Tillage and nitrogen fertilization in irrigated maize: key practices to reduce soil CO_2 and CH_4 emissions.

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Abstract

In newly irrigated Mediterranean agroecosystems, the combined effect of tillage and N fertilization on soil carbon dioxide (CO_2) and methane (CH_4) fluxes is at present poorly understood. The goal of this study was to quantify both soil CO_2 and CH_4 emissions as well as crop performance under different tillage systems and N fertilization rates during three maize (*Zea mays* L.) growing seasons (2015-2017) in a semiarid area converted to irrigated. Three types of tillage (conventional tillage, CT, reduced tillage, RT, and no-tillage, NT) and three mineral N fertilization rates (0, 200, and 400 kg N ha^{-1}) were compared in a randomized block design with three replications. Weekly soil CO_2 and CH_4 emissions, soil temperature and gravimetric moisture were measured. Moreover, maize above-ground biomass, grain yield, and above-ground C-inputs were quantified. Carbon dioxide emissions ranged from 173 to 4378 mg CO_2-C m^{-2} d^{-1}. No-tillage showed a greater mean soil CO_2 flux than CT when applying the highest rate of N (400 kg N ha^{-1}). Although some emissions of CH_4 were observed, all treatments acted as net CH_4 sinks during most of the experimental period. A linear multiple relationship between soil CO_2 fluxes and soil gravimetric moisture (0-5 cm depth) and temperature (10 cm depth) were found. In the 2015 growing season, greater cumulative CO_2 emissions were found under NT and RT compared with CT, while in 2016 NT showed the highest values compared to CT with intermediate values in RT. Differently, in 2017 no differences between tillage systems were found. When applying N fertilizer, NT and RT increased maize grain production and above-ground C-inputs compared to CT, since a severe soil crusting occurred in this last, which caused crop water deficit. The results suggest that tillage intensity and N fertilization rate reduction can increase maize biomass production and yield which leads to greater C-input that returns to the soil.

Keywords

Soil greenhouse gases; Irrigated maize; N fertilization; tillage systems; Management practices; Mediterranean agroecosystem.

1. Introduction

Global atmospheric concentrations of CO_2 and CH_4 have markedly increased in the last decades. Carbon dioxide primarily increased due to fossil fuel burning and land use change. Meanwhile, CH_4 increased as a result of the production and transport of fossil fuel as well as the enteric fermentation in livestock, manure management, rice cultivation, biomass burning, and waste management in the agricultural sector (U.S. EPA, 2012). About 10–12% of global anthropogenic emissions of greenhouse gases (GHG) are generated by the agricultural sector (IPCC, 2014). This effect could be greatly mitigated through a proper choice of crop and land management systems.

Tillage practices can affect soil biochemical and physical properties, consequently influencing the release of CO_2. In the last decades carbon loss from soils to the atmosphere as CO_2 has increased due to inappropriate tillage practices (Rakotovao *et al.*, 2017). During intensive tillage operations, like moldboard plowing, soil structure is greatly disturbed and the CO_2 contained in the soil pore system is lost while releasing organic C protected within aggregates making it more accessible to decomposers. In addition, tillage practices can affect soil temperature and soil moisture conditions which are strongly related to soil CO_2 fluxes (Ren *et al.*, 2007). Meanwhile, the use of conservation tillage systems, such as reduced tillage (RT) and no-tillage (NT), has been promoted as a practice to enhance soil carbon levels. The increase in soil organic carbon (SOC) pool under conservation tillage can be attributed to either an increase in C inputs from crop residues (Stewart *et al.*, 2016) or a decrease in CO_2 efflux from the soil. Therefore, the effect of soil C sequestration is particularly crucial for predicting the future trend of CO_2 concentration in the atmosphere (DeLuca and Zabinski, 2011). This importance is reflected in recent international initiatives such as the 4 per 1000 which was launched during the COP21 in Paris and promotes the adoption of recomended management practices aimed to increase SOC sequestration.

Soils can act as a source or sink of atmospheric CH_4, depending on the amount of moisture, N level and soil microbial community (Gregorich *et al.,* 2005). Tillage influences the processes that regulate the emission or oxidation of CH_4 through its impact on the soil water regime. Moisture usually exerts strong control over CH_4 uptake rates, through soil structure. Therefore, structural degradation, particularly through compaction, which is a common problem in intensively tilled soils, can adversely affect CH_4 consumption (Ball *et al,*. 1999).

The emissions of CO_2 and CH_4 from soils are also affected by the application of nitrogen fertilizer (Lee *et al.,* 2007) which may also play a significant role in soil C sequestration (Lal, 2004). The application of N fertilizer can increase above-ground biomass production and root respiration, which can lead to soil C storage by increasing crop residue C input (Al-Kaisi and Yin, 2005). Moreover, it has been reported that the use of N fertilizer can reduce the uptake of CH_4 by soils (Hütsch, 2001; Bodelier and Laanbroek, 2004) as a result of the inhibition of CH_4 oxidation activity of methanotrophs (Reay and Nedwell, 2004).

In different rainfed Mediterranean areas, RT and NT techniques have been introduced during the last two to three decades aimed at reducing costs, saving time and increase soil water conservation (Lampurlanes *et al.,* 2016). Currently, a significant fraction of the Mediterranean rainfed areas are being transformed into irrigation, allowing farmers the cultivation of more productive summer crops such as maize, which require greater nitrogen fertilizer rates to maximize yields. However, in these newly transformed irrigated cropping systems, farmers have been induced to return to intensive tillage systems, which are the most common in irrigated Mediterranean cropping systems. In these areas, the limited previous experience about the implementation of RT or NT systems constrains the adoption by farmers and puts at risk the soil quality benefits achieved with the long-term use of NT under former rainfed conditions. Moreover, conversion from rainfed to irrigation may lead to increases of GHG emissions (Aguilera *et al.,* 2013) by creating more favorable soil conditions for microbial activity (Calderon and Jackson, 2002) which may counterbalance the increase in C inputs returned to the soil negatively affecting the overall C budget.

