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Soil organic carbon sequestration when converting a rainfed Mediterranean barley-based cropping system to irrigated corn under different tillage systems and N fertilizer rates

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Core Ideas

- C-inputs are an important factor explaining soil organic carbon (SOC) sequestration rates.
- Reduced and no-tillage increased C-inputs at the highest N-fertilizer rate.
- No-tillage significantly increased SOC sequestration at the highest N-fertilizer rate.
- Conversion from a rainfed to an irrigated cropping system resulted in an increase SOC sequestration rate from 222 to 969 kg C ha^{-1} $year^{-1}$.
- Particulate organic carbon was the indicator that best explained SOC increase after the conversion from a rainfed to an irrigated cropping system.

Abstract

The aim of this study was to evaluate the impact of 21 years of tillage and N fertilization and the conversion from a rainfed to an irrigated cropping system on soil organic C (SOC). The study was carried out in NE Spain in a long-term tillage and N rate field experiment established in 1996 under barley rainfed conditions which in 2015 was converted into irrigation with corn. Three types of tillage (conventional tillage, CT; reduced tillage, RT; no-tillage, NT) and three mineral N fertilization rates (0, 60 and 120 kg N ha^{-1} under barley, and 0, 200, and 400 kg N ha^{-1} under corn) were compared. Annual C-inputs as above-ground crop residues and annual SOC sequestration rate (ΔSOC_{rate}) (0-40 cm depth) were calculated in three different periods (P1, P2 and P3) under rainfed (-R) and irrigated (-I) conditions (P1-R, from 1996 to 2009; P2-R, from 2009 to 2015; P3-I, from 2015 to 2017). At the end of P3-I, particulate organic C (POC) was measured from the 0-5, 5-10, 10-20, 20-30 and 30-40 cm depths. Averaged over all treatments, ΔSOC_{rate} was 492, 222 and 969 kg C ha^{-1} $year^{-1}$ for P1-R, P2-R and P3-I, respectively. In P1-R and P3-I, C-input explained 70% of the variability of ΔSOC_{rate}. In P1-R, ΔSOC_{rate} followed the order NT > RT > CT, while for N rate, order was high > medium > 0. In P3-I at the highest N rate, ΔSOC_{rate} followed the order NT>RT>CT. In P2-R, ΔSOC_{rate} did not show differences between tillage and/or N rate treatments. The increase in SOC after conversion from a rainfed to an irrigation system was mainly explained by POC, which was increased by 75% compared to the previous rainfed period. The modification of the cropping system through the introduction of irrigation and adequate crop management practices under no-tillage and adjusted N fertilizer rates can contribute to the sequestration of large amounts of atmospheric CO_2.

Abbreviations

ΔSOC_{rate}, annual soil organic carbon sequestration rate; CT, conventional tillage; NT, no tillage; P1-R, P2-R, P3-I, periods under rainfed (-R) and irrigated (-I) conditions; RT, reduced tillage.

1 Introduction

In arid and semiarid regions, as is the case in Mediterranean areas, crop productivity is severely limited by water availability (Apesteguía *et al.*, 2015; Cantero-Martínez, Angás, & Lampurlanés, 2007). The main production system in the rainfed Mediterranean areas has been the monoculture cropping of winter cereals (primarily barley and wheat), whose yield is highly dependent on seasonal rainfall and water storage capacity of the soil (Austin *et al.*, 1998). During the last three decades, in many areas these rainfed cropping systems are characterized by the use of conservation agriculture, which involves reduced and no-tillage (RT and NT, respectively), as well as a lower application of fertilizer N than in irrigated cropping systems. Conversely, corn is one of the most important field crops in irrigated cropping systems, characterized by the use of high rates of N fertilization and intensive tillage (CT) systems. Currently, in the Mediterranean region, there is an increasing conversion from rainfed to irrigated cropping systems. This conversion generates significant consequences in agroecosystems, since the possibility of irrigation leads farmers to modify crop rotations and management practices, opting for more productive crops and changing the management of the cropping system (type of tillage, fertilization rates, control of biotic stresses, etc.). The conversion from rainfed to irrigated cropping systems could directly affect soil organic carbon sequestration (SOC). Different mechanisms could affect SOC via the modification of the cropping system, as for example, changing water availability in agricultural soils would lead to greater microbial activity enhancing C decomposition (Gillabel *et al.*, 2007). Soil organic carbon could also be influenced by the amount of crop residues returned to the soil, being more abundant in irrigated than in rainfed cropping systems. The greater contribution of crop residues would increase the SOC, since it is known that both variables are directly related (Dimassi *et al.*, 2014). In addition, changing the type of crop could also modify the quality of crop residues and their composition (e.g. ratios C:N, lignin:N). It is widely accepted that the C:N ratio influences the decomposition rate of organic materials. Thus, a material with lower C:N ratio (such as legumes residues) being known as a more labile material, is easily decomposed by the microorganisms than higher C:N ratio organic material (such as cereal residues) (Manzoni, Jackson, Trofymow, & Porporato, 2008). After the transformation of a cropping system, changes in N fertilizarion rates may also affect SOC dynamics. In this regard, Mulvaney, Khan, & Ellsworth, (2009) showed that high fertilizer N rates accelerates SOC mineralization. However, Russell, Laird, Parkin, & Mallarino (2005) found no difference in SOC with N fertilization rate. In addition, N fertilization may also increase SOC stocks, since an increase in crop productivity can lead to greater C-inputs returned to the soil (Luo, Wang, & Sun, 2010). However, N fertilizer addition can also increase C losses to the environment by reducing the soil C:N ratio, enhancing microbial activity and C mineralization (Li *et al.*, 2009; Patrick *et al.*, 2013; Mahal *et al.*, 2019). Likewise, the type and intensity of the tillage operation used by farmers varies in irrigated cropping systems compared to rainfed ones, influencing the stability of soil aggregates and the release of organic matter (Grandy & Robertson, 2006).

Changes in SOC levels are not immediately detectable after a change in agricultural management has occurred. For this reason, long-term experiments are essential to study the impact of agricultural management on SOC changes. Indeed, the identification and quantification of key C fractions sensitive to changes in management practices and land uses may help to elucidate the mechanisms of C sequestration in agroecosystems (Plaza-Bonilla, Álvaro-Fuentes, & Cantero-Martínez, 2014). For example, Álvaro-Fuentes, Cantero-Martinez, & Arrue (2008) found that under semiarid conditions, particulate organic matter (POM) and mineral-associated C (C-Min) increased under NT compared to CT. They argued that the increase in soil surface (0–5cm) SOC under NT compared with

CT was due to the more humified and recalcitrant nature of the C-Min fraction. Greater SOC accumulation as C-Min implies its stabilization in the long term in NT compared with CT. Therefore, an optimal use of different agronomic practices (e.g. soil tillage, N fertilization, etc.) may boost C sequestration in the soil (West & Post, 2002). In semiarid Mediterranean rainfed conditions, several studies have shown significant increases of SOC stocks after the adoption of conservation tillage. For example, Álvaro-Fuentes *et al.* (2009) and Hernanz, Sánchez-Girón, & Navarrete (2009) demonstrated that continuous NT leads to SOC sequestration with rates ranging from 0.40 to 0.50 t C ha^{-1} yr^{-1}.

