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Is it feasible to reduce tillage and N use while improving maize yield in irrigated Mediterranean agroecosystems?

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Abstract

Mediterranean rainfed areas are transformed into irrigation to stabilize or increase crop yields. The gradual occupation of irrigation leads to an increase in nitrogen use and intensity of tillage. The aim of this work was to evaluate the combined impact of tillage systems and mineral N fertilization rates on maize grain yield, water and nitrogen use efficiencies (WUE and NUE) under Mediterranean irrigated conditions. The study was carried out in NE Spain during three maize growing seasons (i.e. years 2015, 2016 and 2017). A long-term (LTE) tillage and N rate field experiment established in 1996 under rainfed conditions was transformed into irrigation with maize (*Zea mays* L.) monoculture as cropping system in 2015. Three types of tillage (conventional tillage, CT; reduced tillage, RT; no-tillage, NT) and three mineral N fertilization rates (0, 200, 400 kg N ha^{-1}) were compared in a randomized block design with three replications. In 2015, an adjacent experiment (short-term experiment, STE) with the same layout was set up in an area previously managed under long-term rainfed NT for the last 21 years. Soil water (SWC) and nitrate (SNC) content were quantified. Maize above ground biomass and N uptake, grain yield and yield components, grain N were measured at harvest. The WUE for above ground biomass and yield (WUE$_B$ and WUE$_Y$, respectively) and NUE, as well as other N-related indexes (nitrogen harvest index, NHI; apparent nitrogen recovery efficiency, NAR) were calculated. In the long-term tillage and N fertilization combination (LTE), the reduction of tillage (NT and RT) led to greater grain yield when applying 200 and 400 kg N ha^{-1} compared to the use of the same rates under CT. Differently, in the sort-term experiment with preceding NT (STE), tillage systems did not influence grain yields, while N application led to greater yields than the control (0 kg N ha^{-1}). In both situations (LTE and STE), NT and RT enhanced SWC before planting leading to greater crop growth compared to CT. The lack of available water under CT caused lower maize above-ground biomass, yield, and yield components in LTE and, therefore, lower WUE$_B$ and WUE$_Y$. In LTE, the use of long-term CT led to a significant accumulation of nitrate compared to NT. Differently, in the STE, SNC did not show differences between tillage systems. In the LTE, water and N were used more efficiently to produce above-ground biomass and grain yield in RT and NT. Our study shows that in Mediterranean agroecosystems transformed into irrigation the use of NT and RT with medium rates of N leads to greater maize yield, WUE and NUE than the traditional management based on CT with high rates of mineral N. In rainfed areas with long-term history of no-till, this soil management system can be successfully maintained if transformed into irrigation.

Keywords

Grain yield; maize; N fertilization; N use efficiency; tillage systems; water use.

1 Introduction

In the Mediterranean rainfed area of the Ebro valley (NE Spain), an increasing adoption of reduced tillage (RT) and no-tillage (NT) techniques has taken place over the last 35 years (Lampurlanés *et al.*, 2016). Currently, a significant fraction of the area is being transformed into irrigation to ensure greater yields of winter and spring crops and to develop summer crops. However, in these newly irrigated areas, farmers have been induced to return to intensive tillage systems to overcome the difficulties to handle the increased level of crop residues from irrigated production. In these irrigated areas, the limited knowledge about the correct use of RT or NT systems makes difficult their adoption by farmers and puts at risk the soil quality benefits attained with the long-term use of NT in rainfed conditions. In general, in Mediterranean irrigated areas traditional soil management has been based on conventional tillage (CT) with deep subsoilers, mouldboard ploughs and rototillers. Therefore, the preservation of adequate management practices, such as NT or the implementation of new strategies of RT adapted to irrigated row crops like strip-tillage are important to improve water capture and retention (Unger *et al.*, 1991), avoid soil degradation (Pareja-Sánchez *et al.*, 2017), increase soil fertility (Alvarez, 2005) as well as enhance crop productivity (Lamm *et al.*, 2009).

