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Effects of conservation tillage, controlled traffic and regulated deficit irrigation on soil CO_2 emissions in a maize-based system in Mediterranean conditions

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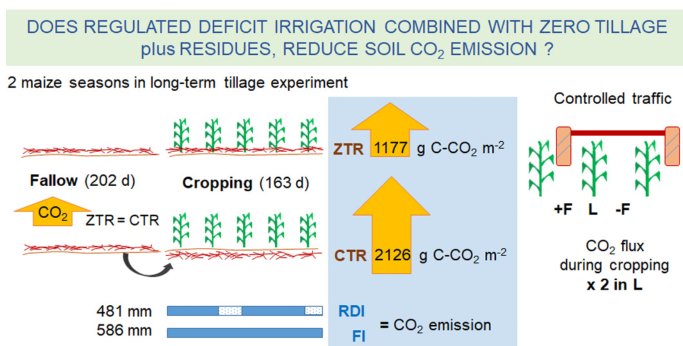
HIGHLIGHTS

- The field experiment combined regulated deficit irrigation (RDI) with zero tillage with surface residues (ZTR).
- RDI was effective in conserving water, but did not affect soil CO_2 efflux.
- ZTR reduced cumulative CO_2 emissions by almost half during the maize season.
- Soil CO_2 efflux in the crop rows was doubled than between the rows.
- CO_2 daily curves showed the representative measuring hours of the 24-hour emission.

GRAPHICAL ABSTRACT



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ABSTRACT

Conservation tillage is promoted as a potential agriculture practice to reduce carbon dioxide (CO_2) emissions but little is known on its impact in irrigated Mediterranean conditions, and particularly, when combined with controlled traffic, adopted to avoid soil compaction effects on the crops, and with regulated deficit irrigation (RDI), adopted to conserve water. CO_2 effluxes were measured during the 2016/2017 and 2017/2018 irrigated maize-cropping and fallow periods on a long-term tillage experiment established in Cordoba (Spain) in which two tillage systems, conventional with residues incorporated (CTR) and zero tillage with surface residues (ZTR), are compared, both combined with controlled traffic. Additionally, two irrigation treatments were introduced: full irrigation (FI) and RDI. We hypothesized that ZTR paired with RDI would make this irrigation strategy more effective for reducing CO_2 emissions. Although tillage and traffic affected CO_2 effluxes, RDI did not in spite of saving 100 mm of water. Frequent irrigations maintained similar superficial soil conditions in FI and RDI. In the short term, soil CO_2 effluxes were higher in CTR than in ZTR after soil preparation and during crop growth, although only significantly in the first case. However, accumulated CO_2 emission during the cropping period (163 days) was 1.8 times higher for CTR than ZTR (2126 and 1177 g m^{-2}, respectively). The accumulated emission during the fallow period (202 days) was less relevant and similar for both systems (628 g m^{-2}). Spatially, crop lines emitted the double CO_2 than furrows during the cropping period in both tillage systems, and in ZTR during the fallow, showing the relevance of the measuring point locations. Three diurnal soil CO_2 efflux curves supported the results. In irrigated Mediterranean maize crops, ZTR combined with controlled traffic can be an efficient soil management system to reduce CO_2 emissions, and can be paired with RDI for water saving.

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1. Introduction

Substantial reductions in agricultural greenhouse gases emissions are considered by numerous countries for complying with the Paris Agreement of the United Nations Framework Convention on Climate Change (Richards et al., 2016). Although the agriculture sector contributes a higher percentage of methane and nitrous oxide anthropogenic emissions than of carbon dioxide (CO_2), the long-lasting effect of the last makes imperative to reduce its balance to net zero by 2050 (IPCC, 2018; Lynch et al., 2021). The Climate Change and Land IPCC (2019) Special Report identifies reducing tillage as a key potential agriculture practice for reducing CO_2 emissions while capturing it in the soil as organic carbon. This view is supported by the scientific community (e.g. Paustian et al., 2016) and it is reflected in part in international initiatives like the "4 per 1000" initiative (www.4p1000.org) or the Global Soil Partnership (www.fao.org/global-soil-partnership). Tillage is in the spotlight because it puts at risk the large potential of the soil as a carbon sink. When soil is tilled, pores are disrupted and the CO_2 occupying this space is liberated resulting in pick emissions of this gas (Reicosky and Archer, 2007), but more importantly, the disruption of soil aggregates and increase in soil porosity promotes the degradation of incorporated crop residues and accelerates the oxidation of soil organic carbon (Plaza-Bonilla et al., 2013; Mehra et al., 2018).

The potential of eliminating tillage of field operations for soil conservation is clear but its potential for climate change mitigation may be overestimated, in part due to methodological limitations when estimating carbon sequestration in the soil (Powlson et al., 2014; Palm et al., 2014; Govaerts et al., 2009), in part to the effects on the emissions of nitrous oxide (Van Kessel et al., 2013). Reviews on the impact of reducing tillage on reducing soils CO_2 emissions shows highly variable results, its effectiveness depending on the agroecological conditions, including the management of residues and fertilization, and the duration of the no-till conditions (Abdalla et al., 2016; Plaza-Bonilla et al., 2014; Sanz-Cobena et al., 2017; Huang et al., 2018). The soil CO_2 emissions in no-till systems will also depend on the evolution of soil compaction due to machinery traffic to carry out other field operations. Soil compaction reduces air diffusivity and blocks release pathways (Ball et al., 1999), and although it can hinder roots and above-ground crop growth in no-till systems, these negative effects can be minimized by confining the traffic into permanent traffic lanes (Boulal et al., 2012; Cid et al., 2014). The resulting spatial differences in soil compaction under controlled traffic will also result in spatial differences in the emission of greenhouse gases from the soil (Cid et al., 2013; Antille et al., 2015).

Irrigation can affect soil CO_2 emissions in cropping systems by promoting crop growth and thus roots respiration, by producing more residues that can feed microorganisms, and by increasing soil moisture and improving the conditions for soil organic matter (SOM) mineralization, particularly in summer when temperatures are high, however, there has been little research on the effect of varying rates of irrigation (Sapkota et al., 2020). This is particularly relevant in Mediterranean conditions where the limited availability of water for irrigation has promoted regulated deficit irrigation (RDI), i.e. to reduce applied water only during the least drought-sensitive crop phenological periods (Fereres and Soriano, 2007). This strategy has been proven effective to save water without yield penalty in diverse crops, including maize (Domínguez et al., 2012), and few recent studies have shown its potential to reduce soil CO_2 emissions in orchards and vineyards (Zornoza et al., 2016, 2018) and wheat (Hou et al., 2019).

Under conservation tillage systems, crop residues are maintained on the surface and soil is not disturbed except for the narrow openings to place seeds, and probably fertilizers, during the sowing operation (Baker and Saxton, 2007). Maintaining residues in no tilled systems can increase water availability for crops by increasing water infiltration into the soil and by reducing soil water evaporation and runoff (Lampurlanés and Cantero-Martínez, 2006; Brouder and Gomez-Macpherson, 2014), particularly in semi-arid environments (Pittelkow et al., 2015; Lampurlanés et al., 2016). Under irrigated conservation tillage, an extra 60 to 120 mm of available water was estimated compared to a conventionally tilled system in an experimental farm (Van Donk et al., 2010). In this study we hypothesized that conservation tillage in combination with RDI will make this irrigation strategy more effective for reducing CO_2 emissions in irrigated Mediterranean cropping systems. The main objective of this study was to evaluate the impact of the combination of conservation tillage with RDI on soil CO_2 emissions in irrigated maize crops profiting of the availability of a long-term trial in which zero tillage with surface residues has been compared to the conventionally tilled system with residues incorporation, both systems applying controlled traffic. Our goal included deepening on the spatial variability of soil CO_2 emissions, as well as on the temporal variations associated to crop and fallow management.

2. Materials and methods

2.1. Experimental site

The experimental site is located at the Alameda del Obispo experimental farm (latitude 37° 51′ 36.9″ N, longitude 4° 47′ 43.9″ W, altitude 110 m) in Córdoba, Spain. The climate in the area is hot-summer Mediterranean-type climate (Csa) in Köppen–Geiger climate classification system (Kottek et al., 2006). The site has annual average rainfall of 598 mm concentrated from early autumn to mid-spring, reference evapotranspiration of 1408 mm (ET_o, FAO-Penman-Monteith method; Allen et al., 1998), and monthly mean temperatures for the coldest and warmest month of 8.4 °C in January and 27.8 °C in August (2001 − 2020). Fig. S1 shows weekly average of daily minimum and maximum air temperatures, and weekly-accumulated rainfall and ET_o during the two agricultural seasons of this study (2016/17–2017/18). Accumulated rainfall from sowing to harvest in 2016 and 2017 seasons (Table 1) was 172 and 129 mm, respectively, and accumulated ET_o for the same periods was 896 and 934 mm. All weather data were obtained from an agrometeorological station located about 600 m from the experimental plot. The soil was classified as Typic Xerofluvent (Natural Resources Conservation Service Soil Survey Staff, 2010) or Eutric Fluvisol (according to the world reference soil groups; IUSS, 2015). The soil has a loam texture, practically uniform up to 0.75 m deep (mean values of 13.7% clay and 45.4% sand, for the top 0.30-m soil horizon; and 12.6% clay and 47.1% sand for the 0.30–0.75 m horizon), without restriction for root growth up to 2-m depth. Volumetric soil water content (SWC) at the field capacity and at the permanent wilting point were estimated as 0.286 and 0.133 $m^3\ m^{-3}$, respectively.

2.2. Treatments and farming operations

The field experiment was conducted for two consecutive agricultural seasons (2016/17 and 2017/18) in a long-term trial set up in 2007 to compare two tillage-planting systems: conservation and conventional irrigated maize (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation systems, both with residue retention, controlled traffic and crops grown over beds (Boulal et al., 2012; Cid et al., 2014). In the last three years (2015–2017), maize was grown consecutively, keeping the two planting systems and the controlled traffic, but without forming the beds, therefore being named conventional tillage with residue incorporation (CTR) and zero tillage with surface residues (ZTR) treatments. At the beginning of the 2016 cropping season (April 2016), the average soil organic carbon concentration in the top 0.05 m layer was higher in ZTR ($p < 0.001$): 6.50 and 9.59 g kg^{-1} in CTR and ZTR respectively (soil bulk density of 1.46 and 1.44 Mg m^{-3} respectively). Below 0.05 m, there were no significant differences in soil organic carbon between planting systems.