Irrigated systems in combination with conservation agriculture practices like NT or RT are assumed to have a larger potential to increase SOC contents than irrigation in combination with CT (Martens, Emmerich, Mclain, & Johnsen, 2005). For instance, Halvorson, Reule, & Mosier (2004) observed an increase in SOC under NT in irrigated continuous corn systems compared to CT although both tillage treatments (NT and CT) produced similar levels of crop residues. Greater SOC decomposition under CT would explain that result.

Currently, long-term NT and other conservation practices such as the maintenance of permanent soil cover, crop rotation or the diversification of plant species, are recommended to maintain or increase SOC stocks in rainfed areas (Plaza-Bonilla *et al.,* 2015) but less is known in irrigated cropping systems, particularly in Mediterranean areas. In addition, there is little information about the change that could occur in carbon sequestration rates when converting from rainfed cropping systems to irrigated. Halvorson, Reule, & Mosier (2004) reported that the annual rate of SOC sequestration increased (1.4 Mg SOC ha^{-1} yr^{-1}, 0-15 cm depth) with increasing N rate under NT in irrigated continuous corn in comparison to CT which had a rate of 0.2 Mg C ha^{-1} yr^{-1} in Colorado (USA). Therefore, there is a need to identify the most beneficial combined management practices to enhance SOC sequestration when converting rainfed cropping systems into irrigated ones.

This study was conducted using a long-term tillage and N fertilization experiment established in 1996 in rainfed conditions which was converted in 2015 into irrigation. In a first rainfed period, Morell *et al.* (2011) already observed a positive effect of NT in SOC. This study is a step forward in which we evaluated (i) 21 years impact of tillage and N fertilization and (ii) the conversion of rainfed into irrigated systems on SOC.

2 Materials and methods

2.1. Site and treatments description.

An ongoing long-term experiment on soil tillage and N fertilization rates was established in 1996 under rainfed conditions at Agramunt, Catalonia, NE Spain (41°48′ N, 1°07′ E, 330 m asl). The extended description of the field experiment including soil and climate conditions is described in Cantero-Martínez, Angás & Lampurlanés (2003). The Mediterranean field site is located in a semi-arid continental climate. Mean annual precipitation, potential evapotranspiration, and temperature are 401 mm, 855 mm, and 14.1°C, respectively (data from 1985 to 2015).

The experiment compared three tillage systems (conventional tillage, CT; reduced tillage, RT; no-tillage, NT) and three increasing rates of mineral N (0, 60 and 120 kg N ha^{-1}) under barley (*Hordeum vulgare* L.) monoculture. In 2015, the rainfed experiment was converted to sprinkler irrigation and monoculture corn (*Zea mays* L.) monoculture as cropping system. After the shift from rainfed to irrigation, the field experiment maintained the same tillage intensities (CT, RT, and NT) while N fertilization rates were adapted to corn needs (0, 200, and 400 kg N ha^{-1}) (Table 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 had a silty clay loam texture (sand, 30.8%; silt, 57.3%; clay, 11.9%) in the upper (0-28 cm) horizon. Other 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}; soil organic carbon concentration 9 g kg^{-1}; Olsen P: 35 mg kg^{-1}; K (ammonium acetate): 194 mg kg^{-1}; water retention (-33 kPa): 16 kg kg^{-1}; water retention (-1500 kPa): 5 kg kg^{-1}. Crop management practices were conducted following the local traditional practices (Table 1). After 2015, irrigation was supplied to meet the estimated evapotranspiration (ET) of corn minus the effective precipitation, which was estimated as 75% of precipitation (when precipitation > 5 mm) (Dastane, 1978). Corn evapotranspiration (ETc) was calculated with the corresponding weekly reference ET values multiplied by the crop coefficient. Crop coefficients were estimated in accordance with crop development (ranging between 0.3 and 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.

2.2 Soil sampling and analysis.

During the rainfed period (1996 to 2015), soil samples were collected in September 1996, after crop harvest in July 2009, and before the conversion from rainfed to irrigated conditions and corn planting in March 2015. The last sampling was carried out in November 2017 after corn harvest. All samples were analyzed in the corresponding year of extraction. However, the samples from 2009, 2015 and 2017 were analyzed by the same technician, while those from 1996 were analyzed by a different technician. The same methodology and the same laboratory were used in all samples. There was an exception to the same methodology as the 1996 samples were treated differently. Nevertheless, in 1996 the Walkley and Black (Nelson & Sommers, 1982) method was followed without external heating and later a coefficient of 1.33 was applied according to a previous calibration. Soil samples were always collected at 0–5, 5–10, 10–20, 20–30, and 30–40 cm soil depths in two samples per plot for the dates described. In each plot and depth, soil bulk density was measured in 2009 (Morell *et al.*, 2011). For C analyses, the soil was air dried and ground to pass a 2-mm sieve. The total SOC content was measured by the wet oxidation method of Walkley and Black with a 1 g subsample (Nelson & Sommers, 1982). SOC contents were calculated on a mass per unit area basis by multiplying the C concentration values obtained from the oxidation method by the corresponding soil bulk density values.

