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RESEARCH ARTICLE

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Soil organic carbon accumulation and carbon dioxide emissions during a 6-year study in irrigated continuous maize under two tillage systems in semiarid Mediterranean conditions

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Abstract

Aim of study: To evaluate the effects of conventional tillage (CT) and no tillage (NT) systems on the soil organic carbon (SOC) changes, CO_2 emissions and their relation with soil temperature and grain yield in a monoculture of irrigated maize during six years.

Area of study: In Zamadueñas experimental field in the Spanish province of Valladolid, from 2011 to 2017.

Material and methods: The SOC content was determined by collecting soil samples up to 30 cm in November at two years interval. Short-term CO_2 emissions were measured simultaneously with soil temperature using a respiration chamber and a hand-held probe immediately before, after every tillage operation and during the maize cycle.

Main Results: The SOC stock of the top 30 cm soil layers was 13% greater under NT than CT. Short-term CO_2 emissions were significantly higher under CT ranging from 0.8 to 3.4 g CO_2 m^{-2} h^{-1} immediately after tillage while under NT system, soil CO_2 fluxes were low and stable during this study period. During the first 48 h following tillage, cumulative CO_2 emissions ranged from 0.6 to 2.4 Mg CO_2 ha^{-1} and from 0.2 to 0.3 Mg CO_2 ha^{-1} under CT and NT systems, respectively. Soil temperature did not show significant correlation with CO_2 emissions; however, it depended mostly on the time of measurement.

Research highlights: No tillage increased the SOC accumulation in the topsoil layer, reduced CO_2 emissions without decreasing maize grain yield and minimized the impact on climate change compared to CT system.

Additional key words: CO_2 emissions; conventional tillage; no-tillage; soil organic carbon

Abbreviations used: BD (bulk density); CT (conventional tillage); GHG (greenhouse gases); NT (no-tillage); OM (organic matter); SOC (soil organic carbon); SOM (soil organic matter)

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Introduction

Maize crop (*Zea mays* L.) is one of the most important crops worldwide and its production is mainly assured by conventional methods as the frequent ploughing of the soil. The use of mouldboard plough for crop residues management and soil preparation is a common practice among farmers. In short-term period, conventional tillage (CT) creates a good soil environment for crop growth, while in a long-term period, this practice would promote the soil erosion and degradation and would increase the mineralization and the depletion of soil organic matter (SOM) (Lenka & Lal, 2013). The conversion from CT to no-tillage (NT) would improve the soil quality and water retention, diversify the soil fauna and reduce the potential for soil erosion and the loss of soil organic carbon (West & Post, 2002; Halvorson *et al.*, 2008). The soil organic carbon (SOC) is a significant indicator of the soil quality as it helps to improve its structure, ameliorate the crop/crop residue ratio and mitigate the effects of climate (Lal, 2007) which is suffering drastic changes caused by the increase of the greenhouse gases concentration (GHGs).

In the agricultural sector, CO_2 is released during the burning of fossil fuels, the use of agricultural machinery, the production of synthetic fertilizers and pesticides, the microbial decomposition and the burning of stubble and SOM (Lal, 2004). However, the land use changes have a double synergistic effect, as a sink (carbon (C) sequestration increase) and as mitigation (reduction of emissions). Soils can function as either a source or a sink for atmospheric GHG depending on land use and soil management. Appropriate management can enable agricultural soils to provide a net sink for sequestering atmospheric CO_2 and other GHGs (Paustian *et al.*, 1997a; West & Post, 2002). Agricultural operations such CT promotes the rapid oxidation processes and the release of a large CO_2 amount into the atmosphere, decreasing the levels of organic matter (OM) and contributing to the global warming. Conservation agriculture such as NT practices improves the soil structure, water retention and helps the nutrients preservation. The non-disturbance of the soil and the remaining of the crop residues on the soil surface promoted the increase of the SOC thanks to the reduction of the SOM mineralisation (Balota *et al.*, 2004; Sombrero & De Benito, 2010). The alteration of soil profile increases the flux of CO_2 emissions into the atmosphere and begins immediately after conducting the operation. Therefore, management and land use could be applied to mitigate GHG emissions by sequestering C in the soil and creating a sink for atmospheric CO_2 (Paustian *et al.*, 1997b). No-tillage system could play an important role by increasing SOC and improving the environmental quality in the production systems (Reicosky *et al.*, 1997) and would be a viable alternative to stabilize CO_2 concentrations in the atmosphere and a way to counteract climate change.

The literature indicates contradictory results respect to tillage effects on CO_2 emissions, as Franzluebbers *et al.* (1995) reported similar or more CO_2 fluxes under a 9 years old NT management compared to CT system, while Al-Kaisi & Yin (2005) observed significantly lower CO_2 emission from NT system than CT during the short period after tillage disturbance. Vinten *et al.* (2002) found higher CO_2 emissions for some periods and lower for others under NT compared to CT. Differences of CO_2 emissions may be the result of short- and long-term effects (Ussiri & Lal, 2009). Pareja-Sanchez *et al.* (2019) found that in the first and second year of experiment, cumulative CO_2 emissions were greater under NT compared to CT, while in the third year, no differences were found between tillage systems in maize growing season. In 2019, the largest non-tilled lands were recorded in Castile and Leon with an area of 2.492.437 ha (MAPAMA, 2019), nevertheless few studies were conducted and limited information is available on the effect of NT system on SOC and CO_2 emissions in irrigated crops in semiarid areas. To maintain the soil quality, the crop productivity, and to contribute to the mitigation of the GHGs, it is necessary to investigate changes in SOC accumulation and CO_2 emissions and to identify tillage systems that enhance soil conservation. Therefore, this study aims to evaluate the effects of NT and CT managements on the SOC changes, the CO_2 emissions and its relation with both soil temperature and moisture and grain yield in a monoculture of irrigated maize during six years in a semiarid region of Castile and Leon.

Material and methods

Site, treatments and experimental design

The trial was carried out from November 2011 to September 2017 in Zamadueñas experimental field located in the Spanish province of Valladolid (41º42´23´´ N, 4º41´36´´ W). The experiment was set up on a Typic Xerofluvent soil (Soil Survey Staff, 1994), characterized by a silty texture with fine detritic deposits and calcilutites as parent material. The soil physicochemical properties recorded at the beginning of the experiment are detailed in Table 1.

The climatic conditions are classified as continental Mediterranean and are characterized by cold winter and warm summer with a mean annual temperature of 12.7 °C. The lowest temperatures recorded were in January and the highest in July and August. The annual precipitation reached 405.6 mm and was concentrated from September to May (85%). The data obtained were collected at the meteorological Zamadueñas station situated at 200 m from the experimental site and are detailed in Table 2.

