Spatial and temporal variability of CO_2 emisions in soils under conventional tillage and no-till farming

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Abstract

Agricultural soils can act as a carbon sink depending on the soil management practices employed. As a result of this functional duality, soil management systems are present in international documents relating to climate change mitigation. Agricultural practices are responsible for 14% of total greenhouse gas emissions (GHG’s) (MMA, 2009)(1). Conservation agriculture (CA) is one of the most effective agricultural systems for reducing CO_2 emissions, as it increases the sequestration of atmospheric carbon in the soil.

In order to assess the performance of CA in terms of CO_2 emissions, a field trial was conducted comparing soil derived CO_2 fluxes under No-till (NT) farming and under conventional tillage. Three pilot farms were selected in the cereal-growing area of southern Spain, located in Las Cabezas de San Juan (Seville), Carmona (Seville) and Cordoba. Each pilot farm comprises six experimental plots with an approximate area of five hectares; three of the six plots implement CA practices, while the other three use conventional tillage techniques. The subdivision of each tillage system into 3 plots allowed the simultaneous cropping of the three crops of the wheat-sunflower-legume rotation each year.

Results showed that carbon dioxide emissions were 31 to 91% higher in tilled soils than in untilled soils, and that there was a great seasonal variability of CO_2 emissions, as weather conditions also differed considerably for the different sampling periods. In all cases, the CO_2 fluxes emitted into the atmosphere were always higher when soil was subject to conventional tillage.

Keywords: Conventional tillage, conservation agriculture, no-till farming, CO_2 emissions.

Introduction

Spain is one of the countries in the European Union that emits the most greenhouse gases into the atmosphere. As a result, urgent measures are required in order to reduce emissions and thereby achieve the objectives established in Kyoto. Spain, as a signatory of the Kyoto Protocol, has committed to limiting average annual net emissions of greenhouse gases to 15% more than the net emissions recorded in the base year (1990) during the period 2008-2012. Data presented at the Fifth National Communication of Spain to the UN Framework Convention on Climate Change, published in December 2009 by the Secretariat General for the Prevention of Pollution and Climate Change of the Ministry of Environment, Rural and Marine Affairs, revealed that total emissions in 2007 exceeded the base-year value by 52.6%.

Analysis of the main types of GHG indicates that carbon dioxide is the dominant component in terms of absolute weight, generally being responsible for 80% of the total. In a sector-by-sector breakdown of activity in 2007, agriculture accounted for 10.5% of total emissions, a figure that has since declined by 3.5%. The Kyoto Protocol provides several mechanisms aiming at reducing GHG, including the promotion of activities with a carbon © sink effect as a solution to reduce atmospheric CO_2 concentrations (Tristan and Wilfred, 2002)(2).

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(3)). Although agriculture is usually excluded from environmental regulations, its capacity to offset GHG emissions stemming from diverse emission sources means agriculture can play an important role in climate policies (Claassen and Morehart, 2009)(4).

Implementing Conservation Agriculture systems, more specifically NT, has important economic and environmental advantages, of which it is worth highlighting the accumulation of Soil Organic Carbon (SOC). As a result, NT is considered a potential means of mitigating the increase in the atmospheric concentration of $CO_{2.}$

Fluxes of CO_2 from agricultural soils are the result of complex interactions between the climate and several biological, chemical and physical soil properties. Tillage systems may affect all these soil properties and therefore influence the release of GHG (Oorts *et al*, 2004(5)). At field level, a change in tillage system can result in GHG emissions mitigation during a period of 10 and 20 years after the change of tillage is implemented (Six *et al.*, 2004(6)).

Tillage contributes to mixing new fresh residue with the soil, modifying soil profile characteristics (e.g., aeration, moisture and temperature regimes) and promoting soil microbial activity (Reicosky et al., 1997(7)). At the same time, tillage promotes macro aggregate turnover, exposing protected SOM to soil microorganisms (Six et al., 1998(8)).

While conventional tillage tends to boost CO_2 fluxes during the first few days after the soil is disturbed, the long-term behaviour of tilled soil with regard to CO_2 emissions is less consistent and may even be inverted when compared to soil under no-till farming (Regina and Alakukku 2010(9), Almaraz et al. 2009(10), Oorts et al. 2007(5)). Complex interactions between the different factors governing CO_2 emissions (temperature, rainfall, soil moisture, SOC and its stratification and crop residues) seem to determine the long-term CO_2 emission balance (Oorts et al. 2007(5)).

Reviewing the scant literature available on this topic, it can be deduced that the effects of agricultural operations on CO_2 emissions are strongly influenced by the type of tillage operation, soil type and climate conditions in the area. Figueroa and Redondo (2007(11)) indicated that depending on the climatic characteristics of an area, it is estimated that fields devoted to agricultural crops are capable of capturing between 0.1 and 1.0 tons of carbon per hectare and per year. In Spain, a number of studies has provided information on short-term emissions due to different types of tillage (Álvaro-Fuentes et al., 2007(12), López-Garrido et al., 2009(13)).

The objectives of this study are to quantify the short-term and long-term impact of tillage on soil CO_2 fluxes following the implementation of different tillage systems and also to determine the influence of climatic conditions, site and time of ploughing on short-term soil CO_2 fluxes. Similarly, we will also study the spatial and temporal variability of data.

Material and methods

Experimental sites

A field trial has been carried out to compare dynamics of CO_2 emissions into the atmosphere and to study the sink effect of soils subject to direct drilling, in comparison with other soils in which conventional tillage operations are performed. For this purpose, three pilot farms were selected in different geographical locations, but all in the cereal-growing area in Andalusia, southern Spain, more specifically in Las Cabezas de San Juan (Seville), Carmona (Seville) and Córdoba city.

Soil properties are shown in Table 1.

Table 1. Physico-chemical characteristic of the upper 0.2 m of the soil studied.

	OC	**C.E.C**	**P**	**K**	**Ca**	**Mg**	**Sand**	**Silt**	**Clay**
	%	***$mol_c kg^{-1}$***	***gr/100gr***				***%***		
Carmona	1.1	0.3	17.2	589.5	12.3	638.5	15.8	25.5	58.7
Las Cabezas	1.1	0.3	28.0	406.7	7.5	519.3	19.9	28.7	51.5
Córdoba	1.7	0.2	13.2	262.7	5.7	263.5	30.7	32.1	37.2

The three towns are located in a Mediterranean region with a Xeric moisture regime, according to the standards set by the Soil Survey Staff, (1999(14)). The climate is characterised by a cold wet period in autumn and winter, which accounts for 80% of rainfall and another very warm and dry period in spring and summer. The temperature regime is thermal. Table 2 presents the monthly average temperatures and rainfall recorded in the three areas and seasons during which data were collected.