There are many studies measuring soil GHG emissions in both rainfed and irrigated systems (Meijide *et al.*, 2010; Anapalli *et al.*, 2019), but to our knowledge no information exists nothing is known about changes in GHG emission due to the transformation to irrigated after long-term rainfed cropping. Previous research in irrigated maize production under Mediterranean conditions showed that GHG emissions can be influenced by N fertilization rates (Álvaro-Fuentes *et al.,* 2016) and tillage systems (Forte *et al.,* 2017). However, little is known about the combined effects of both management practices on CO_2 and CH_4 fluxes in soils recently transformed into irrigation. Therefore, the goal of the present study was to quantify the interactive effects of tillage and N fertilization rate on soil CO_2 and CH_4 emissions and on the performance of irrigated maize to identify environmentally sustainable practices.

2. Materials and methods

2.1 Experimental site and treatments.

This study was conducted during three consecutive maize growing seasons (2015, 2016, and 2017) at Agramunt, NE Spain (41°48′ N, 1°07′ E, 330 m asl). The climate is semiarid Mediterranean with a continental trend. Mean annual precipitation and temperature are 401 mm and 14.1°C respectively (data from 1985 to 2015). Mean annual potential evapotranspiration is 855 mm (data from 1985 to 2015).

The study was carried out on the same plots used since 1996 as a rainfed long-term field experiment which compared three tillage systems (conventional tillage, CT; reduced tillage, RT; no-tillage, NT) and three increasing rates of mineral N under barley monoculture (Angás *et al.,* 2006). In 2015, this rainfed experiment was transformed into irrigation with solid set sprinklers and maize (*Zea mays* L.) monoculture as cropping system. After the shift from rainfed to irrigation, the field experiment maintained the same tillage treatments (CT, RT, and NT) while N fertilization rates were adapted to maize (0, 200, and 400 kg N ha^{-1}). A total of 27 plots (50x6 m) were arranged in a randomized complete block design with three replications. The soil was classified as Typic Xerofluvent (Soil Survey Staff, 2014) and presented a silt loam texture (sand, 30.8%; silt, 57.3%; clay, 11.9%) in the upper (0-28 cm) horizon. The main physico-chemical properties (0-28 cm soil depth) at the beginning of the experiment (1996) were as follows: pH (H_2O, 1:2.5): 8.5; electrical conductivity (1:5): 0.15 dS m^{-1}; P Olsen: 35 ppm; K (Amm. Ac.): 194 ppm; water retention (-33 kPa): 16 g g^{-1}; water retention (-1500 kPa): 5 g g^{-1}. While soil organic carbon concentration (0-30 cm) was 7, 9 and 9 g kg^{-1} under CT, RT and NT, respectively in 2015.

The CT treatment was implemented according to the traditional practices of maize cultivation in the area. Tillage was performed before planting during March or April, consisting of one pass of a rototiller to 15 cm depth, followed by one pass of a subsoiler to 35 cm depth and finally one pass of a disk plough to 20 cm depth with almost 100% of the crop residues incorporated into the soil. The RT consisted of one pass of a strip-till implement during April. Finally, in the NT treatment no tillage practices were carried out. Weeds were controlled by applying a non-selective herbicide (i.e. glyphosate) at 1.5 L ha^{-1} before planting. Planting was performed in April with the use of a pneumatic row direct drilling machine equipped with double disc furrow openers (model Prosem K, Solà, Calaf, Spain) in the three tillage systems. Planting depth was adapted to each tillage treatment. Rotary residue row cleaners were installed to clear the path for the row unit openers. Maize (cv. Kopias) was planted during the last week of April, in rows 73 cm apart at a planting density of 90,000 plants ha^{-1} in the three years. Nitrogen fertilization treatments were split in one pre-planting application with urea (46% N) (April) and two top-dressing applications at the V5 to V10 stages (May and July, respectively) with calcium ammonium nitrate (27% N) with 50, 75 and 75 kg N ha^{-1} applied in each split in the 200 kg N ha^{-1} rate, being doubled in the 400 kg N ha^{-1} rate. Mineral P and K applications were oriented to satisfy crop needs at the same rate for all tillage treatments: ca. 154 kg P_2O_5 ha^{-1} yr^{-1} and 322 kg K_2O ha^{-1} yr^{-1}, in the first two years. In the third year the levels of available P and K in the soil were appropriate for the crop, making unnecessary further P and K applications. Irrigation was supplied to meet the estimated evapotranspiration (ET) of the crop minus the effective precipitation, which was estimated as 75% of precipitation (when precipitation > 5 mm) (Dastane 1978). Maize evapotranspiration (ETc) was calculated with the corresponding weekly ET values multiplied by the crop coefficient. Crop coefficients were estimated in accordance with crop development (ranging between 0.3-1.2). The ET was calculated using the Penman-Monteith equation. Meteorological data were obtained from an automated weather station located near the experimental site. The amount of water applied by irrigation was 631, 672 and 696 mm in 2015, 2016 and 2017, respectively, during the maize growing period. Maize grain was harvested at the beginning of November using a commercial combine. Afterwards, crop residues were chopped and spread over the soil. Weed and pest control were carried out according to the standard practices in the area.