Moreover, the SOC stock (kg C ha^{-1}) was corrected in terms of equivalent soil mass following the procedure of Ellert & Bettany (1995) for the 0 to 40 cm soil depth interval. The annual SOC sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} year^{-1}) (0-40 cm soil depth) was calculated for each treatment in three different periods: from 1996 to 2009 (P1-R), from 2009 to 2015 (P2-R), and from 2015 to 2017 (P3-I). The period 1996-2009 (P1-R) was previously reported by Morell *et al.* (2011). Our intention was to compare these data corresponding to rainfed conditions with the new data obtained under irrigated conditions. Furthermore, at the beginning and at the end of the period under irrigation (2015 and 2017), permanganate-oxidizable organic C (POxC), particulate organic carbon (POC) and mineral-associated organic carbon (C-Min) were also measured (0–5, 5–10, 10–20, 20–30, and 30–40 cm depths). These C fractions were chosen since they were identified as highly sensitive to changes in management practices in our semiarid areas (Plaza-Bonilla, Álvaro-Fuentes, & Cantero-Martínez, 2014). C-Min and POC were isolated using a physical fractionation method adapted from Cambardella & Elliot (1992). Briefly, twenty-gram subsamples of soil from each depth and plot were dispersed in 100 mL of 5 g L^{-1} sodium hexametaphosphate for 15 h on a reciprocal shaker. Then, the samples were passed through a 50-μm sieve to separate the POC and C-Min. The material passing through the sieve (C-Min) was collected in aluminium pans and oven dried at 50°C. The Walkley and Black wet oxidation method was then used to measure the C concentration in the C-Min fraction. The POC content was determined as the difference between total SOC content and C-Min content. POxC was quantified according to the method of Weil *et al.* (2003). Briefly, 2.5 g of air-dried soil were weighed into polypropylene 50 mL centrifuge tubes. To each tube, 18 mL of deionized water and 2 mL^{-1} of 0.2 M $KMnO_4$ stock solution were added and tubes were shaken for exactly 2 min on an oscillating shaker. Tubes were removed from the shaker and allowed to settle for exactly 10 min. After 10 min, 0.5 mL of the supernatant were transferred into a second 50 mL centrifuge tube and mixed with 49.5 mL of deionized water. An aliquot (200 µL) of each sample was loaded into a well plate containing a set of internal standards, including a blank of deionized water, four standard stock solutions (0.005, 0.01, 0.015, and 0.02 M L^{-1} $KMnO_4$), a soil standard and a solution standard (laboratory reference samples). All internal standards were analytically replicated on each plate. Sample absorbance was read with a spectrophotometer at 550 nm. POxC was calculated as Weil *et al*. (2003):

$$\text{POxC (mg kg}^{-1}\text{soil)} = (0.02 \text{ mol L}^{-1} – (a + b \times (\text{Abs})) \times (9000 \text{ mg C mol}^{-1}) (0.02 \text{ L solution} \times W^{-1})$$

where a is the intercept and b is the slope of the calibration obtained with the standards, Abs is the absorbance of the sample and W is the weight (kg) of the soil used.

2.3 Carbon inputs.

In the rainfed period, barley above-ground biomass was determined just before harvest (end of June – beginning of July). Three samples per plot were taken by cutting the plants at the soil surface level on 50 cm along the rows. In the irrigated period, corn above-ground biomass was determined in late-October right before harvest. Samples were taken by collecting plants of two central rows 2-5 m long, depending on plant density, in three sampling areas per plot. In 2015, a 5 m sampling length was taken in all treatments due to the low plant density in CT. In 2016 and 2017, the length of the sampling row was 2 m. Barley and corn above-ground biomass was oven-dried at 60°C for 48 h, threshed and weighed excluding the grain, hereafter referred as crop residues. The C content of barley and corn crop residues was determined by dry combustion (model Truspec CN, LECO, St Joseph, MI, USA). Afterwards, C inputs were calculated by multiplying the crop residues biomass by their C concentration.

2.4 Statistical analysis.

Statistical analyses were performed with the statistical package JMP 13 (SAS Institute Inc, 2018). Data were checked for normality with the Shapiro-Wilk Test. All data complied with normality. Measured ΔSOC_{rate} and C-input were statistically tested with analysis of variance (ANOVA), which was performed for each period (P1-R, P2-R and P3-I) with tillage, N fertilization and their interaction as fixed effects and block as random effect. Meanwhile, an ANOVA of POxC, POC and C-Min was performed with block and soil depth as the repeated measure with tillage, N fertilization, year, and their interaction as fixed effects. Since the interaction of year with the rest of effects was non-significant, a separate ANOVA was finally carried out for each year (2015 and 2017). Statistical analysis of these fractions was performed on C-Min and POC concentration in table 5 and figure 4 whereas analysis on equivalent mass was included in table 4. When significant, differences among treatments were identified at 0.05 probability level of significance with a Tukey HSD test. Simple regression analyses were performed with the statistical package JMP 13 (SAS Institute Inc, 2018) to test the presence of relationships between ΔSOC_{rate} and C-input for each period (P1-R, P2-R and P3-I).

3 Results

3.1. Weather characteristics during the experimental period.

Monthly rainfall, potential evapotranspiration, air temperature and irrigation for each year are presented in Fig. 1. The annual precipitation was highly variable during the study period, ranging between 183 and 645 mm in 2017 and 1997, respectively. Years 1998, 2001, 2004, 2005, 2006, 2007, 2011 and 2012 were characterized by a long drought which affected the autumn soil water recharge period (September-December). Conversely, 1996, 1997, 2002, 2003, 2009 and 2010 were characterized by 25 to 60% more rainfall than the 30-yr average (i.e. 401 mm). During the irrigated phase, the water deficit was offset by irrigation, with a supplemental irrigation water of 631, 672 and 696 mm in 2015, 2016 and 2017, respectively, during the corn growing season (April to September).

The yearly air temperature followed the typical Mediterranean pattern with hot summers, with air temperatures above 35 °C, and the winters mild to cold.

3.2. Crop C-inputs and soil organic carbon stock in each period.

Crop residue C-inputs were significantly affected by the interaction between tillage system and N fertilization under rainfed conditions (P1-R and P2-R). However, in P3-I only tillage and N fertilization main effects (without interaction) significantly influenced C-inputs (Table 2). According to the interaction between tillage systems and N fertilization, in P1-R and P2-R, C-inputs did not show differences among tillage systems when no N fertilizer was applied, while NT showed large C-inputs compared to RT and CT when applying medium N fertilization rates. Moreover, in P1-R, NT showed greater C-inputs compared to RT and CT when applying the high rate of N fertilization. In P2-R, NT and RT showed larger C-inputs compared to CT when applying the high rate of N fertilization (Table 2). In P3-I, averaged across rates of N fertilization, greater C-inputs were observed under NT compared to RT and CT (3255, 2630 and 2213 kg C ha^{-1} yr^{-1}, respectively) (Table 2). Furthermore, in P3-I C- inputs (averaged across tillage systems) were greater for the high N fertilization rate (2968 C ha^{-1} yr^{-1}) than the control (2378 C ha^{-1} yr^{-1}) in whereas medium rate had intermediate values (2752 C ha^{-1} yr^{-1}) (Table 2).