Table 2. Average temperatures (ºC), accumulated rainfall (mm) and standard deviation during the study period (season 2009/10 and 2010/2011).

	CARMONA		***LAS CABEZAS***		***CORDOBA***	
	Rain	Av. Temp	Rain	Av. Temp	Rain	Av. Temp
Jan	150.6±6.7	9.9±1.9	196.4±6.2	11.4±2.5	190.6±6.9	9.3±2.4
Feb	283.0±10.4	10.4±2.7	266.8±9.4	11.1±2.9	306.3±9.9	9.3±2.8
Mar	142.0±5.5	13.6±2.8	153.6±5.4	14.1±2.8	144.6±5.7	12.7±2.7
Apr	119.4±4.0	17.4±2.8	98.2±3.7	18.1±2.4	121.5±4.9	17.3±2.7
May	27.2±2.1	20.8±3.3	48.6±2.5	21.1±2.9	106.1±6.7	20.5±3.0
Jun	27.6±3.7	23.5±3.4	32.2±3.8	23.3±2.9	50.1±3.4	24.0±3.5
Jul	0.0±0.0	23.2±3.6	0.2±0.0	27.1±1.8	0.6±0.0	28.1±1.8
Aug	0.2±0.1	29.4±2.6	1.8±0.2	28.2±2.1	28.8±3.3	29.0±2.2
Sep	55.4±11.9	24.3±2.8	18.8±1.4	23.8±2.3	56.5±4.2	23.8±2.5
Oct	14.6±3.1	19.8±2.6	132.6±8.6	19.8±2.5	157.0±8.2	19.1±2.8
Nov	137.2±9.3	13.4±2.9	128.4±6.1	14.1±2.6	112.3±5.1	12.3±2.7
Dec	570.0±10.7	11.7± 3.6	414.8±10.7	12.8±3.8	671.4±17.7	10.2±.3.5

Field plots and experimental design

Each pilot farm consisted of six experimental plots with an approximate surface area of five hectares each; three of the six plots use conservation agriculture techniques, while the other three are managed traditionally. In these plots, the three crops of the wheat-sunflower-legume rotation are assayed simultaneously.

Each of the five-hectare experimental plots is in turn divided into 10 subplots. Each subplot has one point located in the centre and all of them are georeferenced. The knowledge of the precise location of each sampling point permits us to always work on the same area and, additionally, to evaluate the seasonal variability of CO_2 emissions into the atmosphere.

Emission measurements

Emissions were measured on a monthly basis during two agricultural years (2009/10 and 2010/11), with an IR portable absolute and differential gas analyser EGM-4, coupled with a soil respiration chamber. The respiration chamber is approximately 15 cm high and has a diameter of 10 cm with a CO_2 flow measurement capacity ranging from 0 to 9.99 g CO_2 m^{-2} h^{-1} with a precision of ± 1SD and a resolution of 1 ppm.

The chamber is placed on the soil surface for a period of 2.5 minutes during which time data are taken every 4 seconds, the final value being a mean of the whole period. The principle this technique is based on is that the analyser acts as a closed system, which calculates the concentration of CO_2 in the air found on the surface of the soil, by using fits to quadratic equations.

The analyser also has a column with space for approximately 10ml of a silica-derived substance, which absorbs the moisture in the air circulating in the system and transforms it into dry air to prevent interferences in the detection of $CO_{2.}$

In addition to the monthly measurements, others were performed when soil was prepared and the crop sown in order to ascertain the effect of these operations on gas emissions. Those measurements were taken before tillage, immediately after tillage and two, four, six and 24 hours after these operations in both management systems considered in the study.

Data analyses

In order to analyse the spatial and temporal stability of the CO_2 data for the different measurement points, a similar method to that proposed by Vachaud et al. (1985(15)) was used. This method is based on the concept of the temporal stability of calculating the average for each point (Eq. 1) and its variability (Eq. 2) over time. In this case, unlike the method proposed by the cited author, the temporal means of each zone were calculated rather than the relative differences, in order to ascertain the average level of CO_2.

$$AC_{zone}i = \sum_{t=1}^{n} \frac{CO_2(\%)it}{n} \qquad (1)$$

where AC_zone_i is the temporal mean of CO_2 in zone i (i=1,….); n is the number of samples taken at each measurement point and $CO_2(\%)_{it}$ is the percentage of CO_2 for zone *i* at time *t*.

$$\delta(AC_{zone}i) = \left[\frac{\sum_{t=1}^{n}(AC_{zone}i - CO_2(\%)it)^2}{n-1} \right]^{1/2} \qquad (2)$$

where δ (AC_zone_i) is the standard deviation of the mean, calculated as an indicator of temporal stability.

Distribution maps allow us to represent the spatial variability of any variable measured in the field. For this reason, the distribution maps of CO_2 emissions have been estimated using ordinary point kriging at intervals of 1 m in both directions to assess the spatial variability of the quantity of emissions. The Surfer 10 programme has been used for this statistical analysis.

Results

Seasonal variability of emissions

Regardless of the location, we have observed throughout the field trial how an increase or decrease in moisture beyond optimum levels has a clear effect on the increase of organic matter, which determines the increases or decreases in the amount of CO2 emitted. This can be depicted in Figure 1, where we can see how the highest emissions coincide with the measurements taken in spring and autumn, seasons when mild temperatures also favour the decomposition of soil organic residues. Generally speaking, almost all the emissions recorded were in spring, when soil moisture is highest as a result of the rainfall registered during this period and, above all, when temperatures approaching 20ºC stimulate the activity of the microorganisms that decompose the organic residues protected by the soil (SoCo, 2009(16)).