2.2 Measurements of soil CO_2 and CH_4 emissions.

Soil CO_2 and CH_4 emissions were simultaneously measured with the non-steady-state chamber method (Hutchinson and Mosier, 1981), following the procedure of Plaza-Bonilla *et al.* (2014). In each plot, two polyvinylchloride rings with a 315-mm-diameter were inserted 5 cm into the soil. The rings were only removed during tillage, planting and harvesting operations, allowing a minimum lapse of 24 h following ring rearrangement at the initial location before any gas sampling to avoid the concomitant effects of soil disturbance on gas emissions. For the two top-dressing applications, the rings were not removed since the fertilizer was not incorporated. When the measurements were performed, polyvinylchloride chambers 20-cm high were fitted into the rings. The chambers were covered with a reflective insulation layer (model Aislatermic, Arelux, Zaragoza, Spain). As a sampling port, a metal fitting was attached in the center of the top of the chamber and was lined with two silicon-Teflon septa. Soil CO_2 and CH_4 fluxes were measured weekly during the growing season (April to November), with more intensive samplings during N fertilizer applications (i.e. 24 h. prior and 3 h. and 72 h. after) and every 21 days in the period between crops in winter (November to March) in order to quantify the emissions for the entire year. This process was repeated for 3 consecutive years (from April 2015 to November 2017). Gas samples were collected at regular intervals of 0, 20 and 40 minutes after closure of the chamber, using 20 mL polypropylene syringes and stored into 15 mL borosilicate vials (Exetainer, model 038 W, Labco, High Wycombe, UK). A total of 162 gas samples were collected on every sampling date (27 plots x 2 observations per plot x 3 sampling times per chamber). The concentration of CO_2 and CH_4 in the samples was determined using an Agilent 7890A gas chromatography system equipped with a flame ionization detector (FID) coupled to a methanizer and three valves in order to obtain the gases of interest for each gas injection. A HP-Plot Q column (30 m long, 0.32 mm in section and 20 μm thick) was used, with a 15-m long pre-column of the same characteristics. The injector and the oven temperatures were set to 50°C. The FID and the methanizer were set to 250 and 375°C, respectively. For the detector, H_2 was used as a carrier gas and N_2 as a make-up gas at a flow of 35 and 25 mL min^{-1}, respectively. Soil fluxes of CO_2 and CH_4 were calculated taking into account the linear accumulation of the gases in the chamber headspace over the closure period (40 min) and correcting the values for air temperature.

2.3 Soil and crop measurements.

During each gas flux sampling, soil temperature was measured using a hand-held probe (TM65, Crison, Barcelona, Spain) at 10 cm depth. Moreover, soil samples (0-5 cm depth) were obtained near each chamber. Gravimetric soil moisture was determined by oven drying each soil sample at 105°C until constant weight. Daily average air temperature and total rainfall during the study period were collected from an automated weather station located within 50 m of study site.

At harvest, maize plants were cut at the soil level along 2-5 m (depending on plant density) from the three central rows of each plot. The number of plants and ears was counted and registered. Afterwards, a sub-sample of two entire plants and five ears was dried at 65°C, weighed and ground. Grain moisture was adjusted to 14% moisture content. The C content of maize grain and above-ground biomass was determined by dry combustion (model Truspec CN, LECO, St Joseph, MI, USA).

2.4 Data analysis.

Cumulative emissions of CO_2 and CH_4 were quantified on a mass basis (i.e., kg C ha^{-1}) using the trapezoid rule, differentiating between maize growing seasons (April-November) and periods between crops in winter (November-March) for the three years.

Data analysis was performed with the statistical package JMP 13 (SAS Institute Inc 2018). Data were checked for normality by plotting a normal quantile plot. A logarithmic transformation was carried out to normalize soil CO_2 fluxes. An analysis of variance (ANOVA) was performed with tillage, N fertilization rate, sampling date or year or period (depending on the variable) and their interaction as effects. Sampling date was used for analyzing gravimetric soil moisture, daily CO_2 and CH_4 emissions; period was used for cumulative CO_2 and CH_4 emissions and year was used for above-ground biomass, grain yield and above-ground biomass C-inputs returned to the soil. When significant, differences among treatments were identified at 0.05 probability level of significance with a Tukey HSD test. The possible impact of different predictive variables on the emission of each of the two gases was tested with the use of multiple regressions, identifying the variables with a significant effect. To do so, soil CO_2 emissions were logarithmically transformed.

3. Results

3.1 Weather characteristics during the experimental period.

Air temperature, precipitation and irrigation water during the three years are presented in Table 1. During the maize growing seasons studied, daily mean air temperature ranged from 6.5 to 29.1 ºC (average of 19.3 ºC), from 8.7 to 27.5 ºC (average of 18.8 ºC) and 3.1 to 28.8 ºC (average of 18.8 ºC) in 2015, 2016 and 2017, respectively. Meanwhile, in the 2015-2016 and 2016-2017 periods between crops in winter, air temperature ranged from 0.1 to 14.8 ºC (average of 7.7 ºC) and -3.6 to 16.4 ºC (average of 7.1 ºC), respectively. Cumulative rainfall was 226, 151 and 78 mm for the 2015, 2016 and 2017 growing seasons, respectively (Table 1). During the periods between crops in winter in 2015-2016 and 2016-2017 rainfall was 108 mm and 106 mm, respectively. Irrigation water applied was 631, 672 and 696 mm for 2015, 2016 and 2017, respectively (Table 1).

