–95.

Soil Survey Staff. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys2nd Ed. USDA; 1999.

US-EPA. Global anthropogenic non-CO_2 greenhouse gas emissions: 1990–2020. Washington D.C: United States Environmental Protection Agency, EPA 430-R-06-005; 2006 http://www.epa.gov/nonco2/econ-inv/downloads/GlobalMigationFullReport.pdfaccessed. 26 March 2007.

U.S. Environmental Protection Agency. Inventory of U.S. greenhouse gas emissions and sinks: 1998–2008. Washington, D.C: EPA, Office of Atmospheric Programs (6207J); 2010 http:_//epa.gov/climatecahnge/emissions/usinventoryreport.h.