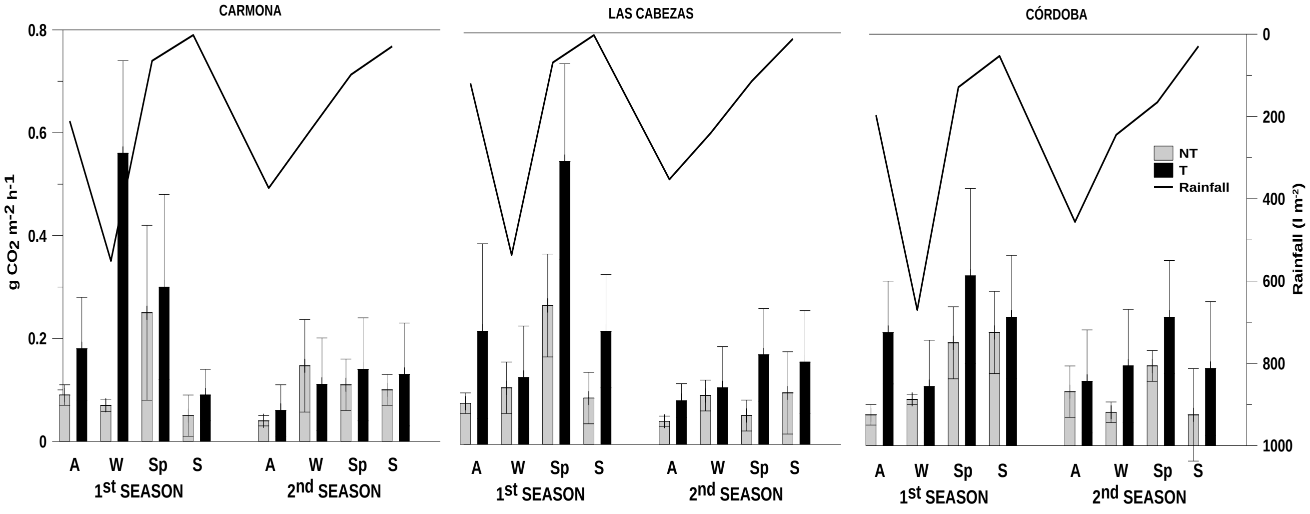


Figure1. Emissions recorded during the various seasons at each of the locations studied. A (autumn); W (winter); Sp (spring); S (summer). NT (No-Till); T=Tillage

During the first year, the highest value was recorded in winter in Carmona, due to the large amount of rainfall during that period, which favoured the activity of decomposing microorganisms. In the case of the other two towns, the highest value was recorded in spring.

If we calculate the emission values (expressed as a percentage) in the plots employing conventional tillage that were in excess of the average value for the plots under NT farming, the greatest differences in the case of Las Cabezas and Cordoba were registered during autumn at 64% and 73%, respectively, whereas in the case of Carmona they were recorded in winter at 70%, coinciding with the highest emission scores.

With regard to the differences in CO2 emissions between the two soil management systems, NT provided lower emissions for all sites and seasons (with the exception of one season at Carmona) when compared to conventional tillage. The greatest differences were registered during autumn of the first year at Las Cabezas and Cordoba, and during winter of the first year at Carmona.

The second agricultural year was characterised by lower CO2 emissions than those registered during the first year. In this case, the highest values at all sites were recorded in spring and the highest percentages of emission differences between farm management systems were 33%, 68% and 60% in autumn, spring and winter for Carmona, Las Cabezas and Cordoba, respectively.

In order to assess the importance of meteorological variables (temperature and rainfall) on CO_2 emissions, we analysed the correlations between these two variables (independently) and the CO2 emissions. The results are presented in table 3.

Table 3. Correlations between CO_2 values measured and temperature(T) and rainfall (R).

		Carmona	*Las Cabezas*	*Cordoba*
Season	***Variables analysed***	***Correlation***		
Autumn	CO_2, R	y=0.02exp(0.637x) R^2=0.94	y=0.04exp(1.34x) R^2=0.80	y=0.06exp(1.33x) R^2=0.945
	CO_2, T	y=22.72exp(-0.06x)	y=-0.13ln(x)+0.24	y=0.03exp(0.38x)

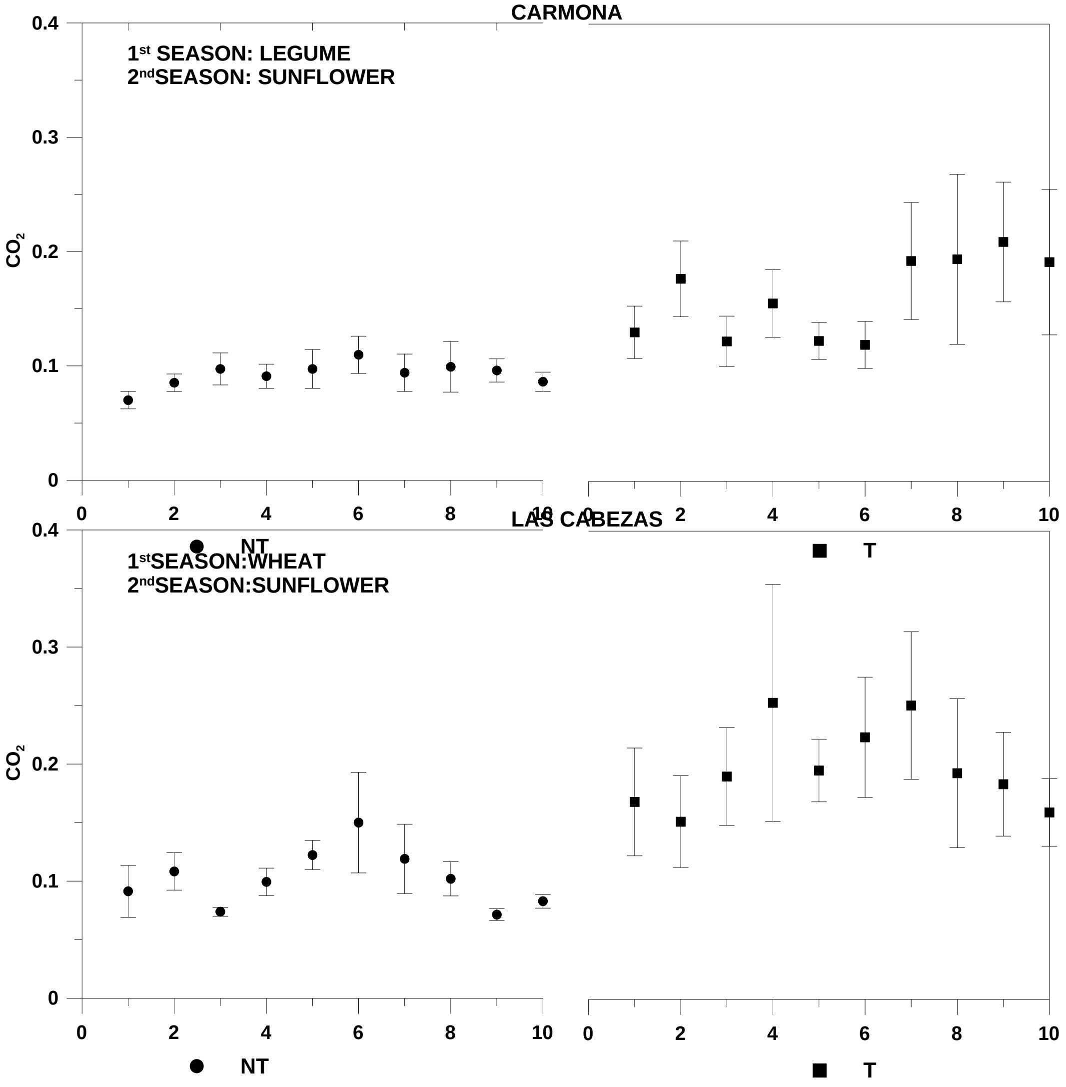
		R^2=0.86	R^2=0.66	R^2=0.61
Winter	CO_2, R	y=6.64exp(-0.526x) R^2=0.91	y=28.88exp(-0.76x) R^2=0.80	y=-7.55ln(x)+8.9 R^2=0.87
	CO_2, T	y=0.145ln(x)+15.34 R^2=0.91	y=0.23exp(-0.27x) R^2=0.70	y=0.05exp(0.21x) R^2=0.20
Spring	CO_2, R	y=9.93exp(-0.106x) R^2=0.32	y=-6.4ln(x)+17.8 R^2=0.61	y=117.04exp(-0.6x) R^2=0.93
	CO_2, T	y=17.34exp(0.012x) R^2=0.53	y=0.39exp(-0.15x) R^2=0.37	y=0.008ln(x)+0.23 R^2=0.10
Summer	CO_2, R	y=-0.06ln(x)+0.08 R^2=0.71	y=-0.08ln(x)+0.14 R^2=0.62	y=-0.17ln(x)+0.27 R^2=0.61
	CO_2, T	y=0.137ln(x)+27.31 R^2=0.10	y=0.07exp(0.09x) R^2=0.28	y=-0.07ln(x)+0.24 R^2=0.34