3.2 Soil environment during the experimental period.

Over the experimental period, soil temperature ranged from 1.1 to 27.3ºC. Mean soil temperature during the maize growing seasons 2015, 2016 and 2017 were 18.6, 17.1 and 19.8 ºC, respectively. Meanwhile, in the periods between crops in winter 2015-16 and 2016-17 mean soil temperature were 6.9 and 8.7 ºC, respectively. During the study, gravimetric soil moisture was significantly influenced by the interaction between tillage system and period (Table 2). In the 2015 and 2017 maize growing seasons, mean of gravimetric soil moisture showed grater values in NT compared to RT and CT, while in 2016 and in the period between crops in winter 2015-2016 gravimetric soil moisture followed the order NT>RT>CT. In addition, in the period between crops in winter 2016-2017 NT and RT showed greater gravimetric soil moisture than CT (Fig 1).

3.3 Soil carbon dioxide and methane emissions.

The interaction between tillage and sampling date had a significant effect on soil CO_2 emissions (Table 2). Greater CO_2 fluxes were observed under NT and RT than under CT on most sampling dates during maize growing seasons. There was an increase in CO_2 emissions in the months of July and August, coinciding with the period of maximum maize growth (Fig. 2a). In the three years of study, the largest differences between tillage systems occurred just after the second top-dressing N application. Conversely, in the two periods between crops in winter (2015-2016 and 2016-2017), no differences between tillage treatments on CO_2 fluxes were found, with an average emission of 420 mg CO_2-C m^{-2} d^{-1} (Fig. 2a). In the control treatment, greater soil CO_2 emissions were observed under NT (1557 m CO_2-C m^{-2} d^{-1}) compared to CT (855 mg CO_2-C m^{-2} d^{-1}) with intermediate values in RT (1372 mg CO_2-C m^{-2} d^{-1}) as an average of the three years covered by the experiment. When applying 200 kg N ha^{-1} greater soil CO_2 emissions were observed in NT and RT (1401 and 1287 mg CO_2-C m^{-2} d^{-1}, respectively) than in CT (1041 mg CO_2-C m^{-2} d^{-1}). Finally, greater soil CO_2 emissions were observed under NT when applying 400 kg N ha^{-1} (1559 mg CO_2-C m^{-2} d^{-1}) compared to CT under the same rate application (1007 mg CO_2-C m^{-2} d^{-1}) with intermediate values in RT (1328 mg CO_2-C m^{-2} d^{-1}) as an average of the three years covered by the experiment.

Methane fluxes ranged from -1.60 to 1.24 mg CH_4-C m^{-2} d^{-1} (Fig. 2b). Although some emissions to the atmosphere were observed, all treatments acted as net CH_4 sinks during most of the experimental period. Only tillage and sampling date single effects significantly influenced CH_4 fluxes (Table 2). Regarding to this, greater uptake of CH_4 was observed in the three tillage systems compared following the order RT>NT>CT (-0.29, -0.23 and -0.14 mg CH_4-C m^{-2} d^{-1}, respectively). Soil uptake of CH_4 tended to decrease with increasing fertilizer N rates.

3.4 Soil temperature and gravimetric soil moisture effects on CO_2 emissions.

Soil CO_2 emissions were regulated by the combination of soil temperature (ºC) at 10 cm soil depth and gravimetric soil moisture (g 100 g^{-1}) at 0-5 cm soil depth ($P < 0.001$, $r^2=0.53$, RMSE=0.55), being the two variables significant predictors. The resulting model was:

Log (soil CO_2 emissions) = Exp (4.30 + 0.10 * Soil temperature + 0.06 * Gravimetric soil moisture).

High soil CO_2 fluxes (> 1500 mg CO_2-C m^{-2} d^{-1}) were observed when soil temperature at 10 cm depth exceeded 15 °C and gravimetric soil moisture (0-5 cm) was greater than 20 g 100^{-1} (Fig. 3).

3.5 Above-ground biomass and maize grain yield.

Above-ground biomass was significantly affected by the interaction between tillage system and N fertilization and the interaction between N fertilization and year (Table 2). In this regard, NT and RT led to greater above-ground biomass when applying 200 kg N ha^{-1} compared to the use of the same rate under CT. Meanwhile, the use of 400 kg N ha^{-1} led to greater values in NT followed by RT and CT (Fig. 4a). Moreover, in 2016 and 2017, the rate of 200 (18785 and 19230 kg ha^{-1}, respectively) and 400 kg N ha^{-1} (20632 and 19348 kg ha^{-1}, respectively) showed greater above-ground biomass compared to the control (12256 and 10005 kg ha^{-1}, respectively) without significant differences between N rates in 2015.

The interaction between tillage and N fertilization and their interaction with the year had a significant effect on maize grain yields (Table 2). In 2015 and 2017, grain yields were higher under NT (11406 and 9844 kg ha^{-1}, respectively) and RT (9548 and

9278 kg ha^{-1}, respectively) than under CT (5594 and 6478 kg ha^{-1}, respectively), without differences between tillage treatments in 2016. As an average of the three seasons, the rate of 200 kg N ha^{-1} showed greater grain yield under NT compared to CT with intermediate values in RT. Meanwhile, when applying 400 kg N ha^{-1}, NT and RT led to greater grain yield compared to CT (Fig. 4b).

3.6 Cumulative soil CO_2 and CH_4 emissions and above-ground biomass C inputs

Cumulative CO_2 emissions were significantly affected by the interaction between tillage and period (Table 2). In the 2015 growing season, greater cumulative CO_2 emissions were found under NT and RT compared with CT. In 2016 NT showed the highest values compared to CT with intermediate values in RT. Differently, in 2017 no differences between tillage systems were observed (Fig 5a). Contrarily to CO_2, cumulative CH_4 emissions were not significantly affected by any effect (Table 2), although a trend of greater uptake of CH_4 was observed under RT compared with CT and NT (Fig 5b).