Tillage operations in CTR system consisted of subsoiling (at 0.50–0.70 m depth) followed by two shallow-passes with a disc harrow (at 0.15-m depth) and a vibro-cultivator (at 0.10-m depth) prior to sowing (Table 1), while weed control in both tillage treatments was carried out using herbicides. Maize (cv. LG 30.600) was sown on April 8 in 2016, and on April 6 in 2017, in 0.86 m spaced crop-rows with an intra-row plant spacing of 0.085 m. The seedlings emerged 8–12 days after sowing, and maize ears were harvested on September 2, 2016, and September 1,

Table 1
Farming practices performed at the experimental plot during 2016 and 2017.
Note: during the 2017/18 fallow period, no herbicides were applied.

Farming operation	Year	
	2016	2017
Herbicide application	Feb. 3rd	Jan. 13th
		Mar. 2nd
	Apr. 8th	Mar. 29th (ZTR)
		May 9th
		May 16th
Subsoiling in CTR; 0.6-m depth	Mar. 30th	Mar. 16th
Disk harrow pass in CTR; 0.15-m depth		
Vibro-cultivator in CTR; 0.10-m depth		
Basal NPK (15-15-15; 750 kg ha^{-1})		
Maize sowing. Soil insecticide application	Apr. 8th	Apr. 6th
Fertilization N (Urea; 46%N)	May 24th (150 kg ha^{-1})	May 17th (200 kg ha^{-1})
	Jun. 7th (175 kg ha^{-1})	May 30th (200 kg ha^{-1})
Irrigation period	May 6th–Aug. 18th	Apr. 18th–Aug. 10th
Regulated deficit irrigation (RDI) period	Jun. 7–28th	Jun. 6–22th
	Jul. 12th–Aug. 18th	July 6th–Aug. 10th
Harvest	Sept. 2th	Sept. 1th
Mowing of maize stalks	Oct. 10–11th	Oct. 5–9th

2017. The farming operations carried out in the two treatments are listed in Table 1.

The experimental plot was irrigated by a 54.8 m linear move sprinkler system (Valley Linear 8120; 1.52 bar of linear pressure) in which a variable rate irrigation (VRI) system (Valmont Irrigation, Valley, NE, USA) was installed. During the two maize growing-cycles, two irrigation (I) treatments were applied: full irrigation (FI), in which 100% of the crop irrigation water requirement was supplied, and regulated deficit irrigation (RDI), in which only 75% of FI was applied, except during early stages of crop establishment and from the early-tasseling to the beginning of grain filling in which FI was applied. Different doses in FI could be obtained by changing the speed of the linear system. A prescription was prepared for turning the electric solenoids valves on and off in the RDI treatment to reduce the applied water to 75% while in FI the valves were always open. An internal GPS indicated the exact location of the linear system in the plot. The irrigation doses for FI were established weekly from the crop ET and effective rainfall, following the FAO methodology (Allen et al., 1998), in order to bring the soil water content near field capacity to the rooting depth, and irrigation water was applied once or twice a week throughout the crop cycle. As commonly done in the region, less water was applied towards the end of the maize growth cycle, to deplete the available soil water and to facilitate harvest. The total amount of irrigation water applied during the irrigation period (Table 1) was 589 and 480 mm in 2016, and 583 and 482 mm in 2017, for FI and RDI respectively. During the irrigation period, accumulated precipitation and ET_o were 92 and 687 mm, respectively, in 2016 (104 days) and 122 and 753 mm in 2017 (114 days) (Fig. S1). The periods of application of irrigation and RDI are shown in Table 1, and the number of biweekly irrigations and the corresponding amount of water for FI and RDI treatments are shown in Table S1.

The experimental plot covered 0.8 ha divided into three blocks. Each block was randomly subdivided into two tillage (T) plots, consisting of ten 0.86-m-spaced rows by 140 m in length, with either CTR or ZTR treatment, maintained since 2007. Thanks to the VRI system, each block could be irrigated independently with seven sprinklers: two part-circle (model Nelson PC-S3000) at both sides of each block, and five full circle (model Senninger I-Wob-UP3) in between. After the VRI installation at the start of this study in 2016, each block was again randomly subdivided into two irrigation (I) plots (20 rows by 70 m) with either FI or RDI treatment. The resulting experimental design was a strip-plot (or split-block) design with four T $\times$ I treatments (10 rows by 70 m per elementary plot or T $\times$ I subplot) replicated three times (Fig. S2A). Sprinklers were approximately 3.0 m above the ground. High irrigation uniformity was confirmed by installing 60 rain gauges, 20 per block, in five irrigations early in the two seasons (before the crop covered the rain gauges). Traffic was controlled throughout the experimental plot, and furrows with tractor wheel traffic (F+) alternated with furrows without traffic (F−). The separation between two contiguous trafficked furrows (1.72 m) was imposed by the width of the tractor used (model ME9000 DTL, Kubota Corporation, Thame, UK; 2.9 Mg of weight and tires of 0.38 m width). In CTR, traffic was random during tillage for soil preparation but controlled at and after sowing. Sowing and mowing operations affected every single F+ furrow, but only some of these F+ furrows (one third) were trafficked by tractor for agrochemical applications during the crop growth. Maize ears were hand-harvested.

2.3. Soil-surface CO_2 efflux measurement

CO_2 emissions from soil were measured using an infra-red gas analyzer (IRGA; LI-COR model LI-820) connected to a portable PVC flow-through non-steady-state (FT-NSS) chamber equipped internally with a fan, a temperature sensor and a pressure relief vent, as described in Cid et al. (2013). During each measurement, the chamber (internal diameter of 0.153 m, and internal volume of 6.33×10^{-3} m^3) was fitted to a PVC collar (0.16 m internal diameter and 0.06 m height), which were previously inserted 0.03 m into the soil in order to avoid soil disturbance and the associated undesirable emissions. Air was circulated from the chamber to the IRGA and back by a pump system governing the chamber's mixing fan at flow rate of 1 L min^{-1} over a sampling period of 3 min. The CO_2 concentration was registered every second by a data-logger (CR-1000, Campbell Scientific) connected to the IRGA, and the efflux was calculated from the concentration increase over time. Before each flow measurement, the chamber was waggled for several seconds until the air inside it reached the ambient CO_2 concentration.

Soil CO_2 efflux was regularly measured during the two maize cropping and fallow periods, and just before and after the first autumnal rainfall event in 2016 and 2017. The number of days of soil CO_2 efflux measurement was 12 and 24 in the 2016/17 and 2017/18 cropping years, respectively, and, on each date, soil CO_2 efflux was measured on three PVC collars per elementary plot: in F+, crop-line (L) and F−, in consecutive positions (measuring site; Fig. S2B). Measurements started in-between 7:15 and 8:30 GMT; exceptionally, the day before and just after tillage of CTR plots in 2017 (Table 1) measurement started around 10:00 and 12:00 GMT, respectively. In CTR, the collars were removed prior to soil preparation in 2017, and then repositioned into the soil just after tillage (F−) and maize sowing (F+ and L positions); whereas collars' position remained unchanged throughout the experiment in ZTR (although the L and F+ collars were removed for sowing). None of the F+ furrows with collars was trafficked by the tractor for application of agrochemicals during the maize growth cycle.

Additionally, on three dates, several measurements per collar were made throughout the day (starting at sunrise and finishing at dawn) in order to estimate diurnal cycles of CO_2 emissions, as well as the daytime period when the soil's CO_2 efflux was equivalent to the daily/hourly mean CO_2 efflux. This diurnal cycles were carried out on June 2, 2016 (seven measurements), on October 27, 2016 (five measurements) and on July 31, 2017 (six measurements), dates that corresponded to the vegetative phase, fallow period and reproductive phase of maize. Measurements were made only in two of the three blocks, due to the time required for a full round of measurements (approximately 120 min for 24 collar positions), which meant four replications for each tillage treatment (CTR or ZTR).

2.4. Hourly and seasonal soil C-CO_2 emissions calculation

For NSS chambers, CO_2 efflux (F_C) estimation requires determining the rate of CO_2 accumulation within the chamber. Fc was calculated using the following equation (Rochette and Hutchinson, 2005):

$$F_c = \frac{\frac{\partial C}{\partial t}\left(\frac{V}{A}\right)}{Mv}$$

where: F_C is the soil CO_2 efflux (μmol m^{-2} s^{-1}), V (m^3) is the chamber enclosed space volume, A (m^2) is the enclosed soil area, Mv (m^3 mol^{-1}) is the molar volume of air at chamber air temperature and pressure (approx. 22.4×10^{-3} m^3 mol^{-1} for ideal gas; and is thus equal to $0.0821 \times 10^{-3} \times$ [T(K)/P(atm)] m^3 mol^{-1}), and $\partial C/\partial t$ (μmol mol^{-1} s^{-1}) is the rate of the CO_2 accumulation within the chamber (determined from the slope of the linear concentration increase). Soil CO_2 efflux (μmol m^{-2} s^{-1}) was converted into C-CO_2 efflux (mg C-CO_2 m^{-2} h^{-1}) by multiplying it by the molar mass of C (12.01 μg C/μmol CO_2) and applying the corresponding corrections for units.

The hourly soil C-CO_2 efflux for each tillage system (CTR and ZTR) was calculated by weighing the hourly values (mg C-CO_2 m^{-2} h^{-1}) obtained for each of the three collars in consecutive positions (F+, L, and F− in a measuring site) by the fraction of the surface area they represent (L = 0.5, F+ and F− = 0.25 each). To compare the C-CO_2 effluxes from the crop-line (L) and the furrow (F), the values for the trafficked (F+) and non-trafficked (F−) furrows in each measuring site were averaged resulting in a single traffic treatment, which corresponds to the mean furrow (F).

From the three diurnal cycles of CO_2 emissions, nocturnal emissions were estimated by assuming a linear decrease between the last diurnal measurement just before nightfall and the first diurnal measurement just after dawn. The average daily/hourly CO_2 efflux (mg CO_2 m^{-2} h^{-1}) was estimated by dividing by 24 the result of the integration of each daily CO_2 emission curve (mg CO_2 m^{-2} day^{-1}).

To estimate seasonal cumulative soil C-CO_2 emissions during maize cropping and fallow periods, the measured hourly effluxes were first converted into daily C-CO_2 emissions. Seasonal C-CO_2 emission was then calculated for each collar as the area under its corresponding curve of data points, after filling the gaps by linear interpolation, for the periods: from soil preparation to harvest (the maize cropping period) and from harvest to the eve of soil preparation (the fallow period). In 2016, measurements started few days after soil preparation, so degassing emissions due to soil disturbance were not characterized. However, to estimate the effect of soil preparation in 2016, we decided to carry out the same tillage operations sequence in spring 2018, and measured soil CO_2 effluxes in collars following the same design, except that the number of collars was doubled and therefore resulting in eight replications for each tillage treatment. Seasonal integrations were made for each tillage system (CTR and ZTR) and for each tillage system × crop-line/furrow position (CTR L, CTR F−, CTR F+, ZTR L, ZTR F− and ZTR F+).