Regardless of the location considered, a closer relationship can be observed between CO_2 emissions and moisture.

In the case of Carmona and Las Cabezas, the best relationship between gas fluxes and the microclimatic conditions of the soil was observed in autumn and winter, while in Cordoba it was in autumn. The high correlation observed between gas emissions and soil moisture and temperature for the various seasons of both year explains why emission scores are linked to the time of the year that measurements are taken and the number of such readings.

Spatial variability of emissions

Using the method proposed by Vachaud et al. (1985(15)) as a basis, we conducted a study of the spatiotemporal variability of the various experimental plots using both farming systems. The result of the study is presented in Figure 2.



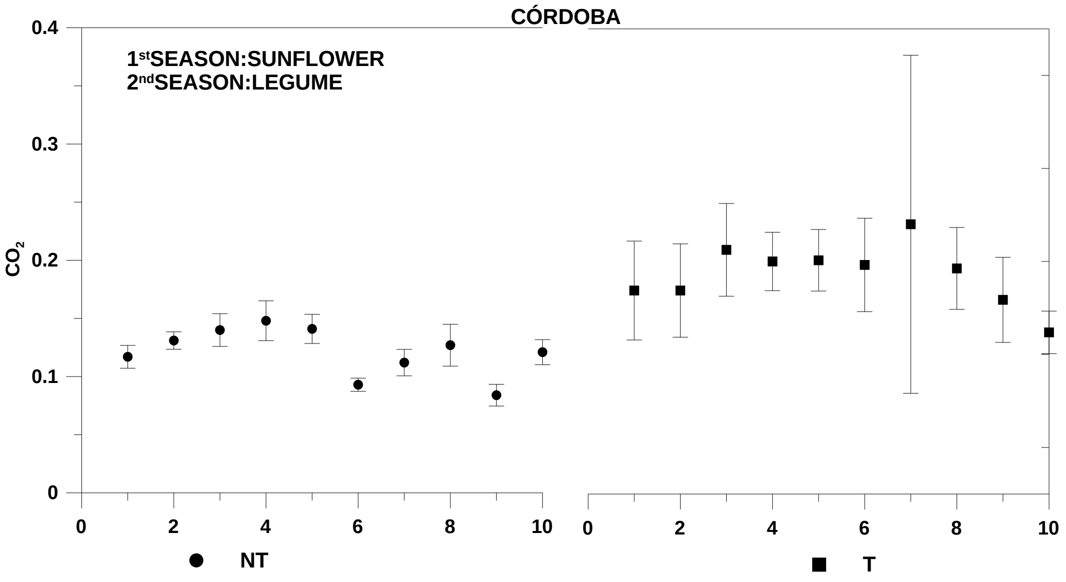


Figure 2. Average value of CO_2 in the ordinate according to its position on the sampling points for the different locations where the study was conducted. Vertical lines indicate the standard error obtained at each point.

The greatest spatial variability is observed in the plots subject to traditional tillage. As can be depicted from Figure 2, the plots under a no-till system show a lower average value than those obtained in the plots using tillage. Similarly, we can appreciate how the deviations from the average value represented by the standard error are higher in the plots using tillage than those under NT farming. These differences can be observed in all three locations studied. It is generally possible to state that soils subject to conventional tillage have a less structured profile with large pores that store a great deal of gas and which differ to a great extent from one point to another in the plot. The soils subject to conservation agriculture techniques generally have a better structure with smaller pores and which is above all more uniform. As a result, there are less differences between points in terms of CO_2 emissions.

Regardless of the soil management system employed, significant differences are observed in the amount of CO2 emitted between points in the same plot. In order to visualise this circumstance more clearly, we have represented the emissions within each of the plots (spatial variability) for different moments in time after carrying out soil relevant operations (temporal variability).

When soil is submitted to any type of operation, CO_2 emissions into the atmosphere increase. This increase begins immediately after the operation is performed and continues over a period of time. This reaction could be due to soil aggregates being broken up, leaving the organic matter within unprotected and exposed to the decomposing activity of microorganisms or to the emission of gas contained in porous spaces in the soil (La Scala *et al*, 2008(17)). In any case, the type of tillage operation changes the pattern of soil CO_2 emissions.

Figure 3 shows the hourly evolution of the CO_2 emissions after seed bed preparation for each study site. It can be seen how, immediately after tillage the CO_2 emissions show a notable rise in the tilled soils when compared to the measurements in the no-till ones.