The experimental design included four blocks randomly chosen and 16 plots of 144 m^2 each where the studied factor was tillage system (CT and NT) in a monoculture of irrigated maize. Under CT, the seedbed preparation

Table 1. Soil physicochemical characteristics at 0-30 cm depth under conventional tillage (CT) and no-tillage (NT) systems

Tillage system	Bulk density (g cm^{-3})	Texture (%)			pH	OC	Total C	Total N	P_2O_5	K_2O
		Sand	Silt	Clay			(g kg^{-1})		(mg kg^{-1})	
CT	1.38	32.1	50.7	19.3	8.2	5.0	9.8	0.8	26	226
NT	1.39	29.8	48.6	19.5	8.4	5.6	10.8	0.8	18	227

OC: organic carbon

Table 2. Mean air temperature and total precipitation in growing seasons 2011-2017 and historic mean values (1981-2010) at Zamadueñas experimental station, Spain.

Months	Mean temperature (ºC)								Total precipitation (mm)							
	2011	2012	2013	2014	2015	2016	2017	1981-2010	2011	2012	2013	2014	2015	2016	2017	1981-2010
January	4.6	2.2	4.6	5.9	1.7	6.2	2.5	4.3	46.5	28.4	36.8	22.8	28.0	116.0	10.3	38.2
February	5.1	2.6	4.0	5.4	4.3	5.8	7.0	5.8	29.8	1.0	31.2	48.1	16.4	38.8	39.9	23.9
March	7.9	8.6	7.1	8.7	8.4	6.1	9.2	9.0	44.0	7.6	117.9	11.0	16.8	32.2	6.0	23.3
April	13.7	8.6	9.5	13.0	11.8	9.1	12.6	10.3	49.4	66.8	28.6	22.4	66.0	99.4	3.8	41.9
May	16.4	16.0	11.0	14.1	15.7	13.1	16.7	14.5	37.0	20.2	27.9	18.8	19.8	47.4	42.0	46.0
June	18.3	19.2	16.3	18.5	19.7	19.1	22.4	19.3	18.6	12.6	33.6	9.6	76.2	1.9	5.4	28.7
July	19.7	20.4	23.0	20.3	23.7	23.0	22.4	22.3	0.0	12.2	9.4	66.2	4.2	5.4	33.2	14.0
August	21.0	21.6	20.9	20.6	21.1	22.4	21.8	22.1	34.8	1.4	29.0	0.2	5.2	0.2	13.6	15.0
September	18.5	17.4	17.6	18.5	16.1	18.6	17.5	18.5	0.0	21.8	0.0	61.2	23.6	13.0	0.2	30.2
October	13.1	12.0	13.2	15.0	12.8	13.5	14.7	13.2	17.2	72.6	23.2	37.0	54.2	46.2	7.2	53.9
November	8.5	7.4	6.8	9.3	8.3	6.9	6.1	7.9	64.4	60.4	3.2	71.4	46.8	48.9	17.6	45.7
December	4.0	5.1	2.7	3.8	5.3	4.1	4.0	5.0	11.0	21.4	1.8	17.2	18.4	12.6	26.2	44.1

consisted of a complete inversion of the soil surface and nearly a 90% incorporation of crop residue in November-December using a mouldboard plough that can reach up to 35 cm soil depth, followed by one pass of spring tine cultivator (10-15 cm depth). While NT system consisted of chemical weed control during the fallow period with glyphosate (2.5 L ha^{-1}) and sowing directly into the standing residues of the previous crop. Prior to the setting up of the experiment, vetch (*Vicia sativa*) crop was sown in November 2010 in order to homogenize the plots. Under CT, it was buried by mouldboard plough while under NT practice, it was chemically treated and the crop residues remained on the soil surface. Every year, a distance of 55 cm between maize rows and 22 cm between plants were left giving a mean plant population of 90,000 plants ha^{-1}. The maize sowing was achieved using a "Nodet" conventional drill in CT plots and a "Semeato" no-till seed drill in NT plots. Moreover, the set 8-15-15 of N, P_2O_5 and K_2O was applied in every plot at a rate of 800 kg ha^{-1} and herbicides such as Camix (4% Mesotrione, 40% S-metolachlor (3.5 L ha^{-1})), Closar (Chlorpyrifos 48% (15 kg ha^{-1}), Emblem (Bromoxynil 20% (2.25 L ha^{-1})) were applied to prevent from the development of some maize diseases. Sprinkler irrigation was established according to the crop hydric needs and the meteorological conditions, and the amount of water applied was estimated according to the crop evapotranspiration (ET_c) which was calculated by multiplying the reference crop evapotranspiration ET0 (obtained using the Penman-Monteith equation, mm d^{-1}) by the crop coefficient K_c. The amount of water applied for irrigation were 5810, 4390, 5450, 7492, 6820 and 3847 m^3 ha^{-1} from 2012 to 2017 respectively. In 2017, irrigation treatments were restricted due to the lack of water in the region which explains the low amount of water provided to the crop. The maize growth stages were visually identified in every plot in order to determine the optimum times of CO_2 flux measurements.

Soil sampling and analysis

At the outset of the study and during the following years, the SOC was determined by collecting soil samples after the maize harvest in 2011, 2013, 2015 and 2017 at three sites in each elementary plot to obtain a composite sample per plot at depths of 10, 20 and 30 cm. The samples were air dried and sieved through a 2 mm mesh. The total C and SOC contents were determined by dry combustion with a LECO CNS 1934. The SOC was obtained using the following equation:

$$SOC_i = OC_i \cdot BD \cdot d_i \cdot 10$$

where SOC_i is the soil organic carbon of the ith soil layer (Mg ha^{-1}), OC is the organic carbon concentration of the ith soil layer (kg Mg^{-1}), BD is the bulk density (Mg m^{-3}), and d is the thickness (depth) of the ith soil layer (in m).