Soil organic carbon sequestration rate (ΔSOC_{rate}) (0–40 cm) significantly varied among periods, with mean values across all treatments of 492, 222 and 969 kg C ha^{-1} yr^{-1}, in P1-R, P2-R and P3-I, respectively (Table 3). In P1-R (1996 to 2009), ΔSOC_{rate} was significantly affected by tillage and N fertilization main effects (without interaction) while in P3-I (2015 to 2017), ΔSOC_{rate} was affected by the interaction among tillage and N fertilization (Table 3). Differently, in P2-R (2009 to 2015), ΔSOC_{rate} did not show differences between treatments (Table 3). In contrast, in P1-R, NT presented the highest ΔSOC_{rate} compared to CT with intermediate values in RT (Table 3), while high N rate showed greater ΔSOC_{rate} compared to the control with intermediate values in the medium N rate (Table 3). In P3-I, the high rate of N fertilizer in NT led to greater ΔSOC_{rate} compared to CT with intermediate values in RT (1959, 731, and 1380, kg C ha^{-1} yr^{-1}, respectively), while under the control and medium N rates ΔSOC_{rate} did not show differences among tillage systems (Fig. 2).

In P1-R and P3-I, a significant positive linear relationship was found between ΔSOC_{rate} and annual C-inputs, explaining 70% of the variance of ΔSOC_{rate} (r^2=0.70; $p < 0.001$) (Fig. 3). In contrast, in P2-R, ΔSOC_{rate} was not correlated with C-inputs.

3.3 Soil C fractions influenced by the conversion of rainfed to irrigated cropping system.

In 2015 and 2017, POC was significantly affected by N fertilization at the 0–40cm depth, with greater values under high N rate compared to the control and medium N rate.

(Table 4). Also, in 2017 POC was significantly affected by tillage system as one of the main effects with NT having significantly higher POC than CT whereas RT had intermediate values. However, C-Min did not show differences between treatments for any of the years (Table 4). At the beginning and at the end of P3-I (2015 and 2017), POxC, POC and C-Min were significantly affected by the interaction between tillage system and soil depth (Table 5). Also, in 2015 POC was significantly affected by N fertilization and tillage system as main effects. In 2017, C-Min were significantly affected by the interaction between N fertilization, tillage system and soil depth while POC was affected by the interaction between tillage system and N fertilization (Table 5). In 2015 and 2017 POxC was significantly affected by tillage systems at the soil surface (0–5 cm depth), with greater values under NT than CT and intermediate values for RT (Fig. 4a and 4b). Similarly, POC was significantly affected by tillage systems at 0-5 and 5-10 cm soil depths in 2015 with a significant decreasing trend of POC when increasing tillage intensity (NT>RT>CT) (Fig. 4c). Meanwhile in 2017, POC was significantly affected by tillage systems at the soil surface (0–5 cm depth), with greater values under NT than CT and intermediate values for RT (Fig. 4d). In 2015, C-Min was higher in NT and RT compared to CT at the soil surface (0-5 cm), while the contrary occurred at the deepest soil layer (30-40 cm) (Fig. 4e). Interestingly, in 2017 C-Min concentration only showed differences among tillage systems in the surface layer (0-5 cm), with greater C-Min under NT than CT and intermediate values in RT (Fig. 4f).

4 Discussion

Results of this study indicated that in Mediterranean conditions, the conversion from a rainfed to an irrigated cropping system generates major changes on the soil organic carbon (SOC) dynamics.

It is well-known that the amount of C inputs returned to the soil is a key factor driving the changes in SOC stocks (Virto, Barré, Burlot, & Chenu, 2012), since SOC results from the decomposition of biotic residues. Our results are fully consistent with this conclusion since C-inputs explained 70% (Fig. 3) of the variation in SOC sequestration rates both in P1-R and in P3-I. These two periods (P1-R and P3-I) faced major changes in the cropping system (in P1-R the adoption of RT or NT vs. the traditional CT and in P3-I the conversion from a rainfed to an irrigated cropping system). According to the C saturation concept, the response of SOC in relation to C-inputs depends on the amount of C that can be retained with clay and silt particles (Hassink, 1996; Hassink, 1997). Consequently, as long as the finer particles are not saturated with C, they will have the capacity to hold more C, protecting it in aggregates, provided that appropriate agricultural practices are carried out. In our study, SOC content at the beginning of the experiment (1996) was low since the traditional practices of the area consisted of intensive tillage and crop residue removal. The maintenance of crop residue in the soil surface under NT and its incorporation in RT and CT after the start of the experiment, would have favoured the increase of SOC in all three tillage systems during P1-R. In our study, in P1-R, ΔSOC_{rate} was greater in NT (46%) compared to CT, while ΔSOC_{rate} was greater under the high N application rate with respect to the control, as previously reported by Morell *et al.* (2011). These authors showed that soil water conservation under NT and RT treatments during dry seasons combined with adequate N fertilization allowed for higher C-inputs returned to the soil compared to CT.

In P2-R, ΔSOC_{rate} was 55% lower than in P1-R with an average value of all treatments of 222 kg C ha^{-1} yr^{-1} and did not show differences among treatments, despite the fact that C-inputs were similar to P1-R. It is known that SOC sequestration is a finite process (Powlson, Whitmore, & Goulding, 2011). In our experiment, although decomposition rates were not measured, the similar C inputs and the reduction in the SOC change rate observed between P1-R and P2-R would be indicating that SOC levels were reaching a steady state (von Lützow *et al.*, 2006). For instance, in a NT chronosequence experiment formerly managed under CT in Mediterranean conditions, Álvaro-Fuentes *et al.*,(2014), observed that more than 75% of the total SOC sequestered was gained during the first 11 years after NT adoption, with the highest SOC sequestration rate during the first 5 years after NT adoption. From the 11th year onwards, the change in the annual rate of SOC sequestration decreased significantly and SOC reached a new equilibrium. Therefore, the greatest differences in SOC sequestration rates occur at the first years after NT adoption, while rates tend to decrease after the first decade. That process would explain the strong decrease in SOC sequestration rate under NT and RT observed in our experiment in P2-R.