The gradual increasing surface transformed into irrigation leads to an increase in nitrogen use, concomitant with increasing crop yield potential. Nitrogen is a key factor determining crop yield, being one main input in maize production (Parry *et al.*, 2005). However, the use of N fertilizer is generally inefficient with farmers applying it in important quantities to achieve high crop yields and without taking into account soil N availability, which leads to an over-fertilization. This strategy does not increase grain yield but, instead, wastes fertilizer, increases costs, and cause potential nitrate pollution to groundwater (Bowman *et al.*, 2008). Surveys conducted in the Ebro valley by Sisquella *et al.* (2004) showed that traditional mineral N rates applied to maize by farmers were about 300–350 kg ha^{-1}, with grain yields in the area ranging from 12,000 to 16,000 kg ha^{-1}. Therefore, the most effective means to ensure high yields while reducing N loss and thus environmental damage is to improve the nitrogen use efficiency (NUE) of crops (Davidson *et al.*, 2015). In a long-term irrigated experiment with maize managed under CT and comparing different mineral N rates (0, 100, 150, 200, 250, 300 and 400 kg N ha^{-1}) also in the Ebro valley, Martínez *et al.* (2017) observed the highest NUE and grain yield when applying 200 kg N ha^{-1}. Therefore, in the study area, it is feasible the reduction in maize N fertilization while maximizing maize yields.

Crop nitrogen uptake is strongly influenced by water supply (Martin *et al.*, 1982), thereby farmers should optimize water use to enhance NUE and reduce economic losses and environmental pollution. In pressurized irrigated systems, a proper water management is important, since irrigation accounts for a great proportion of the production costs that farmers face, due to electric energy needs and high costs of infrastructure establishment. This fact forces to redesign current cropping systems and, more specifically, the management practices to increase WUE in irrigated areas. The simultaneously combination of an efficient management of water, N fertilization and tillage is crucial for closing the yield gap of main cereal crops as well as to prevent water and soil pollution. In this line, authors like Cullum (2012) have shown that NT systems achieved higher maize grain yields than CT based on chisel/disk under the same N rate in northern Mississippi. In turn, Fabrizzi *et al.* (2005) evaluated the effects of RT and NT and two N fertilization rates (0 and 150 kg N ha^{-1}) on maize yield in Buenos Aires (Argentina) and observed lower grain yields under NT than under RT in the control treatment and no differences between tillage systems when applying 150 kg N ha^{-1}. Soil tillage and N fertilization influence soil N dynamics due to their impact on crop residues production and decomposition, soil organic nitrogen mineralization and water dynamics in the soil profile. Under NT crop residues are maintained on the soil surface which reduces their decomposition rate (Salinas-García *et al.,* 2002). In that context, N fertilizer could be immobilized if applied on soil surface (Kitur *et al.*, 1984). Moreover, the lack of soil alteration under NT maintains organic nitrogen protected, reducing its mineralization by soil microbes (Doran, 1980). Consequently, different authors pointed out the need to increase N fertilizer rates during the first years of NT implementation (Sims *et al.,* 1998; McConkey *et al.,* 2002). Indeed, other authors suggest to maintain this strategy until the increase in soil organic matter levels is sufficient to assure enough N from mineralization and available to crops. Therefore, optimum N fertilization level is dependant on the type of tillage implemented (Baker *et al.*, 1996).

Besides a tillage system change, the gradual transformation into irrigated areas could represent an intensification in the use of N. Currently, knowledge about the combined effect of tillage and N fertilization on crop production and WUE and NUE in the Mediterranean areas is limited to rainfed conditions (Cantero-Martínez *et al.*, 2007; Morell *et al.*, 2011; Plaza-Bonilla *et al.*, 2017). Therefore, the aim of this study was to evaluate the combined impact of tillage and mineral N fertilization rates on irrigated maize grain yield, WUE and NUE in two field experiments differing on previous soil management under Mediterranean conditions.

2 Materials and methods

2.1 Experimental design and management practices.

The study was performed in Agramunt, NE Spain (41°48′ N, 1°07′ E, 330 m asl). The climate is semiarid Mediterranean with a continental trend. The mean annual precipitation in the last 30 years is 401 mm, the mean annual of temperature is 14.1°C, and the annual potential evapotranspiration is 855 mm.