The interaction between tillage and N fertilization and between N fertilization and year had a significant effect on above-ground biomass C-input (Table 2). In 2016 and 2017 the fertilizer rates of 200 and 400 kg N ha^{-1} showed greater values compared to the control, while in 2015 no significant differences were observed between N rates (Fig 5c). Moreover, the rates of 200 and 400 kg N ha^{-1} led to greater above-ground biomass C-input in NT (10159 and 11124 kg C ha^{-1}, respectively) and RT (9210 and 9003 kg C ha^{-1}, respectively) than in CT (6978 and 6131 kg C ha^{-1}, respectively), as an average of the three years covered by the experiment. Contrarily, no significant differences between tillage systems on above-ground biomass C-inputs were found in the control treatment.

4. Discussion

4.1 Tillage and N fertilization rate effects on soil CO_2 emissions.

The combined effects of tillage and N fertilization on soil CO_2 emissions observed in this study would be related to the impact of these practices on soil environmental conditions such as soil temperature and soil moisture and on the availability of organic C due to changes in crop residue production. No-tillage showed higher CO_2 emissions when applying high rates of N (400 kg N ha^{-1}) compared to CT. Although irrigation water supply was the same for all treatments, NT led to greater soil moisture (being 60% higher NT than CT). The presence of crop residues on the soil surface under NT enhances soil water availability compared to CT by reducing soil water evaporation and increasing infiltration (Lampurlanés *et al.,* 2016). The increase in soil moisture observed in NT was accompanied by higher CO_2 emissions denoting greater enzymatic activity stimulated by the greater levels of SOC concentration in NT (being 58% greater in NT compared to CT (42.2 vs. 17.8 g kg^{-1}, respectively in the 0–10 cm layer)) and root respiration in the soil in this treatment compared to CT. These data show that in spite of the higher CO_2 emissions in NT, these are compensated by its high capacity for C sequestration. Authors like Manzoni *et al.* (2012) showed that as soil water availability increases, the metabolic activity of soil fauna is enhanced, resulting in higher soil heterotrophic respiration, impacting soil carbon content. The low emissions in CT, even when using high rates of mineral N, could be due to long-term CT leads to a deterioration of the soil physical properties. This degradation was due to a lower structural stability, causing soil surface crusting, which resulted in lower water infiltration (1.70, 2.40 and 3.14 mm h^{-1} for CT, RT and NT, respectively) into the soil profile, compromising plantlet establishment (with a density of plants 19% and 22% lower in CT compared to RT and NT, respectively) and leading to plant water stress (Pareja-Sánchez *et al.,* 2017). Under these circumstances, the impact of tillage systems on soil structure played a major role on crop productivity. Therefore, soil respiration and the amount of C returned to the soil as crop residues were reduced under CT.

The combined effect of increased soil water and a more stable soil structure under NT and RT had a positive response on maize above-ground biomass and grain yield production. Accordingly, increased crop residue production may have led to increased availability of C and increased soil microbial activity impacting soil CO_2 emissions (Tenesaca and Al-Kaisi, 2015). In the previous barley production under rainfed conditions in the same field, there was a reduction greater than 50% in microbial biomass and enzymatic activities in CT compared to NT (Álvaro-Fuentes *et al.,* 2013), which in turn led to higher SOC sequestration under long-term NT (Morell *et al.*, 2011). This increase of SOC sequestration in NT was due to the higher C inputs as well as the absence of soil physical disturbances that benefited the physical storage of carbon in soil aggregates (Álvaro-Fuentes *et al.*, 2008).

Previously, in the same experimental field, in rainfed NT barley conditions cumulative CO_2 emissions were 37% lower compared to the values found in our study in irrigated conditions and in CT this difference dropped to 46% (Plaza-Bonilla *et al.*, 2014). The difference between these studies could probably be attributed to the increase in heterotrophic and autotrophic respiration taking place under irrigated conditions. In particular, the N fertilization applied in our experiment led to higher above-ground biomass and therefore higher heterotrophic respiration rate under NT and RT than in CT. On the other hand, the increase in autotrophic respiration under NT and RT was caused by an increase in root respiration which led to significant increase in crop production (Kou *et al.*, 2008) as well as more organic C available to decomposers. This fact would explain the higher cumulative CO_2 emissions observed under NT and RT in comparison with CT (38% and 28% higher, respectively). Contrarily, the application of N did not enhance soil CO_2 emissions under CT. There is no consensus about the impact of N availability on soil C mineralization with studies showing either a stimulatory or a suppressive effect (Al-Kaisi and Guzman, 2013). In this line, although the application of mineral nitrogen generally estimulates CO_2 emissions (Iqbal *et al.*, 2009) throughout the rise in C inputs, some authors have pointed out that CO_2 fluxes can decrease when using high N rates, as a consequence of a lower activity of enzymes (DeForest *et al.*, 2004). A higher soil mineral N availability under CT could have decreased the need for soil microorganisms to mineralize soil organic matter to obtain the necessary N for growth and reproduction (Smith *et al.*, 2012) and, as a consequence, reduce soil respiration.

4.2 Temporal dynamics of soil CO_2 emissions.

During the maize growing season, mean annual cumulative CO_2 values obtained in our study (2256-3255 kg CO_2-C ha^{-1} yr^{-1}) were within the range of the values reported by Forte *et al*. (2017) and Guardia *et al*. (2017) in irrigated maize under similar Mediterranean conditions. However, during the period between crops in winter, soil CO_2 emissions were reduced (with an average of 655 kg CO_2-C ha^{-1} ha^{-1} yr^{-1}) as a consequence of the lower air temperatures (Al-Kaisi and Yin, 2005) as well as the absence of root respiration during this phase.