2.5. Soil temperature and moisture measurements

Soil temperature (Ts, °C; Testo 106 digital thermometer) and volumetric soil water content (SWC, m^3 water per m^3 total soil volume) were recorded concurrently to the soil CO_2 efflux measurement, down to 0.05 m and to 0.075–0.15 m depth respectively, with three measurements in the proximity of each collar position (F−, L and F+). Average values per tillage system (CTR and ZTR) were calculated by weighing according to the area they represented (L = 50%, F+ and F− = 25% each). SWC was measured using a time domain reflectometry device (TDR, Model 6050X1 TRASE System I) calibrated previously in the same experimental plot.

2.6. Statistical analysis

Treatments' effects on soil CO_2 emissions, Ts and SWC were compared by analysis of variance (ANOVA). Soil C-CO_2 efflux data were analysed as a strip-plot design for the effects of tillage system (T) and irrigation strategy (I) factors. Thus, differences in CO_2 efflux between the crop-lines (L) and the furrows (F) were analysed as a strip-split-plot design, where the levels of each T and I factor were randomized over the main plots, and the collars position factor was assigned to the subplots within each main plot. However, when irrigation treatments (FI and RDI) did not have a statistically significant differential effect on soil CO_2 efflux, differences in C-CO_2 fluxes were analysed as a split-plot design, with T factor (CTR and ZTR levels) applied to the main-plots, and collar position or traffic (L and F, or F− and F+ levels) to the sub-plots. The same procedures were used to analyse the Ts and SWC data.

Differences in seasonal soil C-CO_2 emissions between CTR and ZTR treatments, or between L, F−, and F+ within each tillage system, were analysed as a randomized complete block design, with four replications. Mean values were separated using the Tukey's HSD test with a significance level of 5%, as it is a conservative test that allows comparing each treatment with all the others in pairs when there is the same number of repetitions per treatment. All statistical analyses were performed using Statistix 10 (Analytical Software, FL; USA).

3. Results

3.1. Effect of irrigation strategy on soil CO_2 emissions

Relative to the FI treatment in which irrigation was applied to cover the full water demand, reducing the applied water in the RDI treatment resulted in a water saving of 108 and 101 mm for the 2016 and 2017 maize irrigation seasons, respectively, without affecting the soil CO_2 efflux. We did not find any significant difference($p > 0.05$) in soil CO_2 efflux between FI and RDI treatments in any of the measuring days during the periods in which the RDI treatment was applied (from June 7 to August 18, 2016, and from June 6 to August 10, 2017; Table 1). The interaction between irrigation and tillage treatments was also not statistically significant. Furthermore, soil temperature (Ts) and soil moisture (SWC) in the top horizon did not differ either between FI and RDI treatments ($p > 0.05$) during the RDI periods. Also crop growth was not significantly affected by the irrigation treatment: the average maximum LAI was 4.68 and 4.33 m^2 m^{-2} in FI and RDI, respectively, in 2016, and 4.93 and 4.89 m^2 m^{-2}, respectively, in 2017; ($p > 0.05$). Similarly, no significant effect of the irrigation treatment was found on final above ground-biomass (2621 and 2395 g m^{-2} in FI and RDI treatments, respectively, in 2016, and 2581 and 2616 g m^{-2}, respectively, in 2017; $p > 0.05$). Taking into account that there were no differences in soil CO_2 efflux, topsoil temperature and moisture, and crop growth, between both irrigation treatments (and interactions), the irrigation main treatment (I) was not considered in the analysis of CO_2 emissions between tillage systems during the crop cycle.

3.2. Spatial variability in soil CO_2 efflux by tillage systems: crop line vs. furrow positions

Differences in soil CO_2 efflux due to tillage treatment (CTR vs. ZTR) and spatial variation in collar position (L, crop line vs. F, furrow) were analysed first for each of the 36 measuring dates separately. Except for the dates following tillage, in general, the ANOVA showed no significant differences between tillage treatments but it did between collar positions and for the tillage by collar positions interactions. Regarding the interactions, there was a clear tendency for having the highest soil CO_2 efflux in the L location in CTR (CTR-L) and the lowest in the F location in ZTR (ZTR-F), but these differences were significant in two dates only, one in 2016 and another in 2017 (Fig. 1: different capital letters show significant differences between CTR-L, CTRF, ZTR-L and ZTR-F), in part due to the high variability of the efflux values in CTR. For example, in seven other measurement dates, the efflux was significantly higher in ZTR-L than in ZTR-F, but they did not differ from the efflux in CTR positions. Furthermore, in four other days, the soil CO_2 efflux was significantly higher in ZTR-L than in ZTR-F independently of CTR results (Fig. 1: different lower case shows significant differences between L and F within ZTR and/or within CTR). Regarding the differences between collar positions (L vs. F), these were statistically significant in most dates (28 out of 36; Fig. 1) with emissions clearly higher in L than in F. However, during the maize flowering periods, when soil CO_2 efflux reached maximum values, individual values varied largely and the differences between L and F positions were not significant. Additionally, differences between L and F were also not significant in few sporadic days with low CO_2 efflux values during the fallow periods.

Data of the two seasons were combined, and the average soil CO_2 efflux was calculated for the maize cropping period (i.e., from soil preparation to harvest; $n = 21$ measuring dates) and for the fallow period (i.e., from crop harvest to the eve of soil preparation; $n = 15$ measuring dates) for L and F positions in each tillage treatment (Fig. 2). During the cropping period, the average soil CO_2 efflux was significantly higher from the CTR-L (738 mg C-

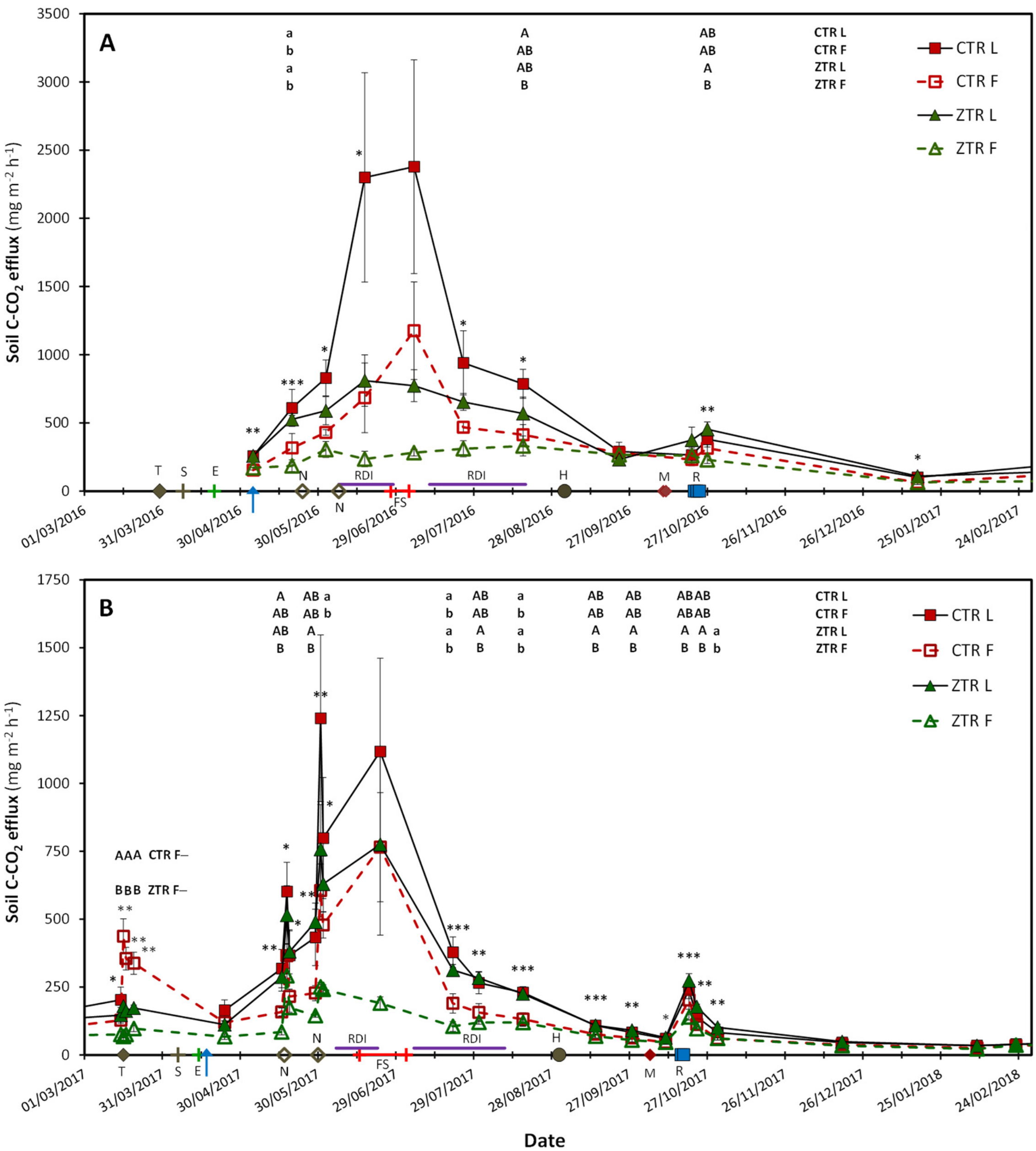

Fig. 1. Soil C-CO_2 efflux from the crop-lines (L) and the furrows (F) for the conventional (CTR) and the conservation (ZTR) tillage systems in the a) 2016/17 and b) 2017/18 seasons. Error bars represent standard error. Different capital letters indicate differences between the treatments of the interaction of tillage system × collars' position factors, while different lowercase letters indicate differences between L and F within each tillage system, according to Tukey's HSD test. *($P < 0.05$), **($P < 0.01$), ***($P < 0.001$) indicate the level of significance of the differences between L and F for the collar position factor. On the dates without ANOVA results, the differences between treatments were not significant. In x-axe: T = tillage, S = sowing, E = crop emergence, N = N-urea application, RDI = RDI period, FS = flowering stage, H = harvest, M = mowing, R = first autumn rainfall. Arrow indicates the first irrigation application in each season.