Soil CO_2 fluxes were measured with an EGM-4 2000 soil respiration chamber (PP Systems International, Amesbury, MA, USA), which is a manual system composed of an EGM-4 IRGA (InfraRed Gas Analyzer) system linked to a cylindrical soil respiration chamber SRC-1 (diameter 10 cm, height 15 cm). This system makes "Auto-zero" in order to adapt to environmental conditions and afford a stabilit chamber is directly inserted about 1-2 cm deep in the soil surface and the airflow rate was adjusted to 900 m L min^{-1}. Soil CO_2 fluxes were considered as the difference of CO_2 concentration when the air flows through the chamber and when it leaves. After 2 minutes, CO_2 fluxes were recorded and the readings were taken when CO_2 flux was stable enough to prevent from possible unrealistic values that could be caused by the disturbance produced after placing the chamber into the soil (Pumpanen *et al.*, 2004). Measurements were taken twice in every plot in order to corroborate a correct data set. The short-term influence of tillage on soil CO_2 evolution was assessed by recording series of successive measurements during the soil´s preparation and sowing. These measurements were recorded before any field operation took place, then immediately after and at 2, 4, 24 and 48 h after each operation and during maize growing seasons in both CT and NT systems. Annual total soil CO_2 flux was obtained by summing all the measured and interpolated hourly values, total micromoles of CO_2 for the year were converted into kg CO_2 ha^{-1}. Cumulative CO_2 emissions were quantified on a mass basis (Mg ha^{-1}) using the trapezoid rule.

From 2012 to 2017, soil temperature was measured with a hand-held probe (model STP-1, PPSystems) which was inserted at 5 cm into the soil away from the edge of the CO_2 chamber. A soil temperature value was recorded at the same time as the soil CO_2 flux was recorded. From 2015 to 2017 a soil-surface sample were collected at 10 cm depth along CO_2 measurements to determine the gravimetric soil water content. To determine the biomass and grain yield of the maize crop, plants samples were picked in one-meter area from four rows and were weighed. Furthermore, in every plot, two strips of 12 m × 1.5 m were harvested and grains were weighed separately to estimate the crop yield at maturity in October-November.

Statistical analysis

Data were statistically analyzed using the general linear model (GLM) procedure (SAS Institute. 9.4) applying Tukey's test at 5% significant level ($p \leq 0.05$). Regression models were fitted to the date to describe the relationship between climatic variables and CO_2 emissions. Spearman and Pearson correlation was calculated to determine the relationship between soil CO_2 flux and both soil temperatures and moistures.

Results

Air temperature and precipitation

During the maize cycle, the coldest months were April and November (Table 2). Mean temperatures in April (2011, 2014, 2015 and 2017) and November (2011, 2014 and 2015) were warmer than the one recorded in 1981-2010. The third year (2013) recorded the lowest temperatures compared to long-term means. The warmest temperatures in this studied period occurred in July when the mean temperatures were warmer in 2013, 2015 and 2016 than the long-term mean. The warmest year was 2017 followed by 2015. Generally, the months of least precipitation were July and August highlighting that in 2012, 2015 and 2016, the rainfall scarcity combined with high temperatures and evapotranspiration led to the increase of the maize hydric needs. The higher precipitation in June and August 2013 and in July 2014 led to the decrease of the number and the amount of irrigation treatments. During 2017, the combination of the precipitation scarcity and the high temperatures from March to July, led to earlier irrigation treatments that were cut off on August 11, because of the water lack in the region.

Soil temperature and moisture

Soil temperature was recorded from tillage to crop maturity during the six years of the study. The lowest soil temperature occurred in winter and late August-September while the warmest was reported from June to late August (Fig1. 1). Soil temperature reported under NT system was significantly cooler in 2012 (mean difference 1.3 ºC) and 2017 (mean difference 2.3ºC) than under CT. In 2013, 2014 and 2016 low and generally non-significant differences were recorded between both tillage systems (under NT from 0.7 to 0.9ºC lower than CT). Nevertheless, from December to March 2015, soil temperature was slightly warmer (0.9 ºC) under NT than under CT system.

The highest soil moisture level was recorded in May 2015, July 2016 and 2017. After the month of August, this parameter decreased until the soil dried in September (Fig. 2). The high level of soil moisture during summer months is caused by irrigation treatments that started in May-June and ended in September. The NT system displayed the highest soil moisture levels and went from 1.8 to 7.7%, from 1.3 to 6.3% and from 1.3 to 6.0% greater than CT system in 2015, 2016 and 2017 respectively.

Grain yield and crop residues

The maize grain yield ranged from 9.4 to 17.3 Mg ha^{-1} under CT system and from 11.2 to 19.6 Mg ha^{-1} under NT system. The crop residues left on the soil surface varied from 4.6 to 24.6 Mg ha^{-1} and from 4.6 to 30.2 Mg ha^{-1} under CT and NT systems respectively (Table 3). Mean grain yield and crop residues were 6.6 and 17.8% higher

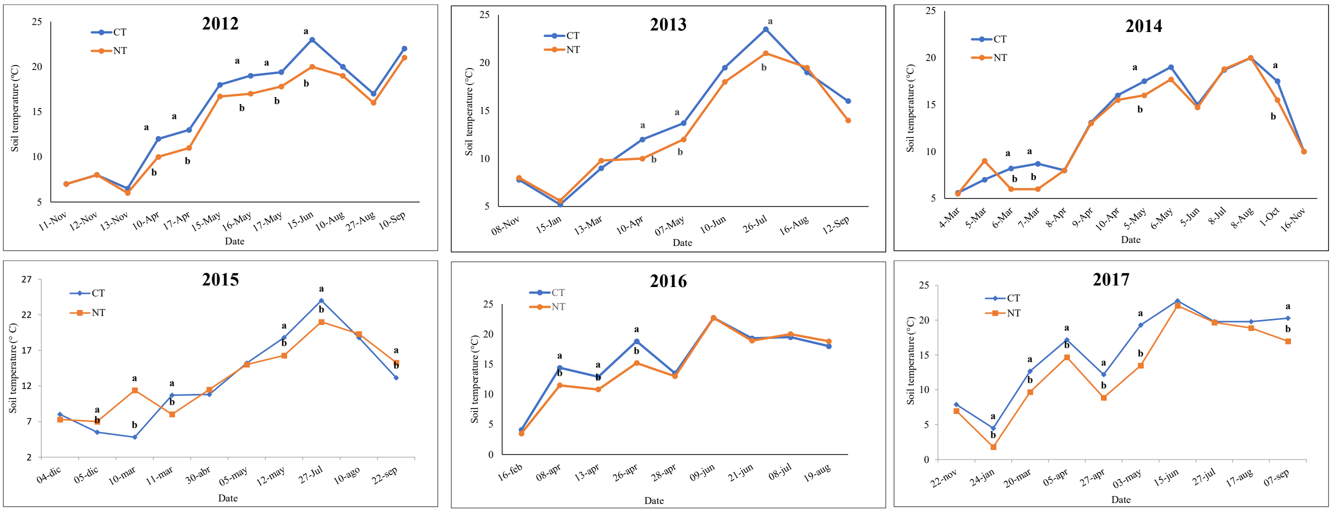

Figure 1. Soil temperature from tillage to maize maturity under conventional tillage (CT) and no-tillage (NT) through 2012-2017. Data with different letter are significantly different (α=0.05).

under NT than CT management, respectively. Nevertheless, both grain yield and maize residues did not display significant differences among tillage systems during the studied years, except in 2013 and 2017, where the maize grain yield was 16 and 19% significantly higher under NT than CT treatment, respectively.