The highest cumulative emissions in 2016 coincided with an increase in above-ground biomass C-inputs to the soil from the previous campaign. Therefore, cumulative values would be closely related to the amount of C available for microbial decomposition. Moreover, an increase in soil CO_2 emissions was observed during July and August in the three maize growing seasons studied (2015, 2016 and 2017), when the maximum maize growth rate occurs. During this period (July and August) around 50% of soil respiration is the result of root respiration plus the decomposition of root exudates (Rochette *et al.*, 1999). Additionally, these results during July and August could also be attributed to an enhancement in soil organic matter mineralization as a result of greater soil surface temperature and moisture as the multiple linear relationship obtained between these variables corroborates. The highest CO_2 fluxes occurred when soil temperatures were greater than 15 °C and gravimetric soil moisture was greater than 20%. This demonstrates that soil temperature and gravimetric soil moisture regulated CO_2 emissions interactively (Almagro *et al.*, 2009).

4.3 Tillage and N fertilization effects on CH_4 emissions and temporal dynamics.

In the experiment, significant differences in CH_4 fluxes were only found between tillage systems. Data showed that CH_4 uptake was lower in CT compared with RT and NT, as observed by Plaza-Bonilla *et al*. (2014) in the same experiment under previous rainfed conditions. In this line, Hütsch, (2001) suggested that CH_4 oxidation can be reduced by tillage due to its effects on gas diffusivity and to long-term damage of methanotrophic bacterial community. Low CH_4 emissions to the atmosphere were observed only few days after N fertilization. Respect to this, Hütsch *et al*. (1993) showed that the addition of mineral N reduces the uptake of atmospheric CH_4 by soils.

Soil properties such as temperature, water content, bulk density, and SOC have an important role in the activity of methanogens and methanotrophs, affecting the sign of CH_4 emissions (Mitra *et al.*, 2002). In the present study, the soil acted as a net sink of CH_4 in all treatments, indicating a greater proportion of methanotrophic activity. Other authors have also reported that CH_4 is primarily consumed by soils under upland field crops cultivation (Kessavalou *et al.*, 1998; Venterea *et al.*, 2005). About 42% and 49% higher uptake of CH_4 occurred during the 2015 maize growing season compared to the 2016 and 2017 seasons, respectively. These results could be explained by the lower soil water contents during the previous rainfed management, closer in time in 2015 compared to 2016 and 2017, which could have favored the methanotrophic communities (von Fischer and Hedin, 2007). This hypothesis would be supported by the greater amount of methane uptake by soil found during a barley rainfed season in the same experiment, which reached average values -0.78 and -1.72 kg CH_4-C ha^{-1} yr^{-1} under CT and NT, respectively (Plaza-Bonilla *et al.*, 2014) while in irrigated maize were-0.55 and -0.65 kg CH_4-C ha^{-1} yr^{-1} under CT and NT, respectively.

Conclusion

This experiment highlights the extent of changes on the dynamics of soil CO_2 and CH_4 emission in Mediterranean agroecosystems recently transformed into irrigation. In this study, soil CO_2 emissions were greater when increasing the rate of N in combination with a tillage reduction as result of enhanced maize growth promoting root respiration and greater soil organic C availability to decomposers. Differently, under CT an increase in N fertilization reduced soil respiration. The higher soil mineral N availability under CT could have decreased the need for soil microorganisms to mineralize soil organic matter. In general the soil acted as a CH_4 sink in all treatments. However, CH_4 oxidation was lower in CT compared with RT and NT, which could be the result of the effect of tillage on gas diffusivity. Compared to a previous period under rainfed barley production, annual soil CO_2 emissions were 37 to 46% greater, depending on the type of tillage. Contrarily, CH_4 uptake decreased after the transformation into irrigation, as a result of the wetter soil conditions which could have affected the methanotrophic communities by reducing soil CH_4 oxidation. Our study suggests that, in maize-based Mediterranean agroecosystems recently transformed to irrigation, the reduction in tillage intensity and N fertilization rates increases soil CO_2 emissions and CH_4 uptake. The higher maize growth and organic C production under these management practices could lead to soil C storage, reducing the C footprint of the cropping system.

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Figure captions

Fig. 1 Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) effects on gravimetric soil moisture at 0-5 cm depth. Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and periods between crops in winter (PC 2015-2016 and PC 2016-2017). Different lowercase letters indicate significant differences between tillage treatments for a given period at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 2 Soil CO_2 (a) and CH_4 (b) emissions as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) during the 2015, 2016 and 2017 maize growing seasons and two periods between crops in winter (2015-2016 and 2016-2017). Arrows indicate dates of N fertilizer application. For a given date, asterisks indicate significant differences between tillage systems at $P<0.05$.

Fig. 3 Effects of soil temperature at 10 cm depth and gravimetric soil moisture (0-5 cm depth) on CO_2 fluxes. Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and two periods between crops in winter (2015-2016 and 2016-2017). Each point corresponds to the average of the different treatments for a given sampling date (n = 102).

Fig. 4 Above-ground maize biomass (a) and grain yield (b) as affected by tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rate (0, 200 and 400 kg N ha^{-1}). Values correspond to the means of three consecutive maize growing seasons (2015, 2016 and 2017). Different lowercase letters indicate significant differences between tillage systems for a given N fertilization rate at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 5 Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) effects on cumulative soil CO_2 (a), and CH_4 emissions (b) and year (2015, 2016 and 2017) effects on above-ground biomass C-inputs (c). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and two periods between crops in winter (PC 2015-2016 and PC 2016-2017). Different lowercase letters indicate significant differences between tillage treatments for a given period (a and b) and significant differences between years for a given N fertilization rate (c) at $P< 0.05$. Vertical bars indicate standard deviation.