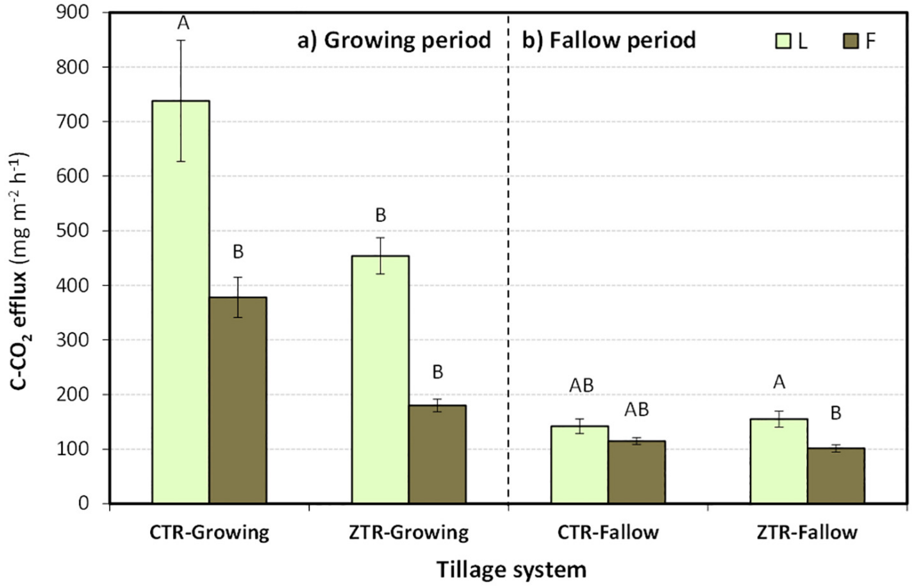

Fig. 2. Average soil C-CO_2 effluxes from the crop-lines (L) and the furrows (F) for CTR and ZTR tillage systems during a) the maize cropping period (n = 21 measuring days, from tillage to harvest) and b) the fallow period (n = 15 measuring days), averaged for 2016/17 and 2017/18 seasons (error bars represent standard error). Different letters within each period indicate significant differences between the treatments of the interaction of tillage system × collars' position factors (Tukey HSD test; $P < 0.05$).

CO_2 m^{-2} h^{-1}) than from the rest of the positions. On the other hand, during the fallow period, only in ZTR the efflux was significantly higher from L than from F position (155 and 101 mg C-CO_2 m^{-2} h^{-1} in ZTR-L and ZTR-F, respectively; Fig. 2). Combining both tillage treatments, the average soil CO_2 efflux was significantly higher in L than in F position for both periods (596 and 279 mg C-CO_2 m^{-2} h^{-1}, and 148 and 108 mg C-CO_2 m^{-2} h^{-1}, in L and F, for cropping and fallow, respectively; $p < 0.001$ and $p < 0.01$, respectively).

Average soil CO_2 effluxes from trafficked (F+) and non-trafficked (F−) furrows were also calculated separately for the cropping and fallow periods, and compared (Table 2). During the cropping period, average efflux from F− furrows in CTR was significantly higher than from F+ for this tillage system and than from F− and F+ for ZTR. During the fallow period, average soil CO_2 efflux from F− and F+ furrows were similar in both tillage systems.

3.3. Temporal variation in soil CO_2 efflux within the season

The evolution of soil CO_2 efflux during the two studied seasons showed four peaks related to crop management or specific environmental conditions, and they were particularly clear during the more thoroughly followed season 2017/2018 (Fig. 1), namely: soil preparation in CTR, application of N fertilizers, crop rapid growth, and first rains in autumn long after the last irrigation.

In the CTR treatment, and as expected, a burst of threefold increase in soil CO_2 efflux was observed immediately after tillage operations compared to the previous day (Fig. 1B). Following this early burst, CO_2 effluxes progressively declined until around crop emergence in mid-late April when they reached similar values to those obtained before tillage. After crop emergence, soil CO_2 effluxes followed a similar trend in both tillage systems increasing with time and with peaks after the broadcast applications of the N-fertilizer (urea). The effect of these urea applications was followed in detail in 2017 (Fig. 1B). Compared to the previous day of the application, soil CO_2 effluxes more than doubled their values, and the impact was higher in CTR than in ZTR after the second application, but the difference between the two tillage systems was not significant. From end-May on, a rapid increase in the soil CO_2 efflux occurred (Fig. 1), coinciding with the period of maximum rate of maize dry-matter accumulation, to reach a plateau at late-June/early-July, and then decrease after the flowering period. In general, soil CO_2 efflux increased to or decreased from the plateau at a faster rate for CTR than for ZTR, and the resulting average soil CO_2 efflux measured from emergence to harvest was higher for CTR than for ZTR (94% and 42% in 2016 and 2017, respectively, for 7 and 11 measurement dates, respectively), although the differences were non-significant ($p > 0.05$).

During the fallow period, the values of the soil CO_2 effluxes and their evolution were similar for both tillage treatments (Fig. 1). After the maize harvest there was a progressive decline that lasted until the first autumn rainfalls, which occurred on late October in both years. This first rainfall resulted in a pulse of CO_2 efflux that was characterized in detail in 2017 (Fig. 1B): compared to the previous day of the rainfall event, there was a fourfold increase passing from 54 to 213 mg C-CO_2 m^{-2} h^{-1} measured two days after the event. For the same dates, the 0.1-m depth SWC increased from extremely dry soil, 5.8%, to approximately soil field capacity, 28.6%. A rapid decay in soil CO_2 effluxes followed afterwards at an exponential-like rate, and reached the lowest emission levels approximately two weeks after the peak. For the rest of the fallow period (late autumn–winter), values remained low (28–42 mg C-CO_2 m^{-2} h^{-1}; Fig. 1B) and no extreme dry/wet cycles were observed again.

The impact of soil moisture (SWC) and temperature (Ts) on the evolution of the soil CO_2 efflux with time was examined during the fallow period after the CO_2 burst due to the first autumn rainfall event. Using data after this event, an exponential correlation was found between soil C-CO_2 efflux and SWC (R^2 = 0.62; $p < 0.01$) and Ts (R^2 = 0.75; $p < 0.001$) for ZTR and CTR treatments (8-dates × 2-tillage treatments), with Ts and SWC ranging between 3.5–17.4 °C and 9.9–30.8%, respectively. However, during the maize cropping period no correlations ($p > 0.05$) were found between the soil

Table 2
Soil C-CO_2 effluxes from the trafficked (F+) and non-trafficked (F−) furrows for CTR and ZTR tillage systems during the maize cropping period (n = 21 measuring days, from tillage to harvest) and the fallow period (n = 15 measuring days), for 2016/17 and 2017/18 seasons (average ± SD). Different letters within each period indicate significant differences (Tukey HSD test; $P < 0.05$).

Tillage system	Furrows traffic	Soil C-CO_2 efflux (mg m^{-2} h^{-1})	
		Cropping period	Fallow period
CTR	F−	500 ± 98 a	126 ± 9 a
	F+	256 ± 62 b	104 ± 20 a
ZTR	F−	196 ± 52 b	101 ± 22 a
	F+	163 ± 22 b	102 ± 17 a

CO_2 efflux and Ts or SWC. Regarding soil moisture, frequent application of irrigation (once or twice a week) allowed maintaining relatively high soil moisture throughout the crop cycle, even in the RDI treatment (e.g., topsoil SWC during the RDI periods ranged from 14.5 to 30.4% for RDI and from 18.1 to 31.8% for FI), without differences in CO_2 efflux between both irrigation treatments. Regarding topsoil temperature, it stayed in a relatively narrow range of moderate temperature (19–25 °C) during the crop cycle.

3.4. Diurnal patterns and seasonal soil CO_2 emissions

Diurnal curves of soil CO_2 emission were carried out on three different dates during this study, in order to characterize the daily emission cycles and determine the measuring time that is representative to the total emission of soil CO_2 in one day. For the three daily emission curves, both CTR and ZTR tillage treatments had similar 24-h mean soil CO_2 efflux and similar maximum and minimum diurnal/hourly values (Table S2), although CTR had the highest daily mean and diurnal maximum value for the three dates. In relation to the 24-h mean soil CO_2 efflux, we found that the relative difference (RD) for the maximum and minimum diurnal/hourly measurements of CO_2 effluxes showed maximum biases from −18.8 to +17.5% in the CTR treatment and of −18.7 to +13.1% in the ZTR treatment. In general, the mean RD values for the three diurnal measuring cycles were close to zero and had similar variability in both tillage systems: −0.3 ± 8.5%, 1.9 ± 11.3% and 0.7 ± 15.2% (median ± SD) in CTR, and 1.9 ± 10.6%, 1.9 ± 7.4% and −1.6 ± 3.9% in ZTR, on June 2, July 31 and October 27 hourly-diurnal curves, respectively. The diurnal variation in CO_2 efflux resulted in general limited, and most measured values at any given hour were not very far to the 24-h mean (Fig. 3).

Diurnal cycles of soil CO_2 efflux had their lowest values before sunrise, increasing through the morning until later afternoon, and then decreasing in the afternoon and into the night (Fig. 3), although the decreasing values were not reached in the autumn curve where the maximum average hourly efflux was measured near sunset. Soil temperature followed a similar diurnal trend to the effluxes for the three dates, reaching its maximum value between 12:30–15:30 h (solar time), depending on day of the year (Fig. 3). Soil temperature curves showed a smaller diurnal amplitude, and lower maximum and higher minimum values on July 31, when the crop covered the soil completely (LAI = 4.5), than on June 2, still with incomplete soil cover (LAI = 1.1). Colder topsoil temperatures were recorded on October 27 under lower levels of incident radiation. The daily curves confirm an interval in mid-morning hours, approximately from 7:20 to 12:30 GMT, in which measuring soil CO_2 efflux can be a good estimate of the 24-h mean at our experimental site. During our two-season study, we have been measuring soil CO_2 efflux within this interval of time.

Table 3
Accumulated soil C-CO_2 emissions for CTR and ZTR tillage systems during the maize cropping period (from tillage to harvest) and the fallow period, for the 2016/17 and 2017/18 seasons (average ± SD).

Tillage system	Accumulated soil C-CO_2 emissions (g m^{-2})		
	Maize cropping period (163 days)	Fallow period (202 days)	Cropping + fallow (365 days)
CTR	2126 ± 654	639 ± 71	2765 ± 721
ZTR	1177 ± 105	617 ± 97	1794 ± 152
P-value	0.0449 (*)	0.7539 (ns)	0.0595 (ns)

ns: not significant.
* $P < 0.05$.