In P3-I, the conversion from rainfed to irrigated land allowed us to modify the cropping system, opting for a more productive summer crop such as corn, as well as the management practices, which directly affected SOC sequestration. In this study, the cultivation of corn resulted in greater amounts of crop residues returned to the soil (in P3-I, C-input increased by 65% and 88% compared to P1-R and P2-R, respectively) and a mean SOC increase about 969 kg C ha^{-1} $year^{-1}$ when averaged over tillage treatments and N rates. In this regard, an 88% increase in SOC (0-40 cm depth) was found with the introduction of irrigated corn in NT in comparison with the total rainfed period (sum of P1-R and P2-R). This increase of SOC in P3-I was the result of the modification of the cropping system, which entails a range of different mechanisms that affect SOC dynamics. For example, there was an increased amount of C-inputs as a result of greater crop productivity under irrigation, which increased the SOC (Powlson, Glendining, Coleman, & Whitmore, 2011). Adviento-Borbe *et al.* (2007) showed an increase in SOC sequestration (440 and 662 kg ha^{-1} yr^{-1} for RT and CT, respectively, at 0-30 cm soil depth) due to increased crop biomass inputs in two continuous corn systems, six years after the introduction of changes in the intensity of management in irrigated agroecosystems in Nebraska. The conversion of a cropping system to irrigation with summer crop cultivation could also influence SOC dynamics by modifying water availability in agricultural soils, when temperatures are higher. The increase in moisture can lead to anoxic conditions which slow down the decomposition of organic matter (krogh *et al.,* 2003), leading to further C sequestration. Another mechanism which could explain the increase of SOC when changing from a rainfed barley to a irrigated corn-based cropping system would be the lignin:N ratio of crop residues which plays an important role in their decomposition (Paustian, Collis, & Paul, 1997). The value of lignin:N can be considered as an index of biodegradability (Nourbakhsh, 2006). For instance, SOC is usually greater in cropping system with corn than with barley since barley produces less residue that has lower lignin:N ratios than corn. Equally, the stability of aggregates and the release of the organic matter can be influenced by the type and intensity of tillage which can vary in irrigated crop rotations compared to rainfed ones.

Interestingly, our study showed that the conversion from a rainfed to an irrigated cropping system led to a strong increase of a labile SOC fraction such as POC. Particulate organic carbon was extremely sensitive to the conversion of a rainfed to an irrigated cropping system with a 75% increase as an average of tillage system (0-40 cm soil depth). In this regard, this fraction was previously identified as one of the most sensitive to changes in tillage and N fertilization management practices in Mediterranean soils (Plaza-Bonilla, Álvaro-Fuentes, & Cantero-Martínez, 2014). Labile soil C fractions such as POC play a key role in the formation of microaggregates and macroaggregates acting as binding agents (Elliott, 1986), allowing the persistence of SOC (Puget, Chenu, & Balesdent, 2000). Conversion of rainfed into irrigated cropping systems may have important effects on soil aggregation, given the feedback mechanism between soil aggregation and SOC dynamics (Six, Bossuyt, Degryze, & Denef, 2004). These effects are mainly linked to changes in the organic carbon cycle, caused by the increase in crop residues (Adviento-Borbe *et al.*, 2007), and the increase in soil microbial activity (Denef, Stewart, Brenner, & Paustian, 2008). In addition, POC can be affected by tillage, with an improvement in C-physical protection within aggregates when NT is used. In this study the main driver of the increase in POC in soils would be the contribution of crop residue (Golchin, Oades, Skjemstad, & Clarke, 1994). Differently to POC, POxC showed a small increase (6%) after the conversion from a rainfed to an irrigated cropping system. This last fraction is usually related to a more active C cycle, which in turn, favours microbial activity (Haynes, 2005). Opposite to the more labile fractions, C-min remained stable given its recalcitrant nature. Moreover, the C fractions studied were affected by tillage, with a greater accumulation of POC, POxC and C-Min at the soil surface under NT compared to CT. The results suggest that the increase of SOC when decreasing tillage intensity (NT > RT > CT) would mainly be a consequence of an enhancement of POC. Tillage disrupts soil aggregation, reducing physical protection of POC occluded within aggregates (Grandy & Robertson, 2006) reducing the opportunity for SOC sequestration.

In the irrigated period (P3-I), N fertilization rate also played an important role on SOC sequestration, since high N rates combined with NT led to increase SOC sequestration due to increased C-inputs as a result of the greater crop productivity of an irrigated cropping system devoted to corn production. Our data showed that under NT and RT the crop made a more efficient use of the nitrogen fertilizer applied compared to CT. The lower response to N application under CT would be due to poor soil structure and surface crusting which reduced water availability. The occurrence of soil crusting under CT reduced the infiltration of water into the soil profile compromising plant establishment (Pareja-Sánchez *et al.,* 2017). Crop growth under CT was limited because of reduced water infiltration and C-inputs as crop residues were 32% lower than under NT at the highest N rate. In this line, Follett, Jantalia, & Halvorson (2013) suggested that increasing N fertilization rates may increase SOC stocks depending on soil depth considered and tillage practice. For example, in irrigated continuous corn systems, Halvorson, Reule, & Mosier (2004) showed that the rate of SOC sequestration (0–15 cm depth) under NT with a high N fertilization rate was 1.4–2.0 Mg C ha^{-1} yr^{-1}, while the CT treatment showed a rate of 0.2 Mg C ha^{-1} yr^{-1} even with about the same level of crop residues as under NT. Similarly, Follett, Castellanos, & Buenger (2005) observed an increase in SOC under NT systems with high N fertilization rate (1 and 1.9 Mg C $ha^{-1}yr^{-1}$ in the 0–15- and 15–30-cm depths, respectively), compared to CT with the same N rate (0.2 and 0.6 Mg C ha^{-1} yr^{-1} in the 0–15- and 15–30-cm depths, respectively) under wheat–corn rotations in irrigated conditions in Mexico. They suggested that the greater SOC sequestration under NT was due to higher above-ground crop residue. As shown by our study under Mediterranean conditions, the use of no-till in irrigated cropping systems based on corn increases SOC sequestration compared to the former rainfed cropping systems based on winter cereal production.

Conversion from rainfed land to irrigation also may lead to other environmental threats as for example an increase of soil greenhouse emissions, which may be compensated with soil C sequestration. The magnitude of soil C sequestration is crucial for the future trend of CO_2 and N_2O concentration in the atmosphere (DeLuca & Zabinski, 2011). In our study, the greater levels of SOC found under NT and, particularly, with the application of N fertilizers could also boost soil N_2O emissions, by nitrification and denitrification, and soil CO_2 emissions, by the increase in the amount of crop residues incorporated to the soil. In this regard, in the previous barley rainfed period (P2-R), cumulative annual N_2O emissions were 34% lower (Plaza-Bonilla, Álvaro-Fuentes, Arrúe, & Cantero-Martínez, 2014), than the values found in the irrigated period (P3-I) (Pareja-Sánchez, Cantero-Martínez, Álvaro-Fuentes, & Plaza-Bonilla, 2020). These data suggest that the increase in soil moisture and the use of higher N fertilization rates when transforming to irrigation were the main causes behind the increase in N_2O emissions. However, the increase in N_2O emissions can be compensated with SOC sequestration. In P3-I, N_2O emissions corresponded to 167 kg CO_2 equivalent ha^{-1} $year^{-1}$, as an average of treatments and years (Pareja-Sánchez, Cantero-Martínez, Álvaro-Fuentes, & Plaza-Bonilla, 2020), while SOC sequestration amounted 3553 kg CO_2 equivalent ha^{-1} $year^{-1}$. Therefore, our data showed that the greater emission of N_2O would probably be compensated with the SOC sequestration at least during the first years after the change to irrigation. However, soil N_2O and CO_2 emissions would continue over time according to crop needs, as CO_2 emissions related to the energy needed for pumping irrigation water.