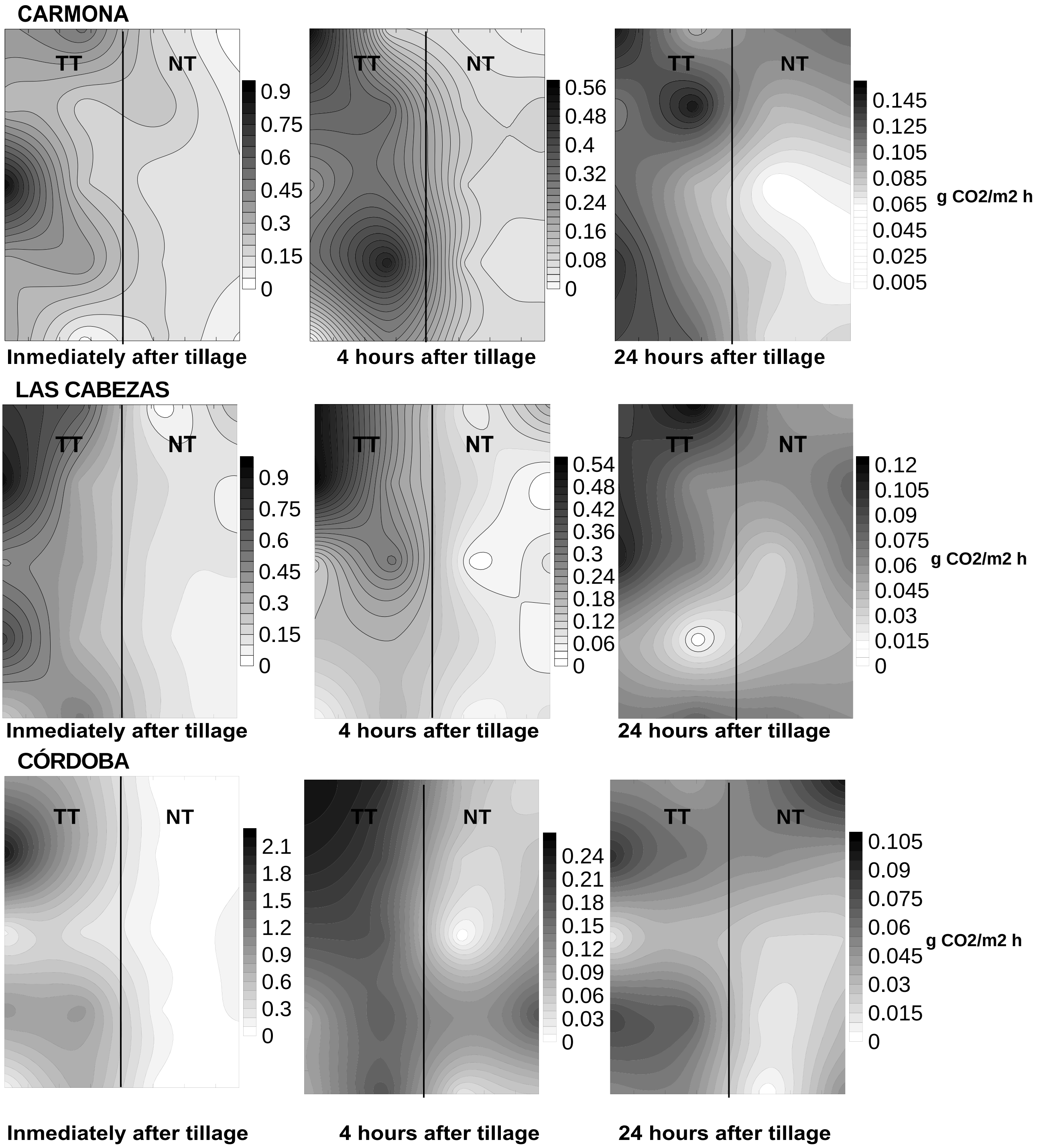


Figure 3. Hourly changes in CO_2 emissions after soil tillage operations for the three locations where the field trial was conducted.

The significant increase in CO_2 emissions that takes place immediately after tilling is due to the physical release of this gas, which is trapped in soil pores.

The highest value of CO_2 emissions is recorded in the majority of situations immediately after tillage is performed. The joint vision of the behaviour of gas in the different sampling exercises indicates that after peaking, CO_2 emissions decrease until they reach similar values in both types of soil management systems. Irregular patterns are also observed in the amount of CO2 emitted. Within the same plot, marked differences in emissions can be observed from one point to another. The reason for this could be the characteristics of the soil and how easy it is for cracks to form due to the differing proportion of expandable clays in the soil under study, through which gas can escape. This is particularly the case in Carmona.

Discussion

Seasonal variability of emissions

The marked seasonal variation in emission data can be explained by the differences in climatic conditions at each time. The high level of rainfall registered in seasons such as autumn and the beginning of winter in some years and spring in others and mild temperatures approaching 20ºC provided ideal conditions for the activity of the microorganisms in the soil resulting in an increase in the soil respiration rate, as could be observed in Figure 1. The content of water in the soil and particularly the content in porous spaces affect the soil respiration rate (Xu & Qi, 2001(18)). There is a wide range of values for the percentage of moisture in the soil in which the respiration rate changes very little in terms of quantity. However, when soil begins to dry out, it reaches a point at which microbial activity is inhibited and respiration decreases.

In a study on the temporal evolution of the CO_2 emissions of Thermic Xerollic Calciothird soil in a semiarid climate, Álvaro et al, (2007(12)) also observed how seasonality and the presence or lack of presence of crops had a clear influence on soil respiration. These authors indicate that rainfall of 22mm induced increments of approximately 0.10-0.15 g CO2 m^{-2} h^{-1} in three tillage treatments.

In Mediterranean regions, such as those in our case study, soil respiration during summers that are typically very dry is limited by a lack of water, whereas during the rest of seasons this aspect is more controlled by temperature (Rey *et al*, 2002(19)). In our case, the lowest emission figures in both agricultural years were recorded during summer.

We must also take into account that in very moist soils, aeration is highly restricted because a large number of pores are full of water. As a result, CO_2 emissions into the atmosphere decrease (Smith *et al*, 2003(20)).

Rochette and Angers (1999(21)), measuring CO_2 fluxes over several days after autumn, spring and summer mouldboard ploughing, observed that climatic conditions following tillage operations play an important role in CO_2 emissions between dates.

When the data from the correlation study were presented in the results section, we already indicated the high degree of correlation obtained in practically all cases. If we compare the data obtained for the different variables studied, we can see that CO_2 values are more correlated to moisture than to temperature. Prior at al., (2004(22)) suggested that these small changes on soil water content and temperature help to interpret differences in CO_2 fluxes between tillage treatments.

Our results differ to those obtained by Álvaro et al. (2007(12)), as these authors found no significant relationship between CO_2 fluxes and soil temperature and water content.

Spatial variability of emissions

CO_2 emissions are closely related to the moisture and temperature conditions in the area we study. Some studies assign greater importance to soil temperature and suggest there is a strong relationship with daily CO_2 emissions (Regina & Alakukku, 2010(9)), while others find a high level of correlation between soil moisture and emissions (Menéndez et al, 2008(23)).

In the case of no-till systems, the fact that the soil is disturbed less or not at all benefits the physical properties of the soil and reduces the decomposition of organic matter (Melero *et al*, 2009(24)). All these statements lead to the conclusion that soils that maintain more stable temperatures, as in the case of no-till soils due to the protection provided by the cover, together with the lower degree of decomposition of organic matter, record lower emissions that are also more homogeneous over time.