Once the measurements time were confirmed to reasonably mimic the mean hourly CO_2 efflux for the day, in our conditions, accumulated soil CO_2 emissions were calculated for the cropping and fallow periods (Table 3). The accumulated soil CO_2 emissions were significantly higher in the cropping than in the fallow period ($p < 0.01$) for both tillage systems, in spite of the shorter duration of the cropping period (163 vs. 202 days, respectively, averaged for the two seasons). Furthermore, the emissions were significantly higher for CTR than for ZTR ($p < 0.05$) for the cropping period, while there were no differences between the two treatments for the fallow period. The mean daily emissions were 13.1 and 7.2 g C-CO_2 m^{-2} day^{-1}, in CTR and ZTR respectively, during the cropping period, and 3.2 and 3.0 g C-CO_2 m^{-2} day^{-1}, respectively, during the fallow period. Combining both periods (Table 3), the annual accumulated CO_2 emissions were 54% higher for CTR than ZTR (27.6 ± 7.2 and 17.9 ± 1.5 Mg C-CO_2 ha^{-1} respectively), although this difference was not significant ($p = 0.0595$).

4. Discussion

4.1. Impact of regulated deficit irrigation and soil moisture on soil CO_2 efflux

We had anticipated that, in RDI, lower soil moisture during specific periods of the crop cycle would limit soil microbial activity and root

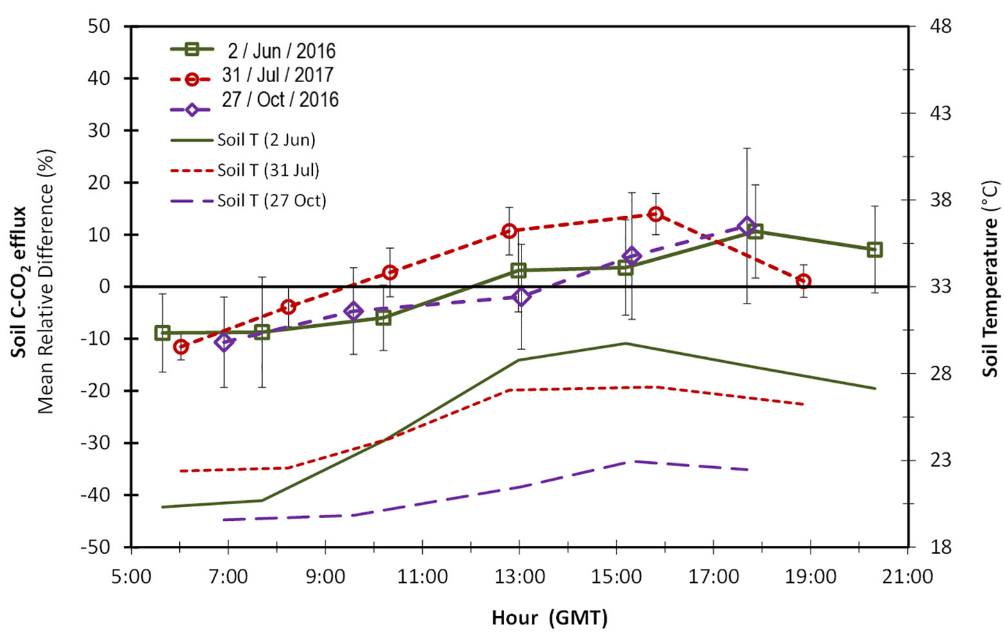

Fig. 3. Relative difference (mean values ± SE; %) of soil C-CO_2 efflux for each measuring time in relation to their corresponding 24-h mean of three diurnal measuring cycles, averaged for the CTR and ZTR tillage systems, and corresponding soil temperature. GMT = local time - 2 h (i.e. solar time - 20 min).

respiration, and the resulting CO_2 fluxes would be reduced (e.g., Davidson et al., 1998; Curiel Yuste et al., 2003; Luo and Zhou, 2006). However, the 100 mm reduction in applied irrigation water in the RDI treatment did not affect soil CO_2 emissions. Although there is extensive research on RDI and its impact on crop yields (Fereres and Soriano, 2007), relatively few studies address its impact on soil CO_2 emissions. The conclusions of these studies are inconsistent but some show that the emissions decrease with RDI, for example, Zornoza et al. (2016, 2018) in drip-irrigated fruit orchards and vineyards, and Hou et al. (2019) in flood irrigated wheat studies. In the first case, they apply frequent irrigations but using a considerably more severe deficit (50% of FI) than in our study (75% of FI). In the second case, flood irrigations took place after prolonged dry periods that stimulated CO_2 efflux. We did not find any study on RDI impact on soil CO_2 emissions in irrigated maize but there are a few on non-regulated deficit irrigation, i.e. sustained deficit irrigation. Hou et al. (2020) found that, compared to full irrigation, deficit irrigation treatment reduced significantly soil CO_2 emissions, however, as for the study on irrigated wheat mentioned before (Hou et al., 2019), they applied spaced flood irrigations that probably stimulated CO_2 efflux by increased microbial activity and crop root respiration. In contrast, Li et al. (2020) found that different applied irrigation depths did not influence significantly the accumulated CO_2 emissions from soil, in drip or flood irrigation systems. In our case, the frequent irrigation and the leaf area covering the ground during the RDI periods, which reduced solar radiation incident on the soil surface, resulted in similar topsoil SWC and temperature in both treatments. Furthermore, the implemented water deficit in RDI periods was not severe enough to cause differences in crop growth and therefore in plant roots respiration, or in the resulting amount of produced crop residues that would be degraded later in the season. Our results agree with Fares et al. (2017), who did not find statistically significant differences in soil CO_2 emissions in drip-irrigated sweet maize between a moderate deficit irrigation (75% of FI; not regulated, i.e., the reduction was applied during the whole season) compared to fully irrigation treatment. In the studied conditions, moderate RDI with frequent irrigations was effective to conserve water but did not reduce CO_2 emissions.

The key role of water in the C dynamics in the plant-soil-atmosphere continuum is described in detail by Brüggemann et al. (2011) or by Kuzyakov (2006). However, in our conditions, during the maize cropping period no correlations ($p > 0.05$) were found between the soil CO_2 efflux and top-soil moisture (or temperature) since CO_2 emissions were significantly influenced by farming operations, like tillage and N application, as well as directly by the crop via roots-rhizosphere respiration. During the steady-state conditions of the fallow period, when heterotrophic respiration prevailed, we have found a relationship between the soil CO_2 efflux and top-soil moisture (or temperature), except when the soil passed from extremely dry to wet conditions with the first autumn rains. Sudden wetness of extremely dry soil, as with the break of rains in Mediterranean conditions, results in a pulse of CO_2 emission, also known as "Birch effect", originated by a rapid response of bacterial activity (Birch, 1958; Jarvis et al., 2007). This response can contribute significantly to the annual CO_2 emission in semiarid ecosystems, particularly in rainfed conditions (Xu et al., 2004; Jarvis et al., 2007; Rey et al., 2017) and also in flood irrigated systems with long periods between water additions (Hou et al., 2020). However, in our irrigation scheduling and with the residues-mulch covering the ground until soil preparation in spring, the "Birch effect" had a minor impact and it was not observed again during the fallow period. Interestingly, the effect was significantly larger in the L than in the F positions (Fig. 1), probably due to higher amount of dead roots and porosity in the L position, as discussed later.

4.2. Short term effects of tillage system on CO_2 efflux

Our study showed higher soil CO_2 fluxes than other studies in maize in Mediterranean conditions (e.g., Guardia et al., 2017; Pareja-Sánchez et al., 2019; Franco-Luesma et al., 2020), but similar to results obtained in the same field in a previous study (Cid et al., 2013) in which measurements were also taken within plant rows (L) and in between rows (F). In our study, the soil CO_2 efflux was larger in L than in F in all measuring days (Fig. 4) and, in most occasions, this difference was significant. When all measurements done during the cropping period (including soil preparation) were averaged, the soil CO_2 emission was approximately the double in L than in F positions in CTR and 2.5 times more in ZTR (Fig. 2). For the fallow period, the averaged soil CO_2 emission was 24% and 53% higher in L than in F in CTR and ZTR, respectively, but significantly higher only in the ZTR treatment (Fig. 2). Our results agree with other studies in which within/between rows spatial variation was considered (e.g., Amos et al., 2005). The larger soil CO_2 emissions in the crop rows were probably the result of having more root density growing below during the cropping period, and more root biomass to decompose during the fallow period. In ZTR, considering that we have followed controlled traffic since the trial establishment in 2007, and therefore, that crop rows have always been located in the same L positions, the soil below will probably have a higher porosity developed by the roots of previous crops, and higher dead root biomass, which could also explain the significant higher CO_2 emissions in L during the fallow period.

During the cropping period, farm operations and crop growth affected largely soil CO_2 efflux. As expected, tillage in CTR resulted in a burst of CO_2 emission (Fig. 1) due to passive degassing following soil disturbance (Reicosky and Lindstrom, 1993; Rochette and Angers, 1999), then followed by a fast decline in efflux in agreement with Cid et al. (2013) in the same experimental trial, and with Forte et al. (2017) in other Mediterranean conditions. Tillage also broke soil macro-aggregates, increasing soil porosity and accessibility to oxygen and previously protected soil organic matter (SOM), and it incorporated plant residues into the soil, thus stimulating microbial activity that decomposes the SOM and the residues. Thus, in general, tillage in CTR would result in higher CO_2 efflux than in no-tilled treatments during several weeks (Dao, 1998; Abdalla et al., 2013) and buried maize residues will decompose faster than surface residues (Parker, 1962; Burgess et al., 2002). In our conditions, only four weeks after tillage the CO_2 efflux in CTR had already decreased to similar levels than in ZTR (Fig. 1B). All residues were on the surface during autumn and winter and, by the time they were incorporated into the soil in spring in CTR, most residues were probably quite degraded and decomposing slowly (Sokol and Bradford, 2019).