5. Conclusion

This study shows that the modification of the cropping system due to the conversion of Mediterranean rainfed agroecosystems into irrigation, exerted a significant impact on soil organic carbon sequestration rates.

The amount of C-inputs as crop residues is an important factor explaining soil carbon sequestration rates. In the rainfed Mediterranean conditions the use of NT increases soil water conservation compared to conventional tillage leading to higher C-inputs and allowing the response of the crop to N application increasing soil carbon sequestration rates. However, 13 years after the implementation of these practices, SOC sequestration rates were reduced from 492 to 222 kg C ha^{-1} yr^{-1}, which suggests that an equilibrium phase was almost reached for SOC. When Mediterranean rainfed cropping systems based on winter cereal production are converted into irrigated cropping systems based on highly productive summer crops such as corn an increase of SOC sequestration rates occurs reaching a value of 969 kg C ha^{-1} yr^{-1} when averaged over all treatments. The application of water through irrigation allows more biomass production and more C-inputs from crop residues. Particulate organic carbon was the main indicator for SOC sequestration due to the conversion of the cropping system, which shows a great sensitivity to the new scenario. If NT is used in these newly irrigated systems, SOC sequestration rates can attain 1959 kg C ha^{-1} yr^{-1} when applying high N fertilizer rates in comparison to 731 kg C ha^{-1} yr^{-1}, which would be attained when using conventional tillage.

Our results indicate that the use of NT practices under rainfed led to an increase of SOC. A second step related to the introduction of irrigation allows the modification of the cropping system to the cultivation of more productive summer crops such as corn, enhancing C inputs to the soil and SOC, which is maximized by the use of NT and adjusted fertilizer rates.

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Figure captions

Fig. 1. Monthly precipitation (dark blue columns), irrigation (light blue columns), potential evapotranspiration (PET, red dash line) and mean air temperature (yellow line) at Agramunt from 1996 to 2017. For each year total precipitation (above) and irrigation water (below) are reported.

Fig. 2. Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and nitrogen fertilizer rate (0, Medium, High) effects on SOC sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} $year^{-1}$) from 2015 to 2017 (P3-I). Different lower case letters indicate significant differences among treatments at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 3. Linear regression between soil organic carbon sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} $year^{-1}$) and annual carbon inputs (C-input) (kg C ha^{-1} $year^{-1}$) from 1996 to 2009 (P1-R), from 2009 to 2015 (P2-R), and from 2015 to 2017 (P3-I). For each period, each point represents the average of each treatment (tillage systems: CT, conventional tillage; RT, reduced tillage; NT, no-tillage; N fertilizer rates: 0, Medium, High).

Fig. 4. Permanganate-oxidizable organic C (POxC) (mg C kg^{-1}), particulate organic carbon (POC) and mineral-associated organic carbon (C-Min) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) at different soil depths before (2015) (a, c and e) and after (2017) (b, d and f) the conversion of rainfed to irrigated land. Different lower case letters indicate significant differences between tillage systems for a given depth at $P < 0.05$.

Table 1. Agricultural management practices carried out in the experimental field during the rainfed and irrigated periods.

	Rainfed period (1996 to 2014)	**Irrigated period (2015 to 2017)**
Tillage	**CT:** one moldboard plough pass (25-30 cm depth) plus two cultivator passes (15 cm depth) during September and October. **RT:** one cultivator pass (10 to 15 cm depth) during September and October. **NT:** No-tillage.	**CT:** one rototiller pass (15 cm depth) plus one subsoiler pass (35 cm depth) and one disk plough pass (20 cm depth) during March or April. **RT:** Strip-tillage (25 cm deep with a working width of 25 cm, 12.5 cm on each side, reducing the surface tilled to 20%). **NT:** No-tillage.
Growing season	November – June.	April – November.
Sowing/Planting	**Barley:** cv. Hispanic from 1996 to 2010 and cv. Cierzo from 2010 to 2014. Planting density of 450 seeds m^{-2} in November.	**Corn:** cv. Kopias from 2015 to 2017. Planting density of 90,000 seeds ha^{-1} in April.
Fertilization	• **Three mineral N fertilizer rates** 0, 60 and 120 kg N ha^{-1}: ▪ 1/3 of the rate in one pre-sowing application as ammonium sulphate (November). ▪ 2/3 of the rate in one top dressing application as ammonium nitrate (between January and February). • **Phosphorous:** 40–50 kg P_2O_5 ha^{-1} yr^{-1} • **Potassium:** 90 kg K_2O ha^{-1} yr^{-1} (both P and K before sowing in November).	• **Three mineral N fertilizer rates** 0, 200 and 400 kg N ha^{-1}. ▪ 1/3 of the rate in one pre-sowing application as urea (April before sowing). ▪ 1/3 of the rate in two top-dressing applications at V5 (May) and V10 (July) as ammonium nitrate. • **Phosphorous:** 154 kg P_2O_5 ha^{-1} yr^{-1} • **Potassium:** 322 kg K_2O ha^{-1} yr^{-1} (both P and K in March or April, before planting).
Weed control	pre-sowing: 1.5 L ha^{-1} of glyphosate [N-(phosphonomethyl) glycine].	pre-sowing: 1.5 L ha^{-1} of glyphosate [N-(phosphonomethyl) glycine].
Grain harvest	Commercial combine at the end of June or beginning of July.	Commercial combine at the beginning of November.
Crop residue management	Chopped and spread over the soil surface (NT) or incorporated (CT and RT) according to the tillage system.	Chopped and spread over the soil surface (NT) or incorporated (CT and RT) according to the tillage system.

Table 2. Above-ground carbon inputs (C-input) (kg C ha^{-1} yr^{-1}) from 1996 to 2009 (P1-R), from 2009 to 2015 (P2-R), and from 2015 to 2017 (P3-I) as affected by tillage (CT; conventional tillage, RT; reduced tillage and NT; no tillage) and N fertilization rate (zero, medium and high). For each variable, different letters indicate significant differences between treatments at P<0.05. Values in brackets indicate standard deviation. Analysis of variance (*P*-values) of C-inputs of P1-R, P2-R and P3-I as affected by tillage (CT, RT and NT), N fertilization rate (zero, medium and high), and their interaction.