Regina & Alakukku (2010(9)) obtained higher respiration rates in soils that had received some type of tillage treatment and attributed this not only to soil temperature, but also to SOC, as the decomposition rate of the organic matter in soils that had not been tilled was lower and registered a higher content of SOC.

In a study about the effects of tillage and cropping systems on soil CO_2 emissions during three cropping seasons in three different sites of the Ebro river valley (Northeast Spain), Álvaro et al. (2008(25)) observed that conventional tillage emitted 30% more soil CO_2 than no-till farming and led to a negative soil C balance, indicating a loss of SOC.

In our case, no-till soils generally record greater SOC than those subjected to tillage operations. The table below presents the data regarding SOC for the three areas studied.

Table 3. OC(%) content in the three locations studied for the 0.05, 0.10 and 0.20 m of soil depth.

		Carmona		**Las Cabezas**		**Cordoba**	
		1stYear: Legume **2ndYear: Sunflower**		**1stYear: Wheat** **2ndYear: Sunflower**		**1stYear: Sunflower** **2ndYear: Legume**	
Depth (cm)		**Initial %**	**Current %**	**Initial %**	**Current %**	**Initial %**	**Current %**
0-5	**NT**	1.22a*	1.14a**	1.06 a	1.36 a	1.65a**	1.50a**
	T	1.19b*	0.98b**	1.16 a	1.31 a	1.21b**	1.22b**
5-10	**NT**	1.25a	1.05a	1.06a*	1.36 a	1.67a*	1.72a***
	T	1.11a	0.96a	1.31b*	1.18 a	1.37b*	1.29b***
10-20	**NT**	1.25a	1.06a*	1.02a	1.25 a	1.58a	1.45a**
	T	1.14a	0.83b*	1.25a	1.14 a	1.67a	1.21b**

We can generally see how SOC content is currently higher in most of the plots where no tillage operations have been performed on the soil. Different soil CO_2 emissions from one site to another were the result of both different amounts of CO_2 stored within soil pores at the plots under tillage and the different tillage operations. The CO_2 stored in soil pores is affected by soil characteristics, soil microclimatic conditions from harvest to tillage, the amount and quality of crop residues and the time elapsed between crop harvest and tillage.

The present study suggests that the spatial variability observed in Fig. 3 is mainly due to soil characteristics such as a greater proportion of expandable clays, which produces cracks in the ground during dry periods. These results coincide with those obtained by Ordóñez *et al*, 2008(26) in a field trial performed on soils with similar characteristics in the Vega de Carmona, where differences were found between some points and others in the same plot due to the presence of discontinuities in the soil surface.

In reference to the hourly variability in CO_2 fluxes following tillage operations, we observe that there are no noticeable differences in the amount of gas emitted prior to tillage operations in both types of soil management systems. However, immediately after tillage operations, CO_2 emissions rise substantially in tilled soils in regard to the measurements taken in non-till soils.

Several studies have observed greater CO_2 fluxes under conventional tillage compared with no-till farming for several days after such operations, due to their promoting soil microbial activity (Reicosky, 1997(27); Curtin et al., 2000(28); Alvarez et al., 2001(29)).

The results obtained in our study in regard to the hourly variability of emissions, albeit slightly lower, are similar to those obtained by Álvaro-Fuentes *et al.* (2004(30)) and Morell *et al.* (2010(31)) in the provinces of Zaragoza and Lleida, respectively, in the northeast of Spain. The magnitude of the response of conservation agriculture systems to carbon sequestration and the reduction in emissions varies considerably depending on the depth of tillage and the edaphic and climate conditions in the area.

Conclusions

The results obtained reveal that No-till Farming particularly favours reductions in CO_2 fluxes into the atmosphere emitted by soils in regard to those subjected to traditional farming systems. This difference increases further after tillage operations are performed on the soil in the plots using conventional tillage, which breaks up soil aggregates and frees the gas trapped therein. At all sites, soil CO_2 emissions under NT were low and remained steady throughout the entire study period. Emissions were up to 80% higher in the case of soils subjected to conventional tillage.

In the Mediterranean area, annual rainfall variability has a strong influence on soil microbial activity and, consequently, on differences in the CO_2 stored in soil pores between seasons. There were also significant increases in the amount of emissions during periods of abundant rainfall in the month prior to data collection.

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Table 1. Physico-chemical characteristic of the upper 0.2 m of the soil studied.

	OC	**C.E.C**	**P**	**K**	**Ca**	**Mg**	**Sand**	**Silt**	**Clay**
	%	***$mol_c kg^{-1}$***	***gr/100gr***				***%***		
Carmona	1.1	0.3	17.2	589.5	12.3	638.5	15.8	25.5	58.7
Las Cabezas	1.1	0.3	28.0	406.7	7.5	519.3	19.9	28.7	51.5
Córdoba	1.7	0.2	13.2	262.7	5.7	263.5	30.7	32.1	37.2

Table 2. Average temperatures (ºC), accumulated rainfall (mm) and standard deviation during the study period (season 2009/10 and 2010/2011).

	CARMONA		***LAS CABEZAS***		***CORDOBA***	
	Rain	Av. Temp	Rain	Av. Temp	Rain	Av. Temp
Jan	150.6±6.7	9.9±1.9	196.4±6.2	11.4±2.5	190.6±6.9	9.3±2.4
Feb	283.0±10.4	10.4±2.7	266.8±9.4	11.1±2.9	306.3±9.9	9.3±2.8
Mar	142.0±5.5	13.6±2.8	153.6±5.4	14.1±2.8	144.6±5.7	12.7±2.7
Apr	119.4±4.0	17.4±2.8	98.2±3.7	18.1±2.4	121.5±4.9	17.3±2.7
May	27.2±2.1	20.8±3.3	48.6±2.5	21.1±2.9	106.1±6.7	20.5±3.0
Jun	27.6±3.7	23.5±3.4	32.2±3.8	23.3±2.9	50.1±3.4	24.0±3.5
Jul	0.0±0.0	23.2±3.6	0.2±0.0	27.1±1.8	0.6±0.0	28.1±1.8
Aug	0.2±0.1	29.4±2.6	1.8±0.2	28.2±2.1	28.8±3.3	29.0±2.2
Sep	55.4±11.9	24.3±2.8	18.8±1.4	23.8±2.3	56.5±4.2	23.8±2.5
Oct	14.6±3.1	19.8±2.6	132.6±8.6	19.8±2.5	157.0±8.2	19.1±2.8
Nov	137.2±9.3	13.4±2.9	128.4±6.1	14.1±2.6	112.3±5.1	12.3±2.7
Dec	570.0±10.7	11.7± 3.6	414.8±10.7	12.8±3.8	671.4±17.7	10.2±.3.5

Table 3. Correlations between CO_2 values measured and temperature(T) and rainfall (R).