A rainfed long-term field experiment (LTE) was established in 1996 to compare three tillage systems (conventional tillage, CT; reduced tillage, RT; no-tillage, NT) and three increasing rates of mineral N under barley monocropping (Angás *et al*., 2006). In 2015 the LTE was transformed to irrigation with solid set sprinklers and 3 years of maize (*Zea mays* L.) monoculture as the main cropping system in the area. After the transformation to irrigation, the same tillage intensity treatments (CT, RT and NT) and three mineral N fertilization rates adapted to maize cultivation (0, 200, 400 kg N ha^{-1}) were compared in LTE maintaining the same experimental layout as the previous rainfed experiment. At the same time, in 2015, a new experiment was created adjacent to the LTE (separated by a 15 m corridor). The layout of this new experiment (so called short-term experiment, STE) was exactly the same as the LTE (same tillage and N fertilization treatments, spatial arrangement and cropping system) but with different historical tillage management. For the previous 21 years, the entire surface occupied by the STE consisted of a rainfed NT winter cereal-based cropping system. The experimental design in LTE and STE consisted of a randomized block design with three replications and plot size of 50x6 m. Soil was classified as Typic Xerofluvent (Soil Survey Staff, 2014) with a sandy clay loam texture (sand, 30.8%; silt, 57.3%; clay, 11.9%) in the upper (0-28 cm) horizon. The main physico-chemical properties at the beginning of the experiment (2015) were as follows: pH (H_2O, 1:2.5) 8.5; electrical conductivity (1:5) 0.15 dS m^{-1}; soil organic carbon (SOC) concentration (0-30 cm) 7, 9 and 9 g kg^{-1} under CT, RT and NT, respectively in LTE and 10, 9 and 10 g kg^{-1} under CT, RT and NT, respectively in STE; P Olsen, 35 ppm; K (Amm. Ac.), 194 ppm; water retention (-33 kPa), 16 g g^{-1}; water retention (-1500 kPa), 5 g g^{-1}.

The experiment was implemented in three successive maize growing seasons (2015, 2016 and 2017). In LTE and STE, tillage operations were carried out at the end of March to the beginning of April in the three growing seasons. The CT treatment consisted of one pass of rototiller (15 cm depth) followed by subsoiler (35 cm depth), finished by one pass of a disk plough (20 cm depth) with almost 100% of the crop residues incorporated into the soil before planting. The RT treatment consisted of a pass of strip-till to a depth of 20-25 cm, implemented on the maize planting row reducing the surface tilled to ca. 20%. Finally, the NT treatment consisted of weed control with a non-selective herbicide (i.e. glyphosate) at 1.5 L ha^{-1}. Planting was carried out with a pneumatic row direct drilling machine equipped with double disc furrow openers (model Prosem K, Solà, Calaf, Spain) in the three tillage systems (CT, RT, and NT). Rotary residue row cleaners were installed to clear the path for the row unit openers (both in RT and NT treatments). The planting depth was adapted to each tillage treatment to reach a constant value (ca. 4 cm). Mineral P and K fertilization was applied prior to maize planting based on soil analysis at rates of 154 kg P_2O_5 ha^{-1} and 322 kg K_2O ha^{-1}, respectively, in the first two years. In the third year the levels of available P and K in the soil were appropriate for the crop, therefore P and N were not applied in 2017. The N fertilizer rates compared were split in one pre-planting application with urea (46% N) on April, and two top-dressing applications on May and July (V5 and V10 stages, respectively) with calcium ammonium nitrate (27% N) with 50, 75 and 75 kg N ha^{-1} applied, respectively, in the three splits in the 200 kg N ha^{-1} rate, being doubled in the 400 kg N ha^{-1} rate. For the three years, maize (cv. Kopias) was planted in late April at a rate of 90,000 seeds ha^{-1} with a 73-cm width between rows. Irrigation was supplied to meet the estimated evapotranspiration (ET) of the crop minus the effective precipitation, which was estimated as 75% of precipitation when precipitation > 5 mm. (Dastane, 1978). Weekly maize evapotranspiration (ETc) was calculated from the corresponding weekly values of ET and Kc. Reference ET was computed with the FAO Penman–Monteith method from meteorological data obtained from an automated weather station located near the experimental site. Crop coefficients (Kc) were estimated in function of crop development. The experiment received a total of 631, 672 and 696 mm of irrigation water in 2015, 2016 and 2017, respectively, during the maize growing period. Harvesting was carried out at the beginning of November with a commercial combine. The crop residues were chopped and spread over the soil. During the winter periods between crops the soil was maintained free of weeds with an application of glyphosate at 1.5 L ha^{-1}.

2.2 Soil and crop samplings and measurements.

Within each plot, two sampling areas were defined. Soil samples from each area were collected prior to maize planting (mid-March) and after harvesting (mid-November). Soil water, ammonium and nitrate contents were quantified at three depth intervals (0–30, 30-60 and 60-90 cm depth). The soil nitrate (NO_3^-) contents were quantified by extracting 50 g of fresh soil with 100 mL of 1 M KCl. The extracts were analyzed with a continuous flow autoanalizer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). Gravimetric soil water content was determined for every depth interval by oven drying a soil sample at 105°C until constant weight. Concentrations were transformed to volume-based values using soil bulk density determined by the soil core method (Grossman and Reinsch, 2002).