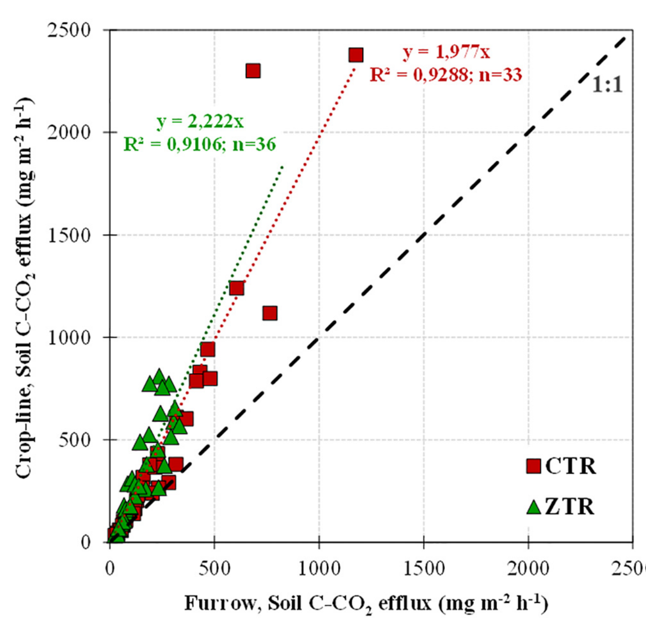

Fig. 4. Soil C-CO_2 efflux from the crop-lines (L) versus the furrows (F) for all measurement days during the 2016/17 and 2017/18 seasons, separately for CTR and ZTR tillage systems. The two slopes were statistically similar; being the regression equation for the data set: y = 2.0256x (R^2 = 0.9222; n = 69).

Crop emergence was approximately four weeks after soil tillage operations and the effect of root-rhizosphere respiration (autotrophic) was added to the decomposition rate of soil organic matter and plant residues (heterotrophic), with an initial tendency of having higher soil CO_2 efflux in CTR than in ZTR. These differences in emissions between tillage systems increased during the fast growth period of the crop in spite of having a similar crop growth rate and final aboveground biomass, in agreement with Franco-Luesma et al. (2020) for sprinkler irrigated maize under similar CTR and ZTR conditions in northern Spain. Additionally, when urea was broadcasted, both tillage systems responded with a quick increase in soil CO_2 efflux, in agreement with Snyder et al. (2009) who described how decomposition of urea in soil also produces bicarbonate and this leads to CO_2 emission. In our conditions, as maize residues have high C:N ratio, their decomposition would have been promoted by the application of the N-fertilizer (Green et al., 1995), as shown before in a similar environment (Maris et al., 2018). The high soil temperature and moisture at the time of N-application in our Mediterranean conditions probably also stimulated heterotrophic respiration (Forte et al., 2017), in addition to contributing to fast crop growth and high autotrophic soil respiration (this was supported by our finding of higher efflux from crop-rows compared to furrows, as discussed earlier). The autotrophic soil respiration is closely coupled to (canopy) carbon assimilation and crop growth; thus, it will depend on its phenological development and on C allocation within plants (Brüggemann et al., 2011). In general, soil CO_2 efflux increases fast with the fast crop growth in maize, during stem elongation, to start leveling after tasseling, and to decrease with grain maturity and the senescence of leaves (Rochette et al., 1999) as also observed in Mediterranean conditions (Forte et al., 2017; Pareja-Sánchez et al., 2019; Franco-Luesma et al., 2020). After maize flowering, roots growth is reduced greatly (Mengel and Barber, 1974; Gregory and Kirkegaard, 2017) and, consequently, their respiration rate (Granato and Raper, 1989; Brüggemann et al., 2011). Nevertheless, soil CO_2 emissions in CTR remained slightly higher than in ZTR until soon after harvest, possibly due to higher soil porosity (and therefore gas conductance) in CTR. From there on, soil CO_2 efflux remained similar in both tillage treatments, while the decline in the soil CO_2 efflux continued, as did soil temperature and moisture, probably limiting the organic matter mineralization.

Although there was a tendency for soil CO_2 efflux to be more responsive to farm operations and crop growth in CTR than in ZTR, practically only after soil tillage the CO_2 efflux was significantly higher in CTR (Fig. 1). Similarly, the diurnal CO_2 emission curves showed a clear tendency towards higher effluxes in CTR than in ZTR (Table S1) but the differences were not significant. This lack of significance was due to the large variation among the values of soil CO_2 efflux measured in CTR collars during the cropping period, in part related to the high spatial variability in the distribution and incorporation of plant residues across field with the tillage, which may have a stronger effect on differential soil microbial activity than the tillage system itself (Spedding et al., 2004), and in part related to the non-homogenous distribution of roots (Han et al., 2007), that, in a more gas-conductive medium like a tilled soil may increase the point-source emission effect. Spatial differences in plant litter distribution and associated microbial activity affect CO_2 emissions across the field (Parkin, 1993; Loecke and Robertson, 2009), as supported by our findings. On average, the coefficient of variation (CV) of daily CO_2 measurements in CTR during the fallow period was similar to that in ZTR, but it increased by 62.6% during the cropping period, while for ZTR this increase was 13.1%. Furthermore, in 2018 we doubled the repetitions in the measurements of soil CO_2 efflux after tillage operations, and the CV of the CTR measurements was, on average, 47.2% lower than in 2017 (average CV of 13.6 vs. 25.7% over a one-week period following the tillage operations). This indicates that to analyse and compare soil CO_2 efflux between different soil management systems more precisely, a higher number of repetitions should be considered if tilled soil with incorporated residues is involved. On the other hand, it is very difficult to find a balance between the number of repetitions and the feasibility of manually measuring them on the same day and under the same conditions.

The daily curves showed a time frame from 7:20 to 12:30 GMT in which measurements of CO_2 efflux will represent the average emission (±10%) of the day (Fig. 3), confirming that our single measures were carried out within an interval in which they were good estimates of the 24-h mean in our conditions, in agreement with Davidson et al. (2002) and Gana et al. (2018). Within a day, CO_2 efflux varied mostly associated to soil temperature, although both were out-phased, with soil temperature reaching the maximum value earlier than the CO_2 efflux, contrary to the results of Parkin and Kaspar (2003). These authors found that CO_2 efflux was more related to air temperature as a significant part was originated from surface residues. However, the differences in CO_2 emission between tillage treatments in our study were not significant, and the delay in maximum CO_2 efflux compared to soil temperature probably reflects the diffusion from deeper soil.

4.3. Long term effects of tillage system on CO_2 efflux

The effects observed in the short term resulted in significantly larger accumulated CO_2 emission in CTR than in ZTR for the cropping period (p = 0.0449). However, when adding the accumulated values during the fallow period to those of the cropping period, the difference in CO_2 emissions between CTR and ZTR for the whole year was not significant (p = 0.0595) in spite of being the emission in CTR 54% higher (Table 3). The high variability in CO_2 emission between repetitions in CTR during the cropping period, together with similar emissions in CTR and ZTR during the longest fallow period, led the not significant difference for the annual accumulated CO_2 emission. For the cropping season (from tillage to harvest), accumulated CO_2 emission in CTR was 1.8 times that of ZTR (an extra 950 C-CO_2 g m^{-2} over a 163 days period in CTR compared to ZTR). The differential effect of tillage on CO_2 emission was slightly larger than that found in other studies in irrigated-maize in Mediterranean conditions: 1.4 times higher emissions in conventionally tilled compared to no-tilled and minimum tilled systems, in sprinkler irrigated systems in northern Spain (Franco-Luesma et al., 2020) and in drip-irrigated systems in southern Italy (Forte et al., 2017), respectively, for the maize growing season. Our results also contrast with those of three other studies in irrigated Mediterranean conditions, where the no- or reduced-tilled system emitted more or the same CO_2 than the conventional system (Pareja-Sánchez et al., 2019, in northern Spain; Oorts et al., 2007, in France; Lee et al., 2009, in California, USA).

In absolute values, CTR accumulated an extra emission of 9.7 Mg C-CO_2 ha^{-1} yr^{-1} compared to ZTR, while in Franco-Luesma et al. (2020) and Forte et al. (2017) the additional emission in the conventional tillage system was on average 1.1 and 1.3 Mg C-CO_2 ha^{-1} yr^{-1} more, respectively. Apart from using a different chamber and equipment, the larger difference in our study (and the larger accumulated CO_2 emissions for both tillage treatments) compared to these studies was probably the result of including measuring points within the maize crop rows. In general, collars are located in between crop rows to facilitate their management and the GHGs measurement. We determined the bias we would have had in our estimates of

Table 4
Relative accumulated soil CO_2 emissions (%) from the L, F− and F+ positions compared to the accumulated emission from each tillage system (CTR and ZTR) for the cropping period (from tillage to harvest), fallow period and the sum of both (averaged for the 2016/17 and 2017/18 seasons). Different letters indicate significant differences within each tillage system and column (Tukey HSD test; $P < 0.05$).

Tillage × crop-line/furrow positions		Relative CO_2 emission to the tillage system emission (%)		
		Cropping period	Fallow period	Cropping + fallow
CTR	L	+31.3 a	+13.0 a	+27.1 a
	F−	−9.7 ab	−1.4 a	−7.8 ab
	F+	−54.4 b	−24.6 a	−47.5 b
ZTR	L	+41.4 a	+21.4 a	+34.5 a
	F−	−35.2 b	−21.8 b	−30.6 b
	F+	−50.0 b	−20.9 b	−40.0 b

seasonal accumulated CO_2 emissions if we had the collars either between rows or within the crop lines (Table 4). Compared to the tillage system emissions, having only collars in the crop lines would have overestimated the system emission by 31% and 41% in CTR and ZTR, respectively, during the cropping period, and 13% and 21%, during the fallow period (27 and 35% for both periods combined). On the other hand, having the collars in the furrows without traffic (F−) would have underestimated the emission by 10% and 35% in CTR and ZTR, respectively, during the cropping period, and by 1% and 22% during the fallow period (8% and 31% for both period combined). The underestimation could be much higher if the collars were to be placed only in the furrows with traffic (F+) and slightly more in CTR. Our results show the importance of the collars location in the field so that the cropping systems is fully represented in the study. This is particularly relevant during the cropping period as the accumulated emission during this period was significantly higher than the accumulated emission during the fallow period in spite of the shorter duration: 4 and 2.5 times in CTR and ZTR, respectively. Larger values during the maize cropping period than during the fallow is a common finding in semiarid irrigated conditions as the most active period of the crop growth coincides with higher temperatures and no moisture limitation (being irrigated). Additionally, we have carried out the CTR tillage for soil preparation in spring before sowing and have included its impact in the cropping period.

5. Conclusions

Under irrigated Mediterranean conditions, our results indicate that RDI in maize using frequent sprinkler irrigations did not reduce soil CO_2 emissions nor did change topsoil abiotic factors for either CTR or ZTR during the RDI periods. In general, during the cropping season, measured soil CO_2 efflux tended to be higher in CTR than in ZTR but the values obtained in the collars of the tilled system were highly variable and differences between treatments seldom significantly (e.g. after tillage in CTR). The variability was probably caused by the random distribution of incorporated residues and of crop roots. This was supported by the consistent differences we have found between the measurements in the crop rows and furrows. During the fallow period, this variability did not exist: CO_2 efflux values for both tillage systems were low and similar as the amount of produced residues covering the soil were similar and the temperatures low during the winter. The daily curves also showed the variability along the day and helped to confirm the representativeness of the punctual measurement as an estimated of 24-day emission.