SOC distribution and accumulation

Throughout the 0-30 cm soil depth, the SOC content increased under both tillage systems in 2017 compared to the initial situation in 2011 (Table 4). In November 2011, the results showed that mean SOC accumulation was significantly higher in NT than CT plots through the studied soil profile. In the first 30 cm soil depth, SOC content was 24% higher in NT plots than in CT plots. In 2013, the SOC content stored in the soil did not vary significantly according to tillage system; however, it was 0.8, 0.3 and 1.0 Mg ha^{-1} higher under NT than CT system at 0-10, 10-20 and 20-30 cm soil depth respectively. In this year, SOC values were also 8% higher under NT system than the mean obtained under CT in the first 30 cm (Table 4). In 2015 and 2017, the SOC stocks were 22% and 36% higher respectively under NT system than CT at 0-10 cm soil depth while at 20-30 cm depth, SOC values were 15 and 5% higher under CT than NT system in both years respectively.

Mean accumulated SOC showed significant differences among years as in 2017, the soil presented 2.1, 1.7 and 1.5 times higher C accumulation at 0-10, 10-20 and 20-30 cm depths respectively, than the initial year 2011. SOC stocks in 2013 and 2015 were significantly higher than the results obtained in 2011; however, the magnitude of SOC values in 2015 were not significantly different from those found in 2013. Mean SOC stocks in the six year-experiment was 25.7 and 7.6% higher in NT plots than in CT plots at 0-10 and 10-20 cm soil depths.

Tillage effects on short- and long-term CO_2 emissions

Figure 3 shows the evolution of CO_2 emissions (g CO_2 m^{-2} h^{-1}) following tillage operations from 2011 to 2017. Before any soil disturbance, soil CO_2 fluxes showed similar values under CT and NT systems. However, immediately after the soil ploughing in CT system, CO_2 emissions

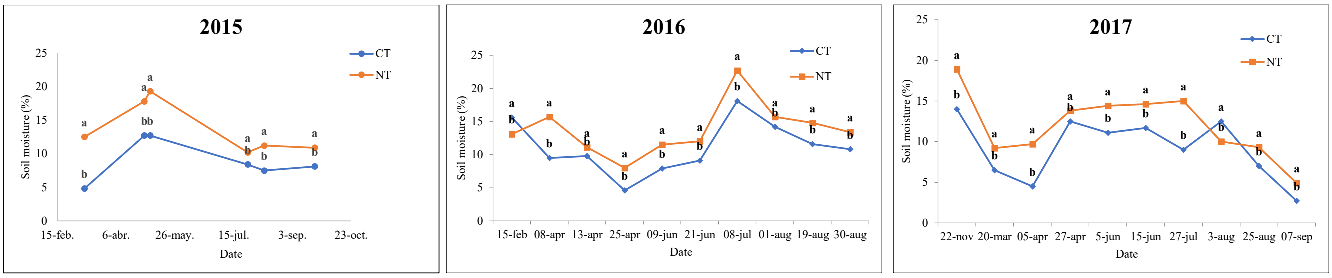

Figure 2. Soil moisture from tillage to maize dough stage under conventional (CT) and no-tillage (NT) from 2015 to 2017. Data with different letter are significantly different (α=0.05).

Table 3. Maize grain yield and crop residues (Mg ha^{-1}) under conventional tillage (CT) and no-tillage systems from 2012 to 2017.

Years	Grain yield				Crop residues			
	CT		NT		CT		NT	
2012	17.3	a	18.2	a	24.6	b	30.2	a
2013	16.9	b	19.6	a	11.4	b	15.8	a
2014	15.3	a	14.7	a	9.8	a	8.4	a
2015	16.2	a	16.7	a	4.6	b	8.4	a
2016	14.3	a	14.9	a	10.2	a	10.2	a
2017	9.4	b	11.2	a	5.2	a	4.6	a

Data with the same letter within a row are not significantly different (α=0.05).

presented an important increase compared to NT system. Under CT, the CO_2 flux measured immediately after tillage ranged from 0.8 to 3.4 g CO_2 m^{-2} h^{-1} in 2017 and 2016, respectively. After the mouldboard ploughing in 2014 and 2016, CO_2 emissions were greater than the results obtained during the other years. In NT plots, soil CO_2 flux was low and stable in this study period. After passing the cultivator, CO_2 emissions presented an increase under CT system and a second peak of the CO_2 flux was observed, except in 2012 and 2014 (Fig. 3). CO_2 emissions reached 1.1 g CO_2 m^{-2} h^{-1} in 2013 and 0.4 g CO_2 m^{-2} h^{-1} in 2017 under CT system and ranged from 0.1 to 0.3 g CO_2 m^{-2} h^{-1} in 2015 and 2016 under NT. During the hours following the cultivator passing, the CO_2 flux decreased under CT system to reach similar values as the ones recorded under NT system.

Finally, a third peak of the CO_2 flux was observed after sowing under both tillage systems. In 2012 (Fig 3), CO_2 emissions presented significant differences between treatments where CT plots had an immediate increase in soil CO_2 flux compared to NT system. The cumulative CO_2 emissions during the first 48 hours after the mouldboard ploughing was significantly higher in CT plots than in the NT plots during the six campaigns studied (Table 5). The CO_2 emissions produced from the plots with the mouldboard plough were 3.0 (December 2017) to 10.6 (March 2016) times higher than in NT plots in which the soil was not disturbed.

Cumulative CO_2 fluxes in the first 48 hours after the cultivator pass were significantly higher in CT plots than in NT plots in all the campaigns studied. During the 48 hours after sowing, the cumulative CO_2 flow did not present significant differences among tillage systems except in 2012 when values were significantly higher under CT than NT. In this case, mean CO_2 fluxes in CT and NT plots were 0.48 and 0.38 Mg CO_2 ha^{-1} respectively. Considering the period of 48 h and all the study years, the CO_2 fluxes means were 1034, 350 and 108 kg CO_2 ha^{-1} higher with mouldboard, cultivator and sowing respectively under CT than NT system (Table 5).