	C-input (kg C ha^{-1} yr^{-1})		
Treatment	**P1-R**	**P2-R**	**P3-I**
CT-0	1245 (81) a	1066 (17) a	1995 (391)
RT-0	1263 (105) a	1069 (91) a	2488 (211)
NT-0	1445 (150) a	1310 (34) a	2651 (332)
CT-Medium	1490 (84) b	1222 (68) b	2341 (35)
RT-Medium	1662 (91) b	1391 (151) b	2723 (395)
NT-Medium	2079 (170) a	1874 (81) a	3191 (267)
CT-High	1540 (118) b	1249 (162) b	2303 (831)
RT-High	1697 (85) b	1707 (89) a	2679 (637)
NT-High	2268 (68) a	2009 (201) a	3921 (96)
ANOVA			
Tillage (Till)	<0.001	<0.001	<0.001
N fertilization (Fert)	<0.001	<0.001	0.02
Till*Fert	0.01	<0.001	ns

ns; non-significant

Table 3. Soil organic carbon sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} yr^{-1}) from 1996 to 2009 (P1-R), from 2009 to 2015 (P2-R), and from 2015 to 2017 (P3-I) as affected by tillage (CT; conventional tillage, RT; reduced tillage and NT; no tillage) and N fertilization rate (zero, medium and high. Different lower case letters indicate significant differences among treatments at *P*< 0.05. Values in brackets indicate standard deviation. Analysis of variance (*P*-values) of soil organic carbon sequestration rate (ΔSOC_{rate}) of P1-R, P2-R and P3-I as affected by tillage (CT, RT and NT), N fertilization rate (zero, medium and high), and their interaction.

	ΔSOC_{rate} (kg C ha^{-1} yr^{-1})		
Treatment	**P1-R**	**P2-R**	**P3-I**
CT	394 (271) b	237 (269)	698 (406) b
RT	508 (204) ab	334 (352)	955 (764) b
NT	574 (189) a	94 (245)	1255 (758) a
0	358 (240) b	95 (315)	431 (265) b
Medium	509 (251) ab	321 (272)	1119 (495) a
High	610 (113) a	249 (293)	1357 (813) a
Average	492 (228)	222 (298)	969 (541)
ANOVA			
Tillage (Till)	<0.001	ns	<0.001
N fertilization (Fert)	<0.001	ns	<0.001
Till*Fert	ns	ns	0.04

ns; non-significant

Table 4. Soil particulate organic carbon (POC) (kg ha^{-1}) (0-40 cm) and mineral-associated organic carbon (C-Min) (kg ha^{-1}) (0-40 cm) before (2015) and after (2017) the conversion of rainfed to irrigated land, as affected by tillage (CT; conventional tillage, RT; reduced tillage and NT; no tillage) and N fertilization rate (zero, medium and high). For each variable, different letters indicate significant differences between treatments at P<0.05. Values in brackets indicate standard deviation. Analysis of variance (*P*-values) of POC and C-Min before (2015) and after (2017) the conversion of rainfed to irrigated land, as affected by tillage (CT, RT and NT), N fertilization rate (zero, medium and high), and their interaction.

	2015		**2017**	
Treatment	**POC (kg ha^{-1})**	**C-Min (kg ha^{-1})**	**POC (kg ha^{-1})**	**C-Min (kg ha^{-1})**
CT	21105 (2143)	20170 (4143)	18186 (2749) b	23835 (3777)
RT	23351(2627)	20372 (2844)	21285 (5339) ab	23893 (3208)
NT	23570 (3649)	19768 (3099)	24602 (2749) a	22544 (3698)
0	20483 (1621) b	19974 (3230)	19165 (6923) b	23102 (3395)
Medium	22377 (1335) b	21270 (3472)	20773 (3248) b	24345 (4063)
High	25166 (3478) a	19066 (3120)	24136 (5365) a	22825 (3167)
ANOVA				
Tillage (Till)	ns	ns	0.02	ns
N fertilization (Fert)	<0.001	ns	<0.001	ns
Till*Fert	ns	ns	ns	ns

ns; non-significant

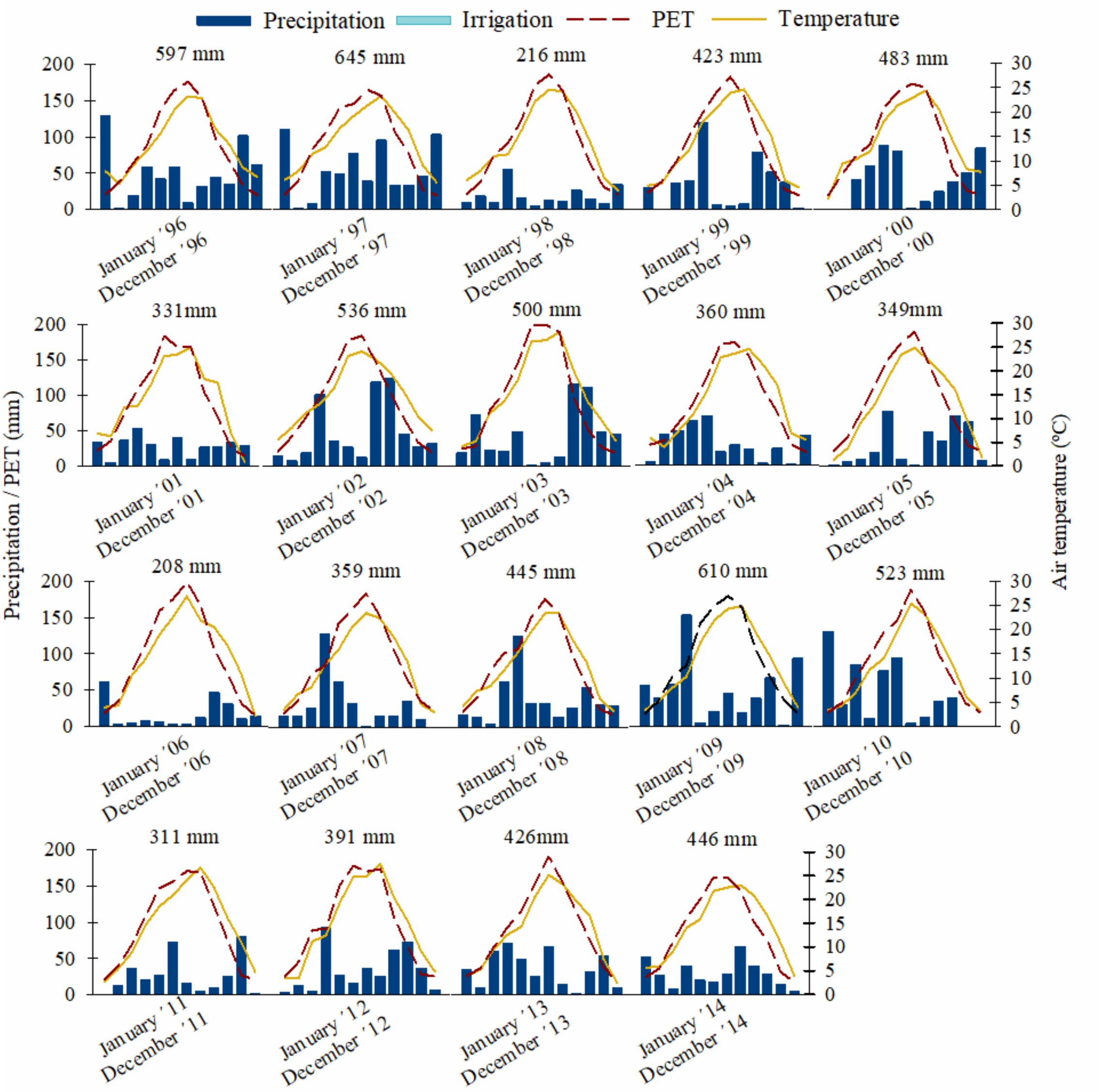
Table 5. Analysis of variance (*P*-values) of soil permanganate-oxidizable organic C (POxC), particulate organic carbon (POC) and mineral-associated organic carbon (C-Min) before (2015) and after (2017) the conversion of rainfed to irrigated land, as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage), N fertilization rate (zero, medium and high), soil depth (0-5, 5-10, 10-20, 20-30, 30-40 cm) and their interaction.