At harvest, above-ground biomass was cuantified by sampling two central rows of 2-5 m long, depending on plant density, in three sampling areas per plot. The number of plants and ears were counted and registered. Afterwards, a sub-sample of two entire plants and five ears was taken, oven-dried at 60°C for 48 h and weighed. Afterwards, the grain was threshed and weighed. Grain moisture was adjusted to 14% moisture content. These determinations allowed calculating above-ground biomass (excluding the grain) as well as maize yield components: plants per square meter, number of ears per plant and thousand kernels weight (TKW). Nitrogen concentration of maize grain and above-ground biomass were determined by dry combustion (model Truspec CN, LECO, St Joseph, MI, USA). Afterwards, grain N and above-ground biomass N excluding the grain were calculated by multiplying the biomass of each fraction by its N concentration. Above-ground N uptake was calculated by the sum of N content in both fractions. Grain protein was calculated by multiplying the grain N concentration by 6.25 (Jones, 1941).

2.3 Water and nitrogen related indicators.

Water use (WU) was calculated as the difference in soil water content (SWC) between planting and harvest plus the rainfall received and the irrigation water applied between both dates. Water use efficiency for above-ground biomass (WUE_B) and yield (WUE_Y) were calculated as follows:

The following N-related parameters were calculated for each treatment:

N use efficiency (NUE; kg kg^{-1}):

Where N supply is the sum of soil nitrate– N at planting and N fertilizer applied.

N harvest index (NHI):

Where N grain is grain N concentration.

N apparent recovery efficiency for each fertilizer treatment:

Where N uptake is the above-ground biomass N of the crop for a given fertilizer treatment and N uptake$_{0N}$ is the above-ground biomass N of the control.

2.5 Statistical analyses.

Statistical analyses were performed using the JMP 12 statistical package (SAS Institute Inc, 2015). Data were checked for normality by plotting a normal quantile plot. For each experiment (LTE and STE), analysis of variance (ANOVA) was used to determine the effect of the main factors and their interactions on the variables measured. The means were compared by using a Tukey HSD test at the 0.05 probability level.

3 Results

3.1 Weather conditions during the experimental period.

Air temperature, precipitation and irrigation applied during the three maize growing seasons are shown in Fig. 1. Air temperature increased from the beginning of each maize season, reaching a maximum in summer months (June to August), to decrease later during autumn and winter months, being the minimum in December and January. The maximum temperature was reached in 2017, being the average of June, July and August 22.6, 24.0 and 24.6 ºC, respectively. Precipitation varied considerably between maize seasons being 226, 151 and 78 mm for 2015, 2016 and 2017, respectively (Fig. 1). During the two periods between crops in winter (2015-2016 and 2016-2017) rainfall was 108 mm and 106 mm, respectively. The amount of water applied by irrigation was 631, 672 and 696 mm in 2015, 2016 and 2017, respectively (Fig. 1).

3.2 Maize grain yield, above-ground biomass, yield components and grain protein.

The interaction between tillage and N fertilization, tillage and year and N fertilization and year had a significant effect on maize grain yields in LTE (Table 1). In 2016 and 2017, the application of 200 and 400 kg N ha^{-1} led to greater yields than the control treatment (Fig. 2). In 2015 and 2017, grain yields in LTE were higher under NT and RT than under CT, without differences between tillage treatments in 2016 (Fig. 3). In the STE, the interaction between N fertilization and year had a significant effect on maize grain yields. Nitrogen application led to greater maize grain yields compared to the control without N in 2016 and 2017 (Fig. 2).

Maize above-ground biomass in the LTE was significantly affected by tillage and the interaction between N fertilization and year (Table 1). In the LTE, when comparing among tillage treatments and as an average of the three years, greater above-ground biomass was found under NT than under RT or CT, being NT values 60% greater than CT (7728 vs 4839 kg ha^{-1}, respectively). Greater above-ground biomass was observed when applying 200 and 400 kg N ha^{-1} in 2017 compared to the control treatment (Fig. 2). In the STE, maize above-ground biomass was significantly affected by the interaction between tillage and year and N fertilization and year (Table 1). Regarding to this, in 2017 the application of 200 and 400 kg N ha^{-1} led to greater above-ground biomass production than the control (Fig. 2). Moreover, greater aboveground biomass was observed under NT than CT, with intermediate values in RT in 2017 (Fig. 3).