The daily variations were minimized by calculating the accumulated CO_2 emissions for periods. For the cropping period (from soil preparation to harvest), the accumulated CO_2 emissions was significantly higher in CTR than in ZTR showing the mitigation potential of the last. Interestingly, the emission due to tillage in CTR was a minor contribution for this period compared to crop growth and residues degradation questioning the studies that assume large differences between tillage systems based only in monitored short periods after tillage operations. The accumulated CO_2 emission in CTR during the cropping and fallow periods were 1.8 and 1.5 times that of ZTR, respectively. Our results also show the relevance of the location of measuring sites, particularly during the cropping period, as the crop lines represented the bulk of the release paths compared to the furrows. The obtained CO_2 emissions can be underestimated when estimated from measurements in furrows only, even more if any traffic of machinery had taken place before. The relevant contribution of the crop lines was also evident in ZTR during the fallow period. In our long term experiments with controlled traffic, CO_2 emissions from sites were crop rows were established in ZTR during few years was also significantly higher than from furrows.

Although RDI did not lead to lower soil CO_2 emissions for ZTR compared to CTR, contrary to our hypothesis, both RDI and ZTR can be combined to save water and reduce soil CO_2 emissions of irrigated maize in our conditions. However, the few available studies show the high dependency on the applied deficit and irrigation system, on timing and depth of tillage in CTR, and on management of residues. Further work is needed for deepening on these aspects and arriving to more general conclusions.

CRediT authorship contribution statement

Helena Gómez-Macpherson and **María-Auxiliadora Soriano** conceived the presented idea and received important feedback from all co-authors. **Luca Testi** provided the methodology for field CO_2 efflux measurements. Field management and measurements were carried out mostly by **Carlos Salamanca-Fresno** with support from all co-authors. The manuscript was written by **Helena Gómez-Macpherson** with help from **María-Auxiliadora Soriano** and **Carlos Salamanca-Fresno**. All authors discussed the methods and results and contributed to the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152454.

References

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., Jones, M.B., 2013. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manag. 29 (2), 199–209. https://doi.org/10.1111/sum.12030.

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2016. No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosciences 13, 3619–3633. https://doi.org/10.5194/bg-13-3619-2016.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization, Rome, Italy.

Amos, B., Arkebauer, T.J., Doran, J., 2005. Soil surface fluxes of greenhouse gases in an irrigated maize-based agroecosystem. Soil Sci. Soc. Am. J. 69, 387–395. https://doi.org/10.2136/sssaj2005.0387.

Antille, D.L., Chamen, W.C., Tullberg, J.N., Lal, R., 2015. The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. T. ASABE 58 (3), 707–731. https://doi.org/10.13031/trans.58.11049.

Baker, C.J., Saxton, K.E., 2007. The 'what' and 'why' of no-tillage farming. In: Baker, C.J., Saxton, K.E., Ritchie, W.R., Chamen, W.C.T., Reicosky, D.C., Ribeiro, M.F.S., Justice, S.E., Hobbs, P.R. (Eds.), No-tillage Seeding in Conservation Agriculture, second ed. FAO and CAB International, Wallingford, UK, pp. 1–10 https://doi.org/10.1079/9781845931162.0001.

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53 (1), 29–39. https://doi.org/10.1016/S0167-1987(99)00074-4.

Birch, H.F., 1958. The effect of soil drying on humus decomposition and nitrogen availability. Plant Soil 10 (1), 9–31. https://doi.org/10.1007/BF01343734.

Boulal, H., Gómez-Macpherson, H., Villalobos, F.J., 2012. Permanent bed planting in irrigated Mediterranean conditions: short-term effects on soil quality, crop yield and water use efficiency. Field Crop Res. 130, 120–127. https://doi.org/10.1016/j.fcr.2012.02.026.

Brouder, S.M., Gomez-Macpherson, H., 2014. The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric. Ecosyst. Environ. 187, 11–32. https://doi.org/10.1016/j.agee.2013.08.010.

Brüggemann, N., Gessler, A., Kayler, Z., Keel, S.G., Badeck, F., Barthel, M., Boeckx, P., Buchmann, N., Brugnoli, E., Esperschütz, J., Gavrichkova, O., Ghashghaie, J., Gomez-Casanovas, N., Keitel, C., Knohl, A., Kuptz, D., Palacio, S., Salmon, Y., Uchida, Y., Bahn, M., 2011. Carbon allocation and carbon isotope fluxes in the plant–soil–atmosphere continuum: a review. Biogeosciences 8 (11), 3457–3489. https://doi.org/10.5194/bg-8-3457-2011.

Burgess, M.S., Mehuys, G.R., Madramootoo, C.A., 2002. Decomposition of grain-corn residues (Zea mays L.): a litterbag study under three tillage systems. Can. J. Soil Sci. 82 (2), 127–138. https://doi.org/10.4141/S01-013.

Cid, P., Pérez-Priego, O., Orgaz, F., Gómez-Macpherson, H., 2013. Short-and mid-term tillage-induced soil CO_2 efflux on irrigated permanent-and conventional-bed planting systems with controlled traffic in southern Spain. Soil Res. 51 (5), 447–458. https://doi.org/10.1071/SR13082.

Cid, P., Carmona, I., Murillo, J.M., Gómez-Macpherson, H., 2014. No-tillage permanent bed planting and controlled traffic in a maize-cotton irrigated system under Mediterranean conditions: effects on soil compaction, crop performance and carbon sequestration. Eur. J. Agron. 61, 24–34. https://doi.org/10.1016/j.eja.2014.08.002.

Curiel Yuste, J., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol. 23 (18), 1263–1270. https://doi.org/10.1093/treephys/23.18.1263.

Dao, T.H., 1998. Tillage and crop residue effects on carbon dioxide evolution and carbon storage in a paleustoll. Soil Sci. Soc. Am. J. 62 (1), 250–256. https://doi.org/10.2136/sssaj1998.03615995006200010032x.

Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperature mixed hardwood forest. Glob. Chang. Biol. 4, 217–227. https://doi.org/10.1046/j.1365-2486.1998.00128.x.

Davidson, E.A., Savage, K., Verchot, L.V., Navarro, R., 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric. For. Meteorol. 113, 21–37. https://doi.org/10.1016/S0168-1923(02)00100-4.

Domínguez, A., de Juan, J.A., Tarjuelo, J.M., Martínez, R.S., Martínez-Romero, A., 2012. Determination of optimal regulated deficit irrigation strategies for maize in a semi-arid environment. Agric. Water Manage. 110, 67–77. https://doi.org/10.1016/j.agwat.2012.04.002.

Fares, A., Bensley, A., Bayabil, H., Awal, R., Fares, S., Valenzuela, H., Abbas, F., 2017. Carbon dioxide emission in relation with irrigation and organic amendments from a sweet corn field. J. Environ. Sci. Health B 52 (6), 387–394. https://doi.org/10.1080/03601234.2017.1292094.

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58 (2), 147–159. https://doi.org/10.1093/jxb/erl165.

Forte, A., Fiorentino, N., Fagnano, M., Fierro, A., 2017. Mitigation impact of minimum tillage on CO_2 and N_2O emissions from a Mediterranean maize cropped soil under low-water input management. Soil Tillage Res. 166, 167–178. https://doi.org/10.1016/j.still.2016.09.014.

Franco-Luesma, S., Cavero, J., Plaza-Bonilla, D., Cantero-Martínez, C., Arrúe, J.L., Álvaro-Fuentes, J., 2020. Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions. Soil Tillage Res. 196, 104488. https://doi.org/10.1016/j.still.2019.104488.

Gana, C., Nouvellon, Y., Marron, N., Stape, J.L., Epron, D., 2018. Sampling and interpolation strategies derived from the analysis of continuous soil CO_2 flux. J. Plant Nutr. Soil Sci. 181 (1), 12–20. https://doi.org/10.1002/jpln.201600133.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit. Rev. Plant Sci. 28 (3), 97–122. https://doi.org/10.1080/07352680902776358.

Granato, T.C., Raper Jr., C.D., 1989. Proliferation of maize (Zea mays L.) roots in response to localized supply of nitrate. J. Exp. Bot. 40 (2), 263–275. https://doi.org/10.1093/jxb/40.2.263.

Green, C.J., Blackmer, A.M., Horton, R., 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. Soil Sci. Soc. Am. J. 59 (2), 453–459. https://doi.org/10.2136/sssaj1995.03615995005900020026x.

Gregory, P.J., Kirkegaard, J.A., 2017. Growth and function of root systems. In: Thomas, B., Murphy, D.J., Murray, B.G. (Eds.), Encyclopedia of Applied Plant Sciences, Second ed. Oxford Academic Press, Kidlington, UK, pp. 230–237 https://doi.org/10.1016/B978-0-12-394807-6.00127-1.

Guardia, G., Cangani, M.T., Andreu, G., Sanz-Cobena, A., García-Marco, S., Álvarez, J.M., Recio-Huetos, J., Vallejo, A., 2017. Effect of inhibitors and fertigation strategies on GHG emissions, NO fluxes and yield in irrigated maize. Field Crop Res. 204, 135–145. https://doi.org/10.1016/j.fcr.2017.01.009.

Han, G., Zhou, G., Xu, Z., Yang, Y., Liu, J., Shi, K., 2007. Biotic and abiotic factors controlling the spatial and temporal variation of soil respiration in an agricultural ecosystem. Soil Biol. Biochem. 39 (2), 418–425. https://doi.org/10.1016/j.soilbio.2006.08.009.

Hou, H., Yang, Y., Han, Z., Cai, H., Li, Z., 2019. Deficit irrigation effectively reduces soil carbon dioxide emissions from wheat fields in Northwest China. J. Sci. Food Agr. 99 (12), 5401–5408. https://doi.org/10.1002/jsfa.9800.

Hou, H., Han, Z., Yang, Y., Abudu, S., Cai, H., Li, Z., 2020. Soil CO_2 emissions from summer maize fields under deficit irrigation. Environ. Sci. Pollut. Res. 27 (4), 4442–4449. https://doi.org/10.1007/s11356-019-07127-1.

Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J.H., Yang, X., Tao, B., Goff, B., 2018. Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis. Agric. Ecosyst. Environ. 268, 144–153. https://doi.org/10.1016/j.agee.2018.09.002.