Figure 4 summarizes CO_2 fluxes during the crop cycle and shows that mean CO_2 emissions were higher during the maize reproductive growth stages (R1-R5) under both tillage treatments. Under CT system, the different stages R2 (2012), R3 (2013), V8 (2014), R3 (2015), R1 (2016) and R1 (2017) displayed maximum rates of 0.52, 0.63, 0.62, 0.43, 0.76 and 0.76 g CO_2 m^{-2} h^{-1} while under NT they reached 0.37, 0.58, 0.48, 0.59, 0.64 and 0.50 g CO_2 m^{-2} h^{-1}. During the growing season, CT system had higher CO_2 emissions than NT in all the studied years, but the differences between these treatments were smaller and not always statistically significant, except at R2 in 2012, V8 in 2014, V5 and V8 in 2016 and R1 and R5 in 2017 where CT had significantly higher CO_2 fluxes than NT (Fig. 4).

Linear regression analysis of CO_2 fluxes and soil temperature under both tillage system (Table 6) showed that CO_2 emissions were significantly affected by temperature in 2013 (R^2=0.84**) and 2014 (R^2=0.56*) under NT and in 2013 (R^2=0.63*) and 2016 (R^2=0.58**) under CT. The lack of relationship between soil temperature and gas emissions in the other years could be due to minor temperature variations in some measurements and the different dates when these values were recorded. Soil CO_2 emissions were not affected by soil moisture, except in 2015 where the effects of soil moisture on CO_2 fluxes were significant (CO_2 flux=0.59–0.02 Moisturesoil, p=0.03) and accounted for 71% of variability for NT, probably

Table 4. Soil organic carbon (SOC, Mg ha^{-1}) accumulation at 0-30 cm soil depth under conventional tillage (CT) and no-tillage (NT) systems from 2011 to 2017.

SOC	2011				2013				2015				2017			
	CT		NT		CT		NT		CT		NT		CT		NT	
0-10 cm	6.7	b	8.6	a	8.7	a	9.5	a	8.4	b	10.3	a	13.5	b	18.3	a
10-20 cm	8.0	b	9.4	a	9.8	a	10.1	a	10.7	a	11.0	a	13.6	a	14.8	a
20-30 cm	7.5	b	9.5	a	9.6	a	10.6	a	9.8	a	8.5	a	13.5	a	12.8	a
0-30 cm	22.2	b	27.6	a	28.1	a	30.2	a	29.0	a	29.8	a	40.6	b	45.9	a

Data with the same letter within a row are not significantly different (α=0.05).

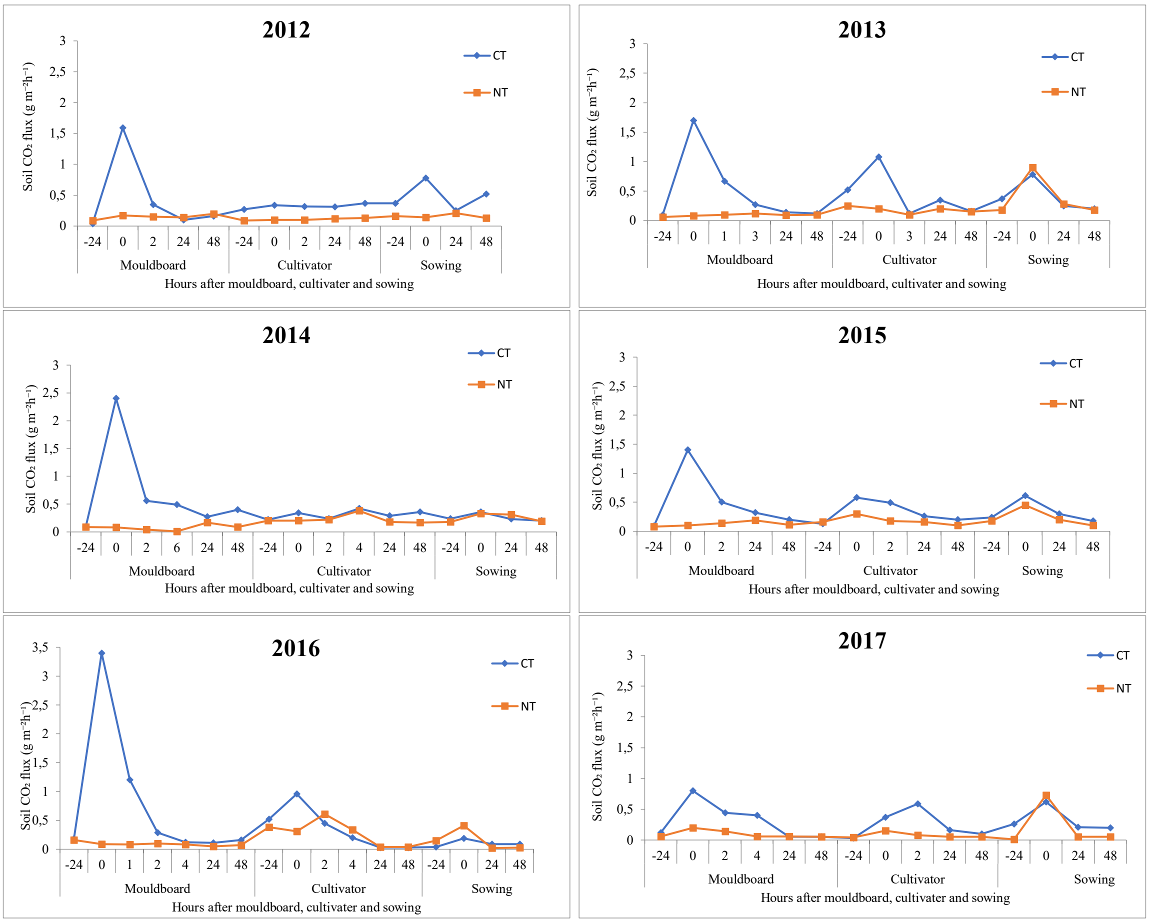

Figure 3. CO_2 emissions response to tillage operations (mouldboard, cultivator and sowing) under conventional tillage (CT) and no-tillage (NT) from 2012 to 2017. Data with different letter are significantly different (α=0.05).

due to major moisture variations between both tillage systems in all measurements. In addition, soil moisture was significantly higher under NT than CT along the maize cycle in 2015 (Fig. 2). The cumulative CO_2 flux (Mg ha^{-1}) measured from sowing to maize maturity and the CO_2 flux/grain yield ratio under CT and NT from 2012 to 2017 are presented in Table 7. It can be noticed that under CT and NT, mean cumulative CO_2 fluxes were 14.3 and 11.0 Mg CO_2 ha^{-1} respectively. The ratio of CO_2 emission to grain yield ranged from 0.64 (2013) to 1.41 (2014) under CT and from 0.49 (2012) to 1.15 (2014) under NT (Table 7). In this study period, there were significant differences between tillage systems, mean ratio of CO_2 emission to grain yield was 39% significantly lower under NT than

Table 5. Cumulative CO_2 emissions (kg CO_2 ha^{-1}) during the first 48 hours after mouldboard ploughing, cultivator and sowing in conventional tillage (CT) and non-tillage (NT) during the 6-years study.