Table 1 Mean monthly air temperature (T) (ºC) monthly precipitation (P) (mm) and monthly irrigation (I) (mm) in the field experiment during three consecutive maize growing seasons (2015, 2016 and 2017) and periods between crops in winter (PC 2015-2016 and PC 2016-2017).

Month	**Maize 2015**			**PC 15-16**			**Maize 2016**			**PC 16-17**			**Maize 2017**		
	T	**P**	**I**	**T**	**P**	**I**	**T**	**P**	**I**	**T**	**P**	**I**	**T**	**P**	**I**
April	13.4	15.0	9.8	-	-	-	12	78.0	5.2	-	-	-	12.5	0.0	0.0
May	18	1.0	119.2	-	-	-	15.4	60.0	55.8	-	-	-	17.7	0.0	42.6
June	21.7	24.0	72.7	-	-	-	20.6	1.0	134.1	-	-	-	22.6	0.0	151.8
July	25.4	25.0	232.6	-	-	-	23.7	0.0	222.3	-	-	-	24	3.0	204.8
August	22.9	36.0	178.1	-	-	-	22.8	5.0	246.8	-	-	-	23.6	12.0	244.1
September	17.5	98.0	20.3	-	-	-	19.9	4.0	52.0	-	-	-	17.3	22.0	52.6
October	14	2.0	0.0	-	-	-	14.4	39.0	0.0	-	-	-	15	26.0	0.0
November	8.9	26.0	0.0	-	-	-	8.4	41.0	0.0	-	-	-	8.8	15.0	0.0
December	-	-	-	5.8	0.0	0.0	-	-	-	3.6	3.0	0.0	-	-	-
January	-	-	-	6.5	2.0	0.0	-	-	-	2.9	14.0	0.0	-	-	-
February	-	-	-	7.1	37.0	0.0	-	-	-	7.6	12.0	0.0	-	-	-
March	-	-	-	8.4	30.0	0.0	-	-	-	10.4	44.0	0.0	-	-	-

Table 2 Analysis of variance (*P*-values) of gravimetric soil moisture, soil CO_2 flux, soil CH_4 flux and cumulative CO_2 and CH_4 emissions, above-ground biomass, grain yield and above-ground biomass C inputs for each maize growing season (2015, 2016 and 2017) and periods between crops in winter (2015-2016 and 2016-2017), as affected by tillage, N fertilization, date/year/period and their interaction.

Source of variation	**Gravimetric soil moisture**	**CO_2 flux**	**CH_4 flux**	**Cumulative CO_2 emissions**	**Cumulative CH_4 emissions**	**Above-ground biomass**	**Grain yield**	**Above-ground biomass C inputs**
Tillage (Till)	<0.001	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001
N fertilization (Fert)	ns	ns	ns	ns	ns	<0.001	<0.001	<0.001
Date/Year/Period	<0.001	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001
Till*Fert	ns	ns	ns	ns	ns	0.009	<0.001	0.01
Till*Date/Year/Period	<0.001	<0.001	ns	<0.001	ns	ns	0.01	ns
Fert*Date/Year/Period	ns	ns	ns	ns	ns	0.04	<0.001	<0.001
Till*Date/Year/Period*Fert	ns	ns	ns	ns	ns	ns	ns	ns

ns, non-significant

Fig. 1 Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) effects on gravimetric soil moisture at 0-5 cm depth. Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and periods between crops in winter (PC 2015-2016 and PC 2016-2017). Different lowercase letters indicate significant differences between tillage treatments for a given period at $P < 0.05$. Vertical bars indicate standard deviation.

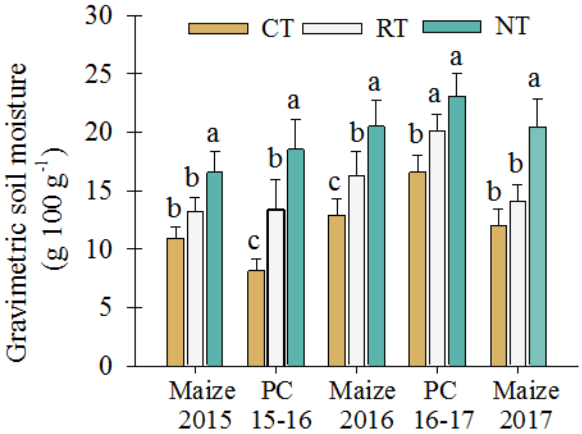

Fig. 2 Soil CO_2 (a) and CH_4 (b) emissions as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) during the 2015, 2016 and 2017 maize growing seasons and two periods between crops in winter (2015-2016 and 2016-2017). Arrows indicate dates of N fertilizer application. For a given date, asterisks indicate significant differences between tillage systems at $P<0.05$.