		Carmona	***Las Cabezas***	***Cordoba***
Season	***Variables analysed***	***Correlation***		
Autumn	CO_2, R	$y=0.02\exp(0.637x)$ $R^2=0.94$	$y=0.04\exp(1.34x)$ $R^2=0.80$	$y=0.06\exp(1.33x)$ $R^2=0.945$
	CO_2, T	$y=22.72\exp(-0.06x)$ $R^2=0.86$	$y=-0.13\ln(x)+0.24$ $R^2=0.66$	$y=0.03\exp(0.38x)$ $R^2=0.61$
Winter	CO_2, R	$y=6.64\exp(-0.526x)$ $R^2=0.91$	$y=28.88\exp(-0.76x)$ $R^2=0.80$	$y=-7.55\ln(x)+8.9$ $R^2=0.87$
	CO_2, T	$y=0.145\ln(x)+15.34$ $R^2=0.91$	$y=0.23\exp(-0.27x)$ $R^2=0.70$	$y=0.05\exp(0.21x)$ $R^2=0.20$
Spring	CO_2, R	$y=9.93\exp(-0.106x)$ $R^2=0.32$	$y=-6.4\ln(x)+17.8$ $R^2=0.61$	$y=117.04\exp(-0.6x)$ $R^2=0.93$
	CO_2, T	$y=17.34\exp(0.012x)$ $R^2=0.53$	$y=0.39\exp(-0.15x)$ $R^2=0.37$	$y=0.008\ln(x)+0.23$ $R^2=0.10$
Summer	CO_2, R	$y=-0.06\ln(x)+0.08$ $R^2=0.71$	$y=-0.08\ln(x)+0.14$ $R^2=0.62$	$y=-0.17\ln(x)+0.27$ $R^2=0.61$
	CO_2, T	$y=0.137\ln(x)+27.31$ $R^2=0.10$	$y=0.07\exp(0.09x)$ $R^2=0.28$	$y=-0.07\ln(x)+0.24$ $R^2=0.34$

Table 4. OC(%) content in the three locations studied for the 0.05, 0.10 and 0.20 m of soil depth.

		Carmona		**Las Cabezas**		**Cordoba**	
		1stYear: Legume **2ndYear: Sunflower**		**1stYear: Wheat** **2ndYear: Sunflower**		**1stYear: Sunflower** **2ndYear: Legume**	
Depth (cm)		**Initial %**	**Current %**	**Initial %**	**Current %**	**Initial %**	**Current %**
0-5	**NT**	1.22a*	1.14a**	1.06 a	1.36 a	1.65a**	1.50a**
	T	1.19b*	0.98b**	1.16 a	1.31 a	1.21b**	1.22b**
5-10	**NT**	1.25a	1.05a	1.06a*	1.36 a	1.67a*	1.72a***
	T	1.11a	0.96a	1.31b*	1.18 a	1.37b*	1.29b***
10-20	**NT**	1.25a	1.06a*	1.02a	1.25 a	1.58a	1.45a**
	T	1.14a	0.83b*	1.25a	1.14 a	1.67a	1.21b**

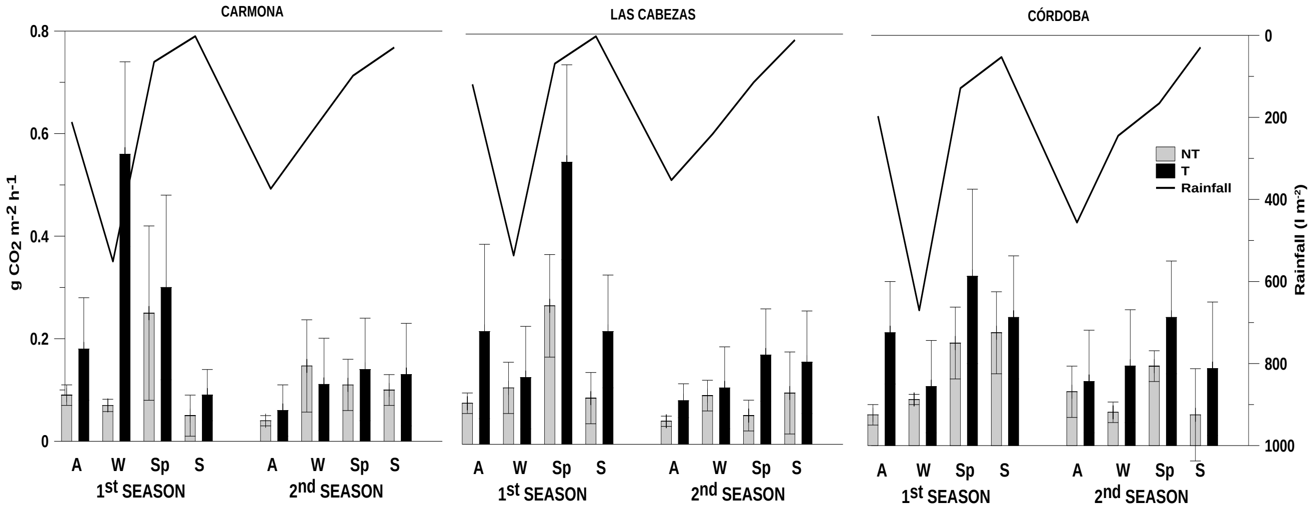

Figure1. Emissions recorded during the various seasons at each of the locations studied. A (autumn); W (winter); Sp (spring); S (summer). NT (No-Till); T=Tillage