Plant population was only affected by the interaction between tillage and year in the LTE (Table 1). In 2015, NT and RT showed greater number of plants per square meter than CT. In 2016, similar values were observed in the different tillage treatments. In 2017 plant population followed the order NT>RT>CT (Fig. 3). Differently, in the STE, plant population was only affected by year. In the LTE, TKW was affected significantly by the interaction between tillage and N fertilization and between tillage and year (Table 1). When using NT, the 400 kg N ha $^{-1}$ treatment showed greater TKW than the control, with 257 g and 190 g, respectively, as an average of the three cropping seasons studied. Thousand kernel weight was higher under NT and RT than under CT in 2015, without differences between tillage treatments in 2016 and 2017 (Fig. 3). In the STE, TKW was significantly affected by the interaction between tillage and N fertilization (Table 1). The rates of 200 and 400 kg N ha^{-1} led to greater TKW than the control in NT and CT, without differences between rates in RT, as an average of the three cropping seasons studied.

In the LTE, grain protein was significantly affected by the interaction between tillage and N fertilization (Table 1). In this regard, greater grain protein concentration was found under CT when applying 400 kg N ha^{-1} (10 g 100 g^{-1}) compared with RT and NT without N application (6.7 and 6.2 g 100 g^{-1}, respectively), as an average of the three cropping seasons studied. In the STE, grain protein was significantly affected by tillage, N fertilization and year simple effects (Table 1). Greater grain protein was found under CT and RT compared with NT (8.9, 8.9 and 7.9 g 100 g^{-1}, respectively). Moreover, the 400 and 200 kg N ha^{-1} rates showed greater grain protein compared to the control (9.5, 8.8 and 7.4 g 100 g^{-1}, respectively). Furthermore, in 2017 greater grain protein was observed compared with 2015 and 2016 (9.3, 8.2 and 8.3 g 100 g^{-1}, respectively).

3.3 Soil water content dynamics and maize water-use efficiency.

In the LTE, SWC was significantly affected by the interaction between tillage and N fertilization and by the interaction of these last with the sampling date. In the STE, SWC was significantly affected by the sampling date and the interaction between tillage and N fertilization (Table 2). In the LTE, SWC dynamics followed a similar pattern during the 2015 and 2016 cropping seasons, with greater SWC in NT and RT than in CT and a trend of increasing SWC from planting to harvest in the three years studied. However, SWC did not show differences between treatments after harvesting in 2017 (Fig. 4). In contrast, SWC showed similar behavior in the different N fertilization rates. In the STE, the control in NT showed grater SWC compared to CT when appliying 400 kg N ha^{-1} which were observed the lowest values, as an average of the three cropping seasons studied.

In the LTE, water use (WU) was significantly affected by the interaction between tillage and N fertilization and the interaction between tillage and year (Table 2). Greater WU was observed under RT and NT when applying 400 kg N ha^{-1} (820 and 806 mm, respectively) than CT under the same N rate (780 mm), as an average of three years. Furthermore, the rate of 200 kg N ha^{-1} showed greater WU in NT (815 mm) than CT (789 mm). In the STE, the interaction between tillage and year significantly affected WU (Table 2). In 2015, 2016 and 2017, WU was similar between tillage systems (data not shown).

The analysis of variance revealed significant effects of the interaction between tillage and year and between N fertilization and year on WUE_B and WUE_Y in the LTE. Differently, the interaction between tillage and N fertilization only affected significantly WUE_Y (Table 2). In this experiment, NT and RT showed larger WUE_Y compared to CT when applying 400 kg N ha^{-1} as an average of the three years studied (Fig. 5), while NT showed greater WUE_Y than CT when applying 200 kg N ha^{-1}. In the same experiment and in 2016 and 2017, the rates of 200 and 400 kg N ha^{-1} led to greater WUE_B and WUE_Y than the control (Fig. 6). In the STE, the WUE_B and WUE_Y were significantly affected by the interaction between N fertilization and year. Regarding to this, the application of N fertilizer led to greater WUE_B than the control in 2017 and greater WUE_Y than the control in 2016 and 2017 (Fig. 6).

3.4 Soil nitrate nitrogen content, nitrogen use efficiency and grain N content.

In the LTE, soil nitrate nitrogen content (SNC) was significantly affected by the interaction between tillage and N fertilization and by the interaction of these last with the sampling date (Table 2). The use of increasing rates of N fertilizer under CT led to greater SNC as an average of the different sampling dates covered by the experiment compared to NT. In the STE, SNC was significantly affected by the interaction between N fertilization and sampling date (Table 2). In this experiment, the rate of 400 kg N ha^{-1} showed greater values than the rate of 200 kg N ha^{-1} and the control in all sampling dates, except before planting in 2015.