IPCC, 2018. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty In press.

IPCC, 2019. Summary for policymakers. In: Shukla, P.R., Skea, J., Buendia, E. Calvo, Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J. Portugal, Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems In press.

IUSS Working Group WRB, 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jarvis, P., Rey, A., Petsikos, Ch., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the "Birch effect". Tree Physiol. 27 (7), 929–940. https://doi.org/10.1093/treephys/27.7.929.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen -Geiger climate classification updated. Meteorol. Z. 15 (3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Kuzyakov, Y., 2006. Sources of CO2 efflux from soil and review of partitioning methods. Soil Biol. Biochem. 38 (3), 425–448. https://doi.org/10.1016/j.soilbio.2005.08.020.

Lampurlanés, J., Cantero-Martínez, C., 2006. Hydraulic conductivity, residue cover, and soil surface roughness under tillage systems in semi-arid conditions. Soil Tillage Res. 85 (1-2), 13–26. https://doi.org/10.1016/j.still.2004.11.006.

Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., Cantero-Martínez, C., 2016. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crop Res. 189, 59–67. https://doi.org/10.1016/j.fcr.2016.02.010.

Lee, J., Hopmans, J.W., Van Kessel, C., King, A.P., Evatt, K.J., Louie, D., Rolston, D., Six, J., 2009. Tillage and seasonal emissions of CO_2, N_2O and NO across a seed bed and at the field scale in a Mediterranean climate. Agric. Ecosyst. Environ. 129 (4), 378–390. https://doi.org/10.1016/j.agee.2008.10.012.

Li, C., Xiong, Y., Huang, Q., Xu, X., Huang, G., 2020. Impact of irrigation and fertilization regimes on greenhouse gas emissions from soil of mulching cultivated maize (Zea mays L.) field in the upper reaches of Yellow RiverChina. J. Clean. Prod. 259, 120873. https://doi.org/10.1016/j.jclepro.2020.120873.

Loecke, T.D., Robertson, G.P., 2009. Soil resource heterogeneity in the form of aggregated litter alters maize productivity. Plant Soil 325, 231–241. https://doi.org/10.1007/s11104-009-9973-5.

Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment. Elsevier/Academic Press, Amsterdam 321 p.

Lynch, J., Cain, M., Frame, D., Pierrehumbert, R., 2021. Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO_2-emitting sectors. Front. Sustain. Food Syst. 4, 518039. https://doi.org/10.3389/fsufs.2020.518039.

Maris, S.C., Lloveras, J., Vallejo, A., Teira-Esmatges, M.R., 2018. Effect of Stover management and nitrogen fertilization on N_2O and CO_2 emissions from irrigated maize in a high nitrate Mediterranean soil. Water Air Soil Pollut. 229, 11. https://doi.org/10.1007/s11270-017-3660-6.

Mehra, P., Baker, J., Sojka, R.E., Bolan, N., Desbiolles, J., Kirkham, M.B., Ross, C., Gupta, R., 2018. A review of tillage practices and their potential to impact the soil carbon dynamics. Adv. Agron. 150, 185–230. https://doi.org/10.1016/bs.agron.2018.03.002.

Mengel, D.B., Barber, S.A., 1974. Development and distribution of the corn root system under field conditions. Agron. J. 66 (3), 341–344. https://doi.org/10.2134/agronj1974.00021962006600030002x.

Natural Resources Conservation Service Soil Survey Staff, 2010. Keys to Soil Taxonomy. 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Oorts, K., Laurant, F., Mary, B., Thiebeau, P., Labreuche, J., Nicolardot, B., 2007. Experimental and simulated soil mineral N dynamics for long-term tillage systems in northern France. Soil Tillage Res. 94 (2), 441–456. https://doi.org/10.1016/j.still.2006.09.004.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. 187, 87–105. https://doi.org/10.1016/j.agee.2013.10.010.

Pareja-Sánchez, E., Cantero-Martínez, C., Álvaro-Fuentes, J., Plaza-Bonilla, D., 2019. Tillage and nitrogen fertilization in irrigated maize: key practices to reduce soil CO_2 and CH_4 emissions. Soil Tillage Res. 191, 29–36. https://doi.org/10.1016/j.still.2019.03.007.

Parker, D.T., 1962. Decomposition in the field of buried and surface-applied cornstalk residue. Soil Sci. Soc. Am. J. 26 (6), 559–562. https://doi.org/10.2136/sssaj1962.03615995002600060014x.

Parkin, T.B., 1993. Spatial variability of microbial processes in soil—a review. J. Environ. Qual. 22 (3), 409–417. https://doi.org/10.2134/jeq1993.00472425002200030004x.

Parkin, T.B., Kaspar, T.C., 2003. Temperature controls on diurnal carbon dioxide flux: implications for estimating soil carbon loss. Soil Sci. Soc. Am. J. 67 (6), 1763–1772. https://doi.org/10.2136/sssaj2003.1763.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57. https://doi.org/10.1038/nature17174.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crop. Res. 183, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020.

Plaza-Bonilla, D., Cantero-Martínez, C., Viñas, P., Álvaro-Fuentes, J., 2013. Soil aggregation and organic carbon protection in a no-tillage chronosequence under Mediterranean conditions. Geoderma 193–194, 76–82. https://doi.org/10.1016/j.geoderma.2012.10.022.

Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J.L., Álvaro-Fuentes, J., 2014. Soil carbon dioxide and methane fluxes as affected by tillage and N fertilization in dryland conditions. Plant Soil 381, 111–130. https://doi.org/10.1007/s11104-014-2115-8.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4 (8), 678–683. https://doi.org/10.1038/nclimate2292.

Reicosky, D.C., Archer, D.W., 2007. Moldboard plow tillage depth and short-term carbon dioxide release. Soil Tillage Res. 94 (1), 109–121. https://doi.org/10.1016/j.still.2006.07.004.

Reicosky, D.C., Lindstrom, M.J., 1993. Fall tillage method: effect on short-term carbon dioxide flux from soil. Agron. J. 85, 1237–1243. https://doi.org/10.2134/agronj1993.00021962008500060027x.

Rey, A., Oyonarte, C., Morán-López, T., Raimundo, J., Pegoraro, E., 2017. Changes in soil moisture predict soil carbon losses upon rewetting in a perennial semiarid steppe in SE Spain. Geoderma 287, 135–146. https://doi.org/10.1016/j.geoderma.2016.06.025.

Richards, M., Bruun, T.B., Campbell, B., Gregersen, L.E., Huyer, S., Kuntze, V., Madsen, S.T.N., Oldvig, M.B., Vasileiou, I., 2016. How Countries Plan to Address Agricultural Adaptation and Mitigation: An Analysis of Intended Nationally Determined Contributions. CCAFS Dataset Version 1.2. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. https://hdl.handle.net/10568/73255.

Rochette, P., Angers, D.A., 1999. Soil surface carbon dioxide fluxes induced by spring, summer, and fall moldboard plowing in a sandy loam. Soil Sci. Soc. Am. J. 63 (3), 621–628. https://doi.org/10.2136/sssaj1999.03615995006300030027x.

Rochette, P., Hutchinson, G.L., 2005. Measurement of soil respiration in situ: chamber techniques. In: Hatfield, J.L., Baker, J.M. (Eds.), Micrometeorology in Agricultural Systems, Agronomy Monograph no. 47. ASA, CSSA, SSSA, Madison, WI, pp. 247–286 https://doi.org/10.2134/agronmonogr47.c12.

Rochette, P., Flanagan, L.B., Gregorich, E.G., 1999. Separating soil respiration into plant and soil components using analyses of the natural abundance of carbon-13. Soil Sci. Soc. Am. J. 63 (5), 1207–1213. https://doi.org/10.2136/sssaj1999.6351207x.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., Del Prado, A., Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., Álvaro-Fuentes, J., Gilsanz, C., Báez, D., Doltra, J., González-Ubierna, S., Cayuela, M.L., Menéndez, S., Díaz-Pinés, E., Le-Noë, J., Quemada, M., Estellés, F., Calvet, S., van Grinsven, H.J.M., Westhoek, H., Sanz, M.J., Gimeno, B.S., Vallejo, A., Smith, P., 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: a review. Agric. Ecosyst. Environ. 238, 5–24. https://doi.org/10.1016/j.agee.2016.09.038.

Sapkota, A., Haghverdi, A., Avila, C.C., Ying, S.C., 2020. Irrigation and greenhouse gas emissions: a review of field-based studies. Soil Syst. 4 (2), 20. https://doi.org/10.3390/soilsystems4020020.

Snyder, C., Bruulsema, T., Jensen, T., Fixen, P., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133 (3–4), 247–266. https://doi.org/10.1016/j.agee.2009.04.021.

Sokol, N.W., Bradford, M.A., 2019. Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nat. Geosci. 12, 46–53. https://doi.org/10.1038/s41561-018-0258-6.

Spedding, T.A., Hamel, C., Mehuys, G.R., Madramootoo, C.A., 2004. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. Soil Biol. Biochem. 36 (3), 499–512. https://doi.org/10.1016/j.soilbio.2003.10.026.

Van Donk, S.J., Martin, D.L., Irmak, S., Melvin, S.R., Petersen, J.L., Davison, D.R., 2010. Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-Central Nebraska. T. ASABE 53 (6), 1787–1797. https://doi.org/10.13031/2013.35805.

Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N2O emissions in reduced tillage systems: a meta-analysis. Glob. Chang. Biol. 19 (1), 33–44. https://doi.org/10.1111/j.1365-2486.2012.02779.x.

Xu, L., Baldocchi, D.D., Tang, J., 2004. How soil moisture, rain pulses, and growth alter the response of ecosystem respiration to temperature. Glob. Biogeochem. Cycles 18, GB4002. https://doi.org/10.1029/2004GB002281.

Zornoza, R., Rosales, R.M., Acosta, J.A., De la Rosa, J.M., Arcenegui, V., Faz, A., Perez-Pastor, A., 2016. Efficient irrigation management can contribute to reduce soil CO_2 emissions in agriculture. Geoderma 263, 70–77. https://doi.org/10.1016/j.geoderma.2015.09.003.

Zornoza, R., Acosta, J.A., Gabarrón, M., Gómez-Garrido, M., Sánchez-Navarro, V., Terrero, A., Martínez-Martínez, S., Faz, A., Pérez-Pastor, A., 2018. Greenhouse gas emissions and soil organic matter dynamics in woody crop orchards with different irrigation regimes. Sci. Total Environ. 644, 1429–1438. https://doi.org/10.1016/j.scitotenv.2018.06.398.