	Mouldboard				Cultivator				Sowing			
	CT		NT		CT		NT		CT		NT	
2012	1056	a	317	b	643	a	216	b	744	A	230	b
2013	1166	a	182	b	821	a	312	b	590	A	653	a
2014	1726	a	175	b	634	a	408	b	379	A	398	a
2015	1162	a	259	b	734	a	355	b	523	A	360	a
2016	2436	a	182	b	646	a	415	b	178	A	221	a
2017	643	a	216	b	586	a	158	b	494	A	398	a

Data with the same letter within a row are not significantly different (α=0.05).

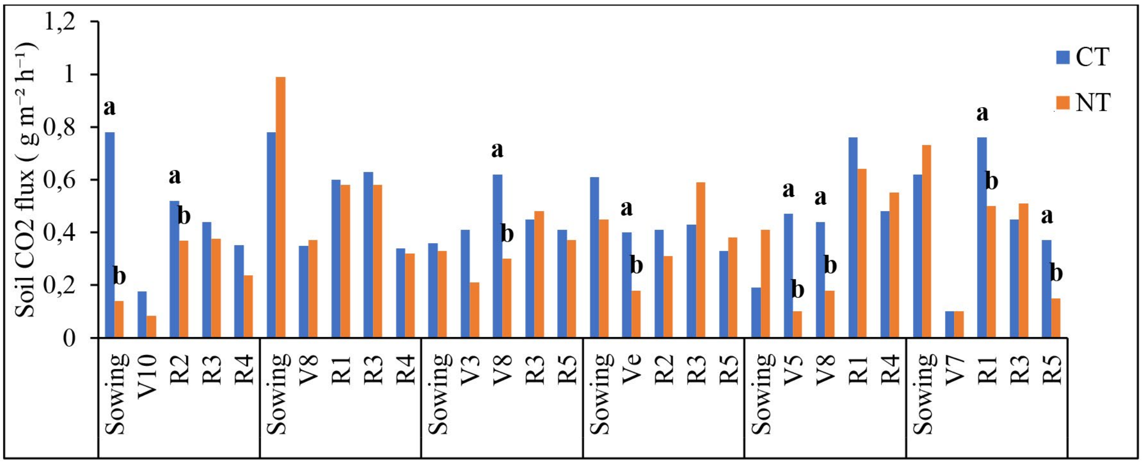

Figure 4. CO_2 flux (Mg ha^{-1}) during the maize growing cycle under conventional tillage (CT) and no-tillage (NT) system from 2012 to 2017. Ve: emergence, V3, V5, V7, V8, V10: 3rd, 5th,7th, 8th, 10th leaf developed, respectively. R1: stigma emergence, R2: rennet, R3: milky grain, R4: pasty grain, R5: dented grain. Data with different letter within the same stage are significantly different (α=0.05).

Table 6. Linear regression of CO_2 fluxes and soil temperature and moisture under conventional tillage (CT) and no-tillage (NT).

Year	**Tillage system**	**Mean soil temperature (°C)**	**Regression model**	R^2	***p* value**
2012	CT	18.5	$CO_{2\ flux}$=0.72 - 0.017 T_{soil}	0.04	ns
	NT	16.5	$CO_{2\ flux}$=0.06 + 0.008 T_{soil}	0.14	ns
2013	CT	14.7	$CO_{2\ flux}$=0.03 - 0.044 T_{soil}	0.63*	0.01
	NT	13.7	$CO_{2\ flux}$=-0.01 + 0.03 T_{soil}	0.84**	0.003
2014	CT	13.2	$CO_{2\ flux}$=1.68 + 0.13 T_{soil}	0.24	ns
	NT	12.6	$CO_{2\ flux}$=0.17 + 0.16 T_{soil}	0.56*	0.02
2015	CT	14.5	$CO_{2\ flux}$=0.17 + 0.02 T_{soil}	0.44	0.07
	NT	13.8	$CO_{2\ flux}$= 0.11 + 0.014 T_{soil}	0.34	0.07
2016	CT	13.6	$CO_{2\ flux}$=-0.05 + 0.03 T_{soil}	0.58**	0.006
	NT	12.4	$CO_{2\ flux}$=0.35 + 0.07 T_{soil}	0.16	ns
2017	CT	14.9	$CO_{2\ flux}$=0.12 + 0.02 T_{soil}	0.25	ns
	NT	12.4	$CO_{2\ flux}$=-0.01 + 0.02 T_{soil}	0.43	0.05
		Mean soil moisture (mm)	**Regression model**	R^2	***p* > F**
2015	CT	9	$CO_{2\ emissions}$= 0.21 - 0.01 M_{soil}	0.11	ns
	NT	13.7	$CO_{2\ emissions}$= 0.59 - 0.02 M_{soil}	0.71*	0.03
2016	CT	11.2	$CO_{2\ emissions}$= 0.35 + 0.01 M_{soil}	0.02	ns
	NT	13.8	$CO_{2\ emissions}$= 0.08 + 0.03 M_{soil}	0.34	ns
2017	CT	9.5	$CO_{2\ emissions}$= 0.23 + 0.01 M_{soil}	0.09	ns
	NT	11.98	$CO_{2\ emissions}$= 0.31 - 0.01 M_{soil}	0.03	ns

T_{soil}, soil temperature. M_{soil}, soil moisture

Table 7. Cumulative CO_2 flux (Mg ha^{-1}) from sowing to maturity of maize crop and CO_2 flux / grain yield ratio under CT and NT from 2012 to 2017

Year	Soil CO_2 flux (Mg ha^{-1})		CO_2 flux / grain yield	
	CT	NT	CT	NT
2012	13.9 a	8.9 b	0.8 a	0.5 b
2013	10.7 a	10.4 a	0.6 a	0.5 b
2014	21.6 a	16.9 b	1.4 a	1.2 b
2015	13.5 a	11.5 b	0.8 a	0.7 b
2016	14.5 a	10.4 b	1.0 a	0.7 b
2017	11.7 a	7.8 b	1.2 a	0.7 b

Data with the same letter within a row are not significantly different (α=0.05).

under CT, indicating that the amount of CO_2 emission per unit grain decreased under NT.