In the LTE, above-ground N uptake was significantly affected by the interaction between tillage and N fertilization and by their interaction with the year. Grain N content was affected by the interaction between tillage, N fertilization and year (Table 2). In this regard, as an average of the three years, the application of 200 kg N ha^{-1} under NT showed greater above-ground N uptake than CT with intermediate values under RT (Fig. 5). Differently, when applying 400 kg N ha^{-1} N uptake followed the order NT > RT > CT (294, 239 and 171 kg N ha^{-1}, respectively). When comparing between N rates greater above-ground N uptake was observed under the application of 400 kg N ha^{-1} compared to the control in 2015, 2016 and 2017, in the LTE (Fig. 6). In the three years studied, NT led to grater grain N content compared to CT with intermediate values in RT when applying 400 kg N ha^{-1}. The rate of 200 kg N ha^{-1} only showed differences in 2017 with greater values in NT and RT compared to CT. In the STE, above-ground N uptake and grain N content were significantly affected by the interaction between N fertilization and year (Table 2). Regarding to this, greater above-ground N uptake was found under the rate of 200 kg N ha^{-1} compared to the control in 2015, while in 2016 and 2017 greater above-ground N uptake was observed when applying N fertilizer compared to the control (Fig. 6). In turn, in STE greater grain N content was observed under the application of 200 and 400 kg N ha^{-1} compared with the control in 2016 and 2017, whereas in 2015 no differences were observed between N fertilization rates (Fig. 6).

In the LTE, NUE was affected by the interaction between tillage and N fertilization and between N fertilization and year while NHI was affected by the interaction between tillage, N fertilization and year (Table 2). When N fertilizer was not applied greater NUE was observed under NT and RT compared to CT (78, 93 and 20 kg kg N^{-1}, respectively) as an average of the three years covered by the experiment (Fig. 5). In 2015, NHI did not show significant differences between treatments, whereas in 2016 and 2017 the lowest NHI was found under NT in the 0 kg N ha^{-1} treatment (data not shown). In the STE, NUE was affected by the interaction between N fertilization and year, with greater NUE in the control treatment compared with the application of N fertilizer in the three years of study (Fig. 6).

Finally, NAR was significantly affected by the interaction between tillage, N fertilization and year in the LTE (Table 2). In 2015 and 2016, NAR did not show differences between treatments, although a trend of greater values was observed when reducing tillage intensity. However, in 2017 NT and RT led to greater NAR compared to CT when applying 200 kg N ha^{-1} (Fig. 7). In the STE, NAR was affected by N fertilization, with a 47% increase on NAR when applying 200 kg N ha^{-1} compared to 400 kg N ha^{-1}.

4 Discussion

This study, carried out during three campaigns, has demonstrated that soil tillage exerts a significant impact on maize performance in Mediterranean irrigated conditions. On this point, lower yield was observed in CT compared to NT and RT. The impact of tillage systems on soil structure played a major role on crop productivity. In this regard, in a study recently published on this experimental field, it was reported that long-term CT leads to a deterioration of the soil physical properties. This degradation was due to a lower structural stability, causing soil surface crusting, which resulted in lower water infiltration (Pareja-Sánchez *et al.*, 2017). Therefore, although the contribution of irrigation water was the same for all tillage systems (666 mm of water as an average of the three years), the worse structural conditions under CT reduced soil water availability for the crop, causing lower maize yields. In addition, crop establishment was also affected by soil surface degradation, showing a density of plants 22% and 19% lower in CT compared to NT and RT, respectively, which could have been another key cause behind the greater maize yield in NT and RT. Regarding to this, it is well known that grain yield of modern hybrid maize varieties is highly sensitive plant density (Tokatlidis and Koutroubas, 2004; Grassini *et al.*, 2011). Other studies have compared the impact of different tillage systems on maize production in soils previously managed under conventional tillage, with opposite results. For instance, Alletto *et al.* (2011) compared the impact of CT, consisting of one pass of moldboard plow followed by one pass of cultivator and one of roller, with RT, consisting of one pass of harrow and another of roller, on maize production in an irrigated area in SW France. The last authors observed lower soil moisture under CT compared to RT during the growing period of maize, which led to similar or greater grain yields under RT. Differently, Salem *et al.* (2015)