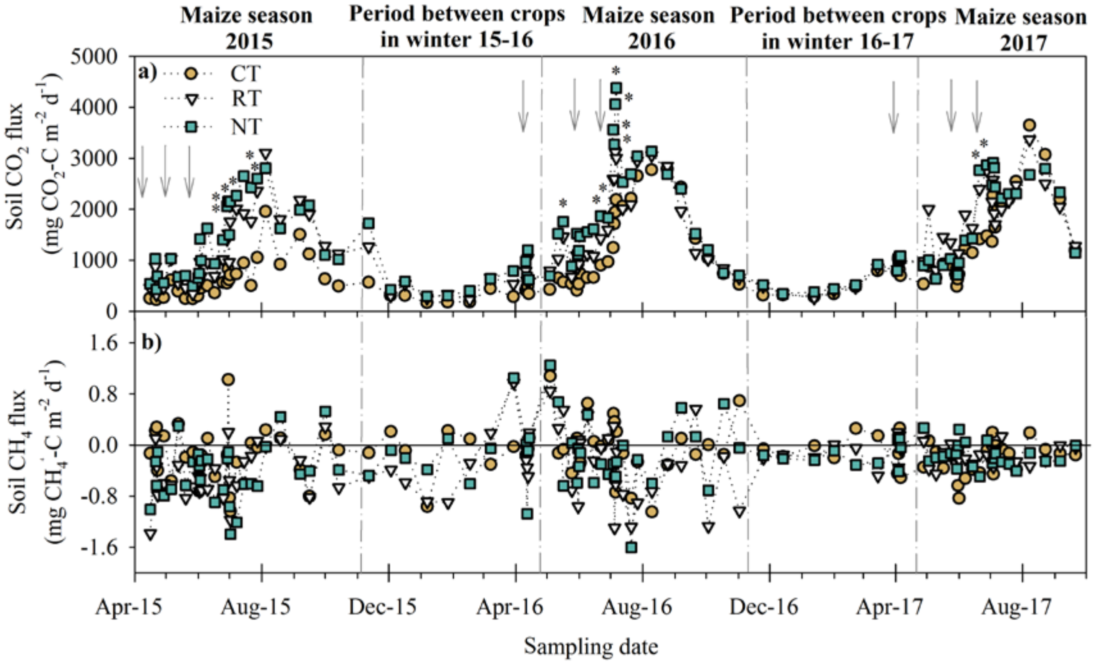

Fig. 3 Effects of soil temperature at 10 cm depth and gravimetric soil moisture (0-5 cm depth) on CO_2 fluxes. Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and two periods between crops in winter (2015-2016 and 2016-2017). Each point corresponds to the average of the different treatments for a given sampling date (n = 102).

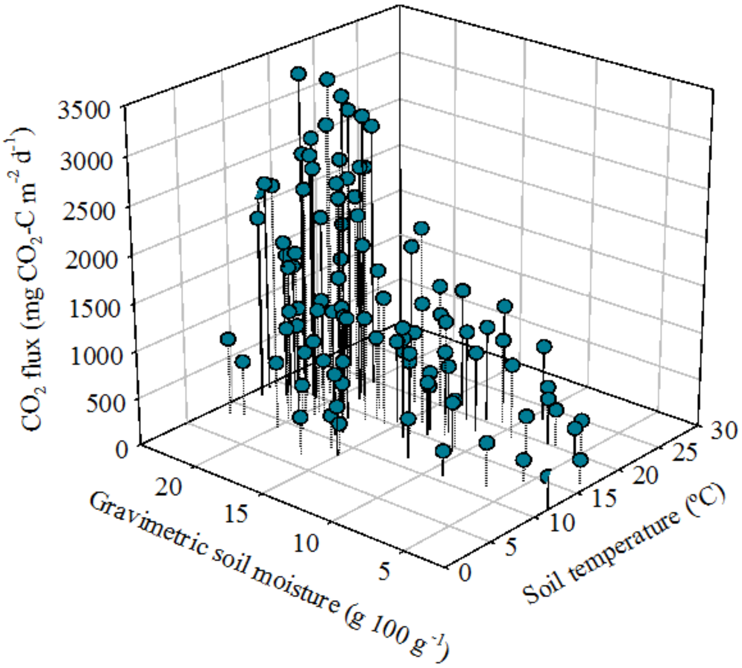

Fig. 4 Above-ground maize biomass (a) and grain yield (b) as affected by tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rate (0, 200 and 400 kg N ha^{-1}). Values correspond to the means of three consecutive maize growing seasons (2015, 2016 and 2017). Different lowercase letters indicate significant differences between tillage systems for a given N fertilization rate at *P*< 0.05. Vertical bars indicate standard deviation.

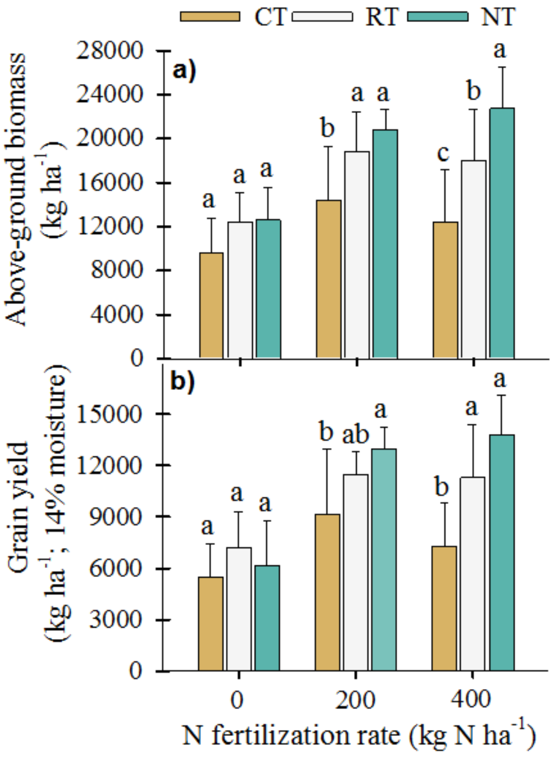

Fig. 5 Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) effects on **c**umulative soil CO_2 (a), and CH_4 emissions (b) and year (2015, 2016 and 2017) effects on above-ground biomass C-inputs (c). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and two periods between crops in winter (PC 2015-2016 and PC 2016-2017). Different lowercase letters indicate significant differences between tillage treatments for a given period (a and b) and significant differences between years for a given N fertilization rate (c) at *P*< 0.05. Vertical bars indicate standard deviation.