Discussion

Soil temperature and moisture

No-tillage system recorded low temperature during all different studied seasons, suggesting that crop residues in NT plots diminished the effect of high air temperatures and the solar radiation (Fig.1). However, from December to March 2015, the increase of soil temperature under NT could be explained by the fact that the mean air temperature during these months was generally lower than the reported ones during the same months of the other years (Table 2). In this context, the crop residues left on the soil surface could have been involved in buffering the impact of the low air temperature on the soil surface. This result coincides with the one found by Ussiri & Lal (2009), who reported higher soil temperature under NT system from November to March. Soil moisture content was higher under NT than CT (Fig. 2), the presence of crop residues on the soil surface in NT plots minimised water losses due to evaporation and surface runoff and increased soil moisture, and this was similar to the results found by Ussiri & Lal (2009) in a cultivated maize crop. The low soil temperature and high moisture obtained under NT (Figs. 1 and 2) are in accordance with the results reported by Moitinho *et al.* (2013), who stated that the absence of residues and the greater surface exposure of the tilled plots enhanced water evaporation and decreased soil moisture in CT system.

SOC distribution and accumulation

The results obtained in Table 4 showed an increase of the SOC throughout the studied years under both tillage systems. This increase could be explained by the fact that OM acts as a reservoir of nutrients for the crop, participating in the soil biological activity, which lead to a quantitative and qualitative changes of the structure due to tillage (Roldan *et al.*, 2005). Generally, the biological and biochemical parameters of the soil play an important role as early sensitive indicators to ecological stress and soil restoration (Izquierdo *et al.*, 2003; Roldan *et al.*, 2003). During all the studied years, NT system presented significantly higher values than CT at 0-10 cm soil depth, except in 2013 where tillage system did not affect significantly the SOC values at the same depth. Actually, in November 2013, when the soil samples were collected (Table 4), low temperature and precipitation could have caused a low activity of the soil microorganisms, which decreases the OM degradation, and this could explain the absence of the significant difference between tillage systems. The differences found among tillage system was also reported by Huang *et al.* (2015), who studied the long-term effects of tillage system on different parameters of soil quality in a maize monoculture and found that concentration of OM increased by 18% in the first few centimeters of soil with NT and the amount was associated with the soil aggregates. The crop residues left on the soil surface acted as a protective layer that prevented from losses through evapotranspiration, water and wind erosion and increased the OM content that contributed to improve the soil quality (Traore *et al.*, 2007; Blanco-Canqui, 2013; Zhang *et al.*, 2018). Basamba *et al.* (2006) and Zhang (2012) pointed out the importance of the accumulation of OM in the upper soil horizon as it improved the quality of the interface between soil and atmosphere and gave the soil greater resistance to different degradation processes that occur on the surface. The results reported by Varvel & Wilhem (2008), Wen-Guang *et al.* (2015) and Nie *et al.* (2016) supported the ones obtained in this study, as they found that NT maize led to an accumulation of SOC at or near the soil surface while different tillage treatments including chisel, disk or plough displayed lower SOC values. The crop residues left on the soil surface under NT had a considerable influence on SOC increase at 10 cm depth in 2015 and 2017 (Table 4). In CT plots, the mouldboard plough broke the soil structure and SOC content could have been lost due to mineralization. This process did not occur under NT system where the absence of soil disturbance promoted the soil stabilization and the greater accumulation of SOC on the surface. Tillage affects SOC stocks in the ploughed layer by distributing crop residues mechanically throughout the tillage zone (Yang & Wander, 1999) which caused low rates for mineralization distribution of crop residues and homogenization of SOC stocks in the ploughed layers.

In this area, maize crop grows with high temperature and soil moisture (from irrigation) which could lead to high activity of the soil microorganisms promoting a rapid degradation of SOC. However, because of the lack of water during the whole crop cycle in 2017, soil microorganisms' activity decreased and the SOC content was significantly higher than other years. These results coincided with Dimassi *et al.* (2014) who concluded that the climate interacted with tillage, leading to a greater C sequestration in dry than in wet regions. These authors found that SOC changes under the reduced tillage over time were negatively correlated with the water balance, indicating that sequestration rate was positive in dry periods and negative in wet conditions. De Bona *et al.* (2006) reported that irrigation increased the decomposition rate of OM by 19% and 15% under CT and NT systems respectively after 8 years of research. Luo *et al.* (2010) found an increase of the soil C in the topsoil (0-10 cm) under NT but no significant difference was reported over the soil profile to 40 cm, because of the C redistribution through the soil profile under CT system.

Tillage effects on short and long term CO_2 emissions

In CT plots, the CO_2 emissions were significantly higher than in NT plots due to soil inversion by mouldboard ploughing that activated the rapid oxidation processes, decreasing the levels of OM in the soil, releasing a large amount of CO_2 into the atmosphere, and contributing to a greater global warming than in NT system. The results obtained in this study (Fig. 3) coincide with those obtained by Reicosky *et al.* (1997) who recorded a CO_2 flux that ranged from 0.7 to 2.2 g CO_2 m^{-2} h^{-1} under NT and CT systems respectively in a sorghum monoculture after the mouldboard ploughing. Al-Kaisi & Yin (2005) reported lower soil CO_2 emissions in NT compared with mouldboard plough with the greatest differences occurring immediately after tillage operations in maize-soybean rotation. CO_2 emissions displayed an important increase in the tilled soil after the mouldboard plough use (Fig. 3) compared to the non-tilled. These results are in accordance with the ones obtained by Prior *et al.* (2000), who indicated that CO_2 flux increases after the soil ploughing and that it depends on both tillage depth and the degree of soil alteration. The mouldboard ploughing caused aggregates disruption leading to the exposure of the C, previously protected within these aggregates, to the microbial action (Six *et al.*, 2000), resulting in higher CO_2 emissions values under CT when compared to NT treatment. In addition, aggregates disintegration improves soil aeration, so that higher soil CO_2 emissions under CT were related to the higher number of macropores under this management (Silva *et al.*, 2019). The CO_2 flux decreased more than four times considerably in the first 2 hours after the mouldboard pass under CT in all the studied years (Fig. 4). Reicosky *et al.* (1997) observed a decrease in the first two hours after the mouldboard pass. After 2 hours, the flux began to decrease until reaching similar values in both treatments at 24 h. Other studies observed that the measurements of CO_2 emissions during short periods after tillage were significantly lower under NT than CT (Alvarez *et al.*, 2001; Alvaro-Fuentes *et al.*, 2007; Carbonell-Bojollo *et al.*, 2011). The results obtained showed that soil tillage operations accelerate CO_2 emissions and the soil C losses (Rakotovao *et al.*, 2017).