Year	**2015**			**2017**		
Source of variation	**POxC**	**POC**	**C- Min**	**POxC**	**POC**	**C- Min**
Tillage (Till)	ns	<0.001	ns	ns	ns	ns
N fertilization (Fert)	ns	<0.001	ns	ns	ns	ns
Till*Fert	ns	ns	ns	ns	<0.001	ns
Fert*Depth	ns	ns	0.03	ns	ns	0.004
Till*Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fert*Till*Depth	ns	ns	ns	ns	ns	0.002

ns; non-significant

Fig. 1. Monthly precipitation (dark blue columns), irrigation (light blue columns), potential evapotranspiration (PET, red dash line) and mean air temperature (yellow line) at Agramunt from 1996 to 2017. For each year total precipitation (above) and irrigation water (below) are reported.

a) Rainfed period



b) Irrigated period

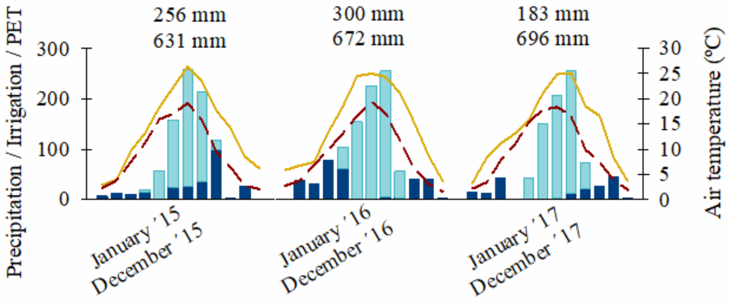


Fig. 2. Tillage system (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and nitrogen fertilizer rate (0, Medium, High) effects on SOC sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} year^{-1}) from 2015 to 2017 (P3-I). Different lower case letters indicate significant differences among treatments at $P< 0.05$. Vertical bars indicate standard deviation.

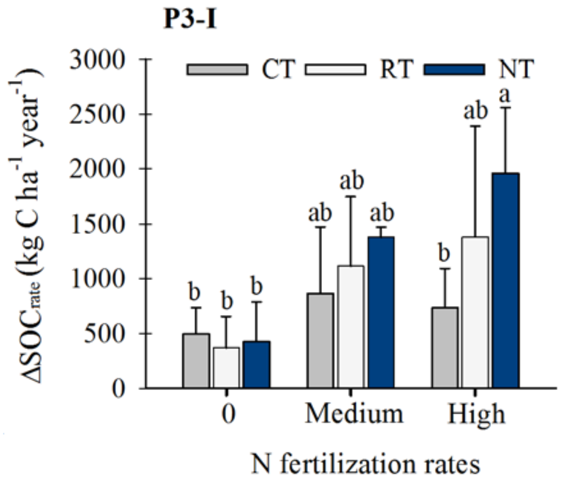


Fig. 3. Linear regression between soil organic carbon sequestration rate (ΔSOC_{rate}) (kg C ha^{-1} year^{-1}) and annual carbon inputs (C-input) (kg C ha^{-1} year^{-1}) from 1996 to 2009 (P1-R), from 2009 to 2015 (P2-R), and from 2015 to 2017 (P3-I). For each period, each point represents the average of each treatment (tillage systems: CT, conventional tillage; RT, reduced tillage; NT, no-tillage; N fertilizer rates: 0, Medium, High).

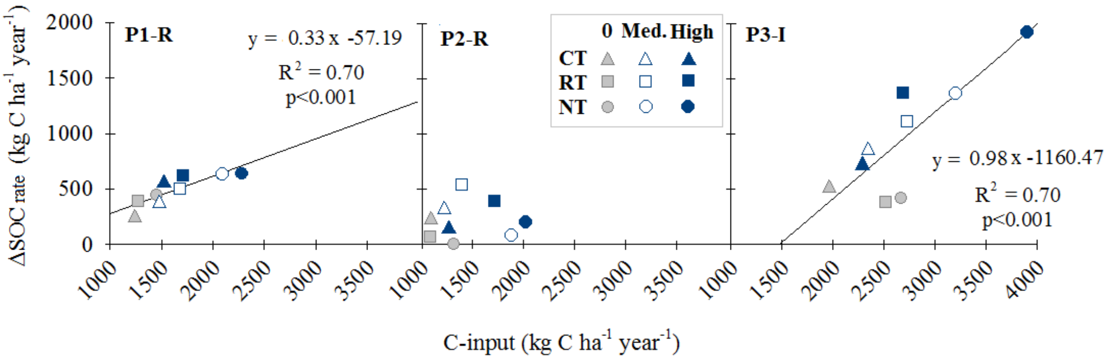


Fig. 4. Permanganate-oxidizable organic C (POxC) (mg C kg^{-1}), particulate organic carbon (POC) (g C 100g^{-1}) and mineral-associated organic carbon (C-Min) (g C 100g^{-1}) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) at different soil depths before (2015) (a, c and e) and after (2017) (b, d and f) the conversion of rainfed to irrigated land. Different lower case letters indicate significant differences between tillage systems for a given depth at P< 0.05.