determined the short-term impact (1 year) of four tillage treatments on soil physical properties and maize productivity in a central Spain area transformed into irrigation with previous management based on continuous CT under rainfed barley. The previous authors observed a decrease in maize grain yields and yield components when using NT compared to CT and RT. They pointed out that the higher soil compaction under NT would be the cause for maize yield decrease. However, our study showed that if the soil presents a long history (21 years, in our case) of continued management under NT before the transformation from rainfed to irrigation (STE), maize production as well as the use of water and N resources differ depending on the type of tillage system used. This last aspect indicates a soil structure maintenance effect (i.e. soil structure resilience), since the maintainance of NT in the long-term results in the formation of soil macroaggregates with greater stability (Álvaro-Fuentes *et al.*, 2009, Panettieri *et al.*, 2013) and greater SOC levels (Plaza-Bonilla *et al.*, 2013), specially in the soil surface (0-10 cm). Therefore, the greater SOC concentration and better structural condition of the soil surface played an important role in the response of the soil to the transformation from rainfed to irrigated conditions (Pareja-Sánchez *et al.*, 2017). Due to this aspect, maize grain yields as well as yield components were not negatively influenced by the use of CT over the three years of the experiment. However, this study is not long enough to determine how many years of intensive tillage would be needed to reach the poor soil structural conditions observed in CT in the long-term experiment. These differences between tillage systems and between both scenarios of historical soil management influenced the use of resources. In relation to this last, although WU was similar among tillage systems in the short-term experiment, we hypothesized that the degradation of soil structure would have reduced water infiltration. Therefore, the CT treatment would have led to less water available to the crop, resulting in a lower WUE and NUE supported this last by the large amount of residual soil N observed in CT.

Over-fertilization with N does not provide any extra grain yield, but simply wastes fertilizer, reduces crop profitability and is a potential source of reactive N contamination (Cox *et al.,* 1993). Therefore, a reduction in fertilizer application could lead to a better balance between crop demand and soil N supply (Cassman *et al.,* 2002). In Mediterranean conditions where water is a limiting factor, yield varies according to the amount of water available for the crop and its use efficiency. Soil management techniques and N fertilization rates affect both factors. For instance, conservation tillage reduces the evaporation of the water stored in the soil due to the presence of crop residues on the surface, therefore promoting greater soil water availability than intensive tillage (Lafond, 1994). The water used by the crop through transpiration is strongly affected by N fertilization, with a positive relationship between foliar area and water transpired in N fertilized crops (Samuelson *et al.,* 2007). In our study, when conventional tillage was long-term used prior to transformation into irrigation (LTE), the application of mineral nitrogen under NT and RT produced an increase in maize WUE_Y compared to CT at the same N rates. The lack of enough water available in CT due to reduced water infiltration would partially explain the lack of response of WUE_Y to the application of N fertilization. Similarly, Lamm *et al.* (2009) observed a greater water use efficiency when using strip-till and NT in comparison to CT, in a field of irrigated maize in Kansas. Another factor that is influenced by tillage and N fertilization is the residual N content in the soil and, therefore, it is important to adjust these two cultivation techniques in combination. In the maize-based cropping systems under Mediterranean irrigated conditions, N is an important factor to increase the production and that must be adjusted. In these conditions, farmers normally over-fertilize

(Berenguer *et al.*, 2009). In this line, our results showed that in the scenario of long-term conventional tillage prior to the transformation into irrigation (LTE), the application of high rates of nitrogen under CT leads to a greater content of mineral N in the soil than under NT. This result would be explained by several causes. First, the long-term use of CT during the previous rainfed experimental period (from 1996 to 2014) led to an accumulation of soil nitrate due to the limited soil water available for barley N uptake (Angás *et al*., 2006; Morell *et al.*, 2011). Secondly, the lower production of maize biomass in CT mostly attributed to the lower N uptake. Therefore, the optimal rate of N fertilization for maize should consider the amount of N available in the soil to avoid over-fertilization and long-term N accumulation in the soil profile. In a study with sprinkler-irrigated maize carried out in Colorado (USA), Halvorson *et al.* (2006) observed that the residual soil nitrate tended to be slightly higher in a CT system fertilized with 202 kg N ha^{-1} than under NT at the same N rate, indicating excess of applied N. The high residual soil nitrate content in CT had a great influence on the NUE measured. In the unfertilized treatment (0 kg N ha^{-1}), NUE was higher in the conservation tillage systems compared to CT but without differences in the rates of 200 and 400 kg N ha^{-1}. Similarly, in a NT maize production system in Argentina, Barbieri *et al.* (2008) reported a greater NUE when nitrogen was not applied. In our study, the high availability of soil mineral N before planting also caused a lack of response to the application of N of the grain N content and the NAR. In this line, lower NAR values were observed at the beginning of the experiment as a result of the high initial soil nitrate content which led to a lower recovery of N applied. In contrast, in the third year of the experiment, the NAR increased, showing higher values when using NT and RT with a rate of 200 kg N ha^{-1} compared with CT at the same rate. These data suggest that under NT and RT the crop makes a better use of the nitrogen fertilizer applied during the crop cycle leading to better yields. In this study, similar grain yields were obtained when 200 and 400 kg N ha^{-1} were applied in NT and RT, with CT showing the lowest yields in both N rates. However, the application of a high rate when NT or RT is used does not lead to a higher yield of maize grain than the medium rate. This could be due to the high initial soil nitrogen content in the plots fertilized with 400 kg N ha^{-1}. Consequently, a reduction in N fertilization with a reduction of tillage could help to increase the productivity and profitability of maize crops and reduce the risk of N losses by leaching (Quemada *et al.*, 2013) and the increase in greenhouse gas emissions to atmosphere (Meijide *et al.*, 2009; Sanz-Cobena *et al*., 2012).