The CO_2 emissions reached their maximum in July and August, from the vegetative phenological stages of the crop (V3-V10) to flowering- filling stages (Fig. 4). At these growth stages, CO_2 emissions were greater under CT than in NT system. The absence of crop residues under CT system induced the increase of soil temperatures and promoted the rapid oxidation of OM. In addition, the microbiological and radicular activity in the soil increased, generating oxidation reactions that resulted in higher CO_2 emissions. Aon *et al.*, (2001) reported that high temperatures resulted in higher decomposition rates of OM. Kuzyakov & Domanski (2000) found that the crop growth had a significant impact on microbial activity through root exudates, and soil microorganisms easily broke them down. This could explain the increase in soil CO_2 emissions observed from the leaf development to the silking stage (R1). Hanson *et al.* (2000) pointed out that for annual crop the contribution of the root to soil respiration are higher during the crop growth and lower during the periods of inactivity. In maize crop, the contribution of rhizosphere respiration (root respiration plus decomposition of root exudates) to total soil respiration can be significant with values close to 50% around the period of maximum crop activity (Rochette *et al.*, 1999). The CO_2 flux ranged from 10.7 (2013) to 21.6 (2014) Mg ha^{-1} under CT tillage and from 7.8 (2017) to 16.95 (2014) Mg ha^{-1} in NT plots from sowing to phenological maturity (Table 7). The lower CO_2 emissions under NT system compared to CT could be attributed to a greater surface of crop residues, which could serve as barrier for CO_2 emissions from soil to the atmosphere and reducing soil temperature (Omonode *et al.*, 2007). The slower decomposition of crop residues placed on the soil surface under NT could lead to lower CO_2 fluxes in NT soil (Curtin *et al.*, 2000). The lower CO_2 emissions in NT plots results agree with those obtained by Reicosky & Archer (2007) and Almaraz *et al.* (2009). Because of the earlier maturity of maize crop and the lower amount of irrigation water in 2017, CO_2 emissions decreased compared to the other years. The differences of CO_2 emissions reported among the studied years could be caused by the SOC different concentrations in the upper soil layer between years, changes in soil physical processes or soil temperatures and moisture variability.

Rochette *et al.* (1999) indicated that CO_2 emissions were related to temperature and crop growth and that the highest CO_2 emissions in the warmer months could be associated with root respiration, as the plant growth was also much higher during these months. A significant relationship between CO_2 emissions and both soil temperature and moisture (R^2=0.60) was detected under both tillage systems in 2015 and could be caused by the high amount of water applied during irrigation. Omonode *et al.* (2007) found a weak significant relationship between CO_2 emission and soil temperature and moisture when applying different tillage treatments. Under NT, the surface residues provide a barrier between the soil and the atmosphere, which reduces soil evaporation leading to the increase of soil moisture and affects the microbial mobility and gas diffusion in the soil. The general low relationship between CO_2 emissions with soil temperature and moisture found in this study was consistent with other reports (Alkaisi & Yin, 2005; Omonode *et al.*, 2007).

In the six studied years, there were significant differences between tillage systems, CO_2 flux was higher under CT than under NT, except in 2013 (Table 7). In this year, the non-significant difference between treatments could be explained by three hypotheses: (i) the combination of the higher amount of crop residues left on the soil surface of 2012 compared to other years, and of the significant increase of grain yields in NT obtained in 2013 (Table 3); (ii) in 2013, despite the lower water amount irrigated, soil moisture was higher under NT (Rodríguez-Bragado, 2015), which displayed higher yield than CT and led to similar CO_2 fluxes in both treatments; (iii) there was a strong correlation between CO_2 emission and soil temperature in 2013 (R^2=0.78**) across both tillage systems, while in other years this correlation was lower.

The ratio of CO_2 emissions to grain yield was low under NT system, which means that the amount of CO_2 emissions per unit grain decreased under this practice. Under this soil management, CO_2 emissions decreased due to the amount of crop residues left on the soil surface which led to low soil temperatures and high soil moisture (Figs. 1 and 2). In these conditions, the results obtained could be explained by the changes occurring in the root level and microorganism activities, thus enhancing the increase of SOC sequestration at 0-30 cm laying and the decrease of CO_2 emissions.

In conclusion, this study was initiated to assess SOC stocks, to observe the grain yield response and to determine short-term and seasonal soil CO_2 fluxes under CT and NT practices in continuous maize cropping system during six years in a semiarid region of Castile and Leon. The results showed that SOC stock was 36% greater under NT (18.3 Mg C ha^{-1}) than under CT (13.5 Mg C ha^{-1}) with a rate of 1.61 and 1.13 Mg ha^{-1} yr^{-1} respectively at 0-10 cm depth. In the lower layers, SOC values were 7 and 3% higher in NT plots than in CT plots at 10-20 and 20-30 cm depths. These results suggest that tillage accelerated the decomposition in the 0-10 cm depth but had minimal influence in the 10-30 cm depth. In 2013 and 2017, maize grain yield reached higher values under NT system than CT, this demonstrates that the non-disturbance of the soil promotes moisture retention for a longer period compared to soil disruption. Generally, this study confirmed that NT management could lead to equal and even higher grain yield than CT system. Short-term CO_2 emissions measured for 48 h after ploughing and cultivator labor were higher under CT than for NT for all measurements. On a seasonal basis, mean CO_2 emissions during the growing season were affected by tillage systems and were 3.32 Mg CO_2 ha^{-1} greater under CT than NT system. Soil temperature and moisture effects on CO_2 flux did not show any significant difference except in 2013 and 2014 under NT and 2015 under CT. Generally specific correlations of soil temperature and moisture with CO_2 emission was insignificant and depended on the moment when the measurements were carried out. From the obtained results in this study, it can be pointed out that the conversion from CT to NT system in irrigated maize would increase the sequestration of OC in the soil and reduce CO_2 emissions to the atmosphere, which can contribute positively to the reduction of GHGs emissions by the agricultural sector without compromising the grain yield.

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