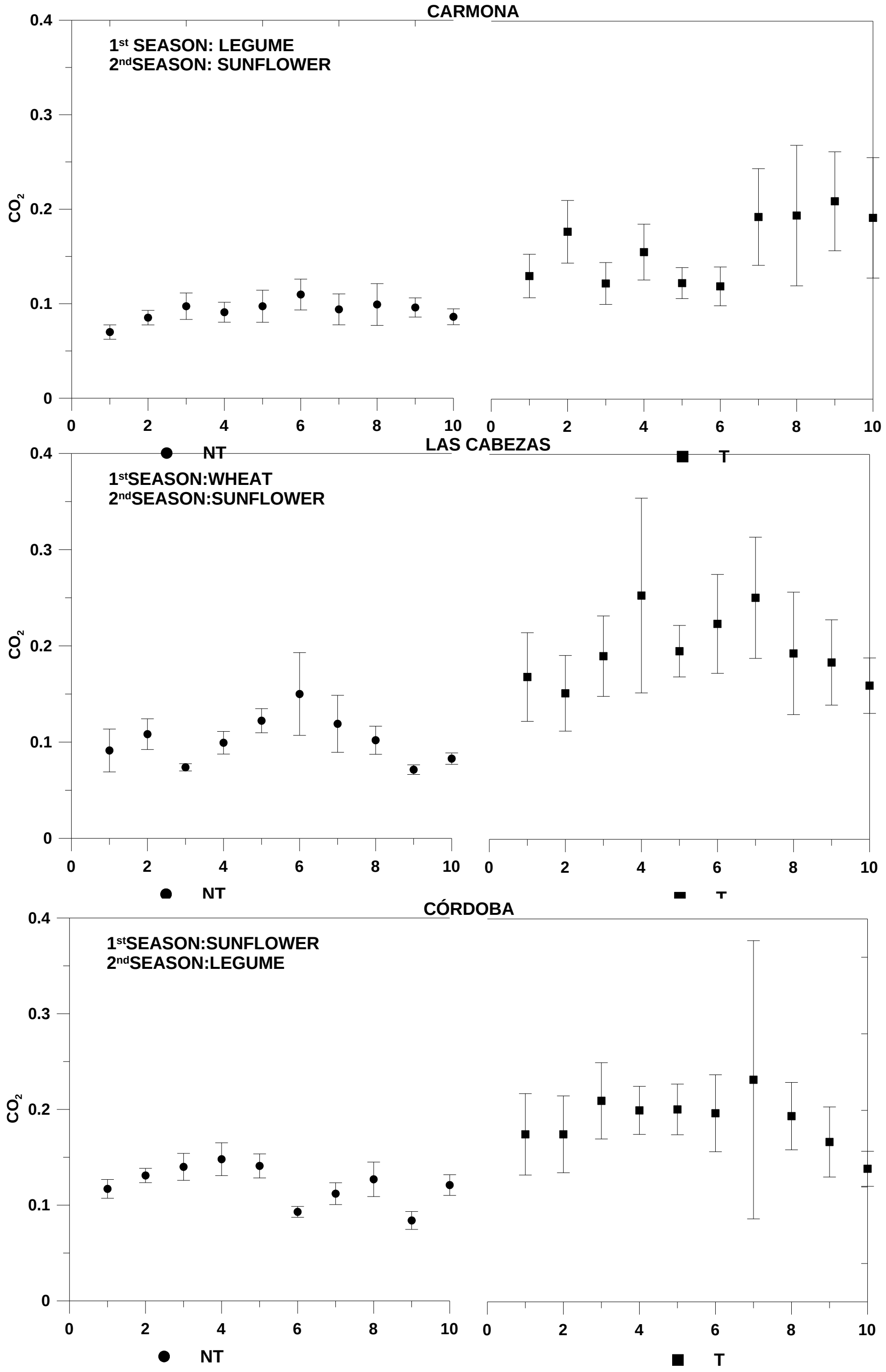

Figure 2. Average value of CO_2 in the ordinate according to its position on the sampling points for the different locations where the study was conducted. Vertical lines indicate the standard error obtained at each point.

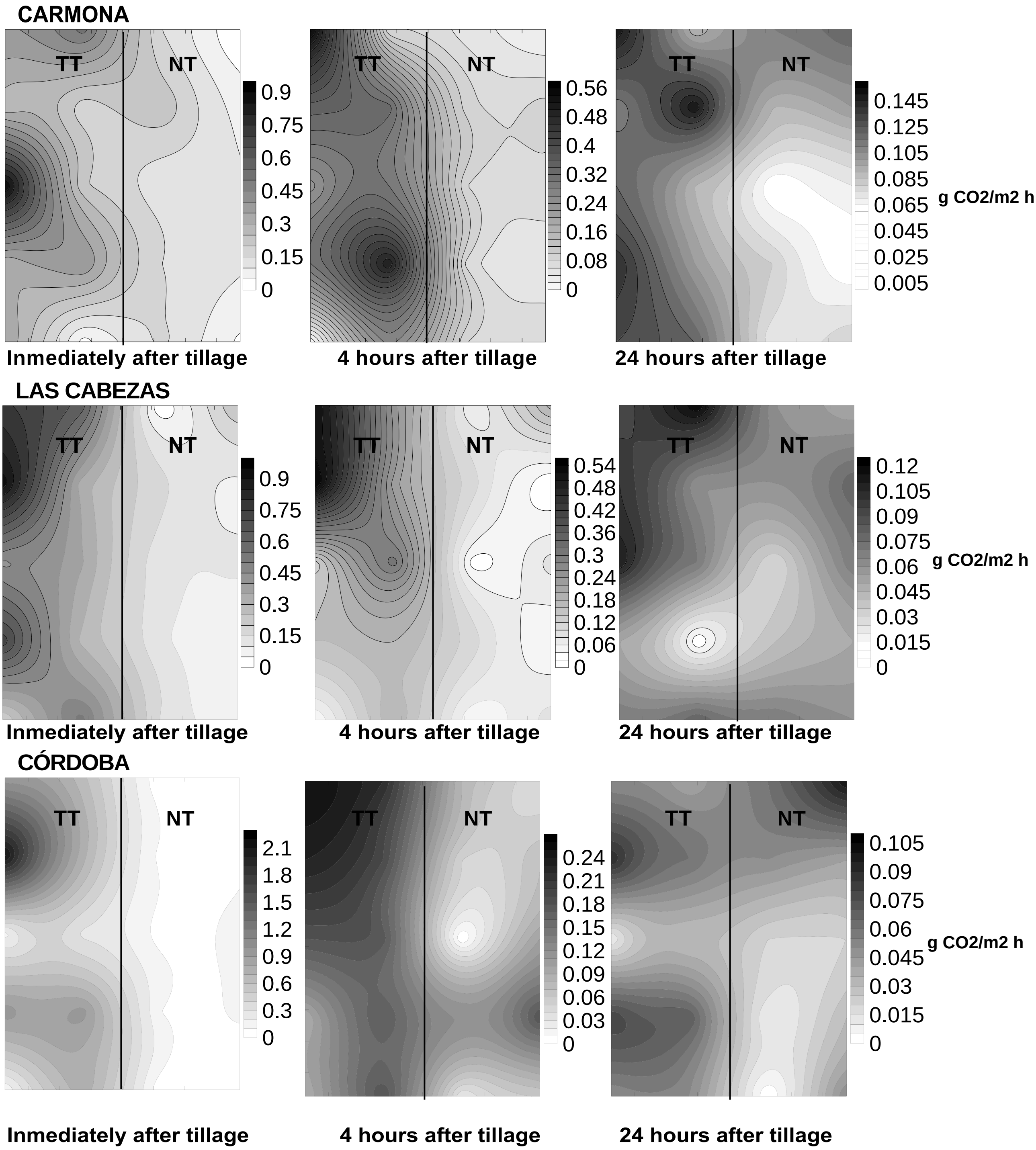

Figure 3. Hourly changes in CO_2 emissions after soil tillage operations for the three locations where the field trial was conducted.