Differently, when the soil was continously managed under NT during the 21 years previous to the transformation from rainfed to irrigated conditions (STE), the first year of the study (2015) already showed differences in the mineral nitrogen content in post-harvest, showing greater soil nitrogen content in the rate of 400 kg N ha^{-1} compared to the application of 0 and 200 kg N ha^{-1}. This trend was maintained over the three years of study. This fact indicates the importance of considering the residual levels of nitrogen in this area, due to the high rates of N fertilization that are handled and the long-term accumulation of nitrate in the soil profile, susceptible of being lost by leaching. In addition, the rate of 200 kg N ha^{-1} increased grain yield, above-ground biomass, TKW and grain protein, with no increases when applying beyond 200 kg N ha^{-1}.These data suggest that the N rate could be reduced by half without compromising grain yield or yield components. In this line, Al-Kaisi and Yin (2003) suggested that the traditional application rate used by farmers in north eastern Colorado in maize production (250 kg N ha^{-1}) could be reduced to 140 kg N ha^{-1} without losses in grain yield, since high N rates led to a decrease in nitrogen use efficiency as soil water content decreased. Similarly, in a maize experiment in the NE Spain comparing different mineral N application rates, Martínez *et al.*, (2017) reported that the lowest N fertilization rate sufficient to achieve optimal yields was 200 kg N ha^{-1}. In our experiment, in all the three years studied, the NUE and the NAR decreased when increasing the rate of N from 200 to 400 kg N ha^{-1}, obtaining an improvement of 47% in NAR when 200 kg N ha^{-1} were applied compared with 400 kg N ha^{-1}. This would prove that the rates of fertilization adapted to the needs of the crop are used more efficiently.

Conclusions

In the Mediterranean region, large rainfed areas managed under long-term conservation tillage practices are being transformed into irrigation. In this context, the limited knowledge existing on the performance of conservation tillage under irrigation systems, move farmers to return to intensive tillage and high N fertilization rates. The results of this study have shown that conservation tillage must be maintained after the transformation into irrigation. In this context, the use of NT and RT in combination to medium N rates (i.e. 200 kg N ha^{-1}) led to greater WUE, which was sufficient to produce optimal grain yield while also achieving relatively high NUE. Adverse soil structural conditions under long-term CT led to lower available soil water, leading to crop water stress, causing lower maize yields and therefore reducing water and nitrogen use efficiency. Moreover, the application of N fertilizer under CT led to the accumulation of residual nitrate in the soil over time. The traditional application of high N fertilizer rates did not bring improvements in grain yield, WUE and NUE compared to medium rates. The use of less aggressive tillage practices, such as no-tillage and strip-tillage, as well as the reduction of N fertilization, could be viable options to stabilize or, even, increase crop yields and optimize NUE and water use simultaneously, saving production costs in comparison with the traditional management based on conventional tillage with high rates of mineral N.

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References

Al-Kaisi, M.M., Yin, X., 2003. Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency. Agron. J. 95, 1475–1482.

Alletto, L., Coquet, Y., Justes, E., 2011. Effects of tillage and fallow period management on soil physical behavior and maize development. Agric. Water Manag. 102, 74–85.

Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manag. 21, 38-52.

Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Paustian, K., Denef, K., Stewart, C.E., Arrúe, J.L., 2009. Soil aggregation and soil organic carbon stabilization: effects of management in semiarid Mediterranean agroecosystems. Soil Sci. Soc. Am. J. 73, 1519–1529.

Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization-Effects on N dynamics and barley yield under semiarid Mediterranean conditions. Soil Tillage Res. 87, 59-71.

Baker, C.J., Saxton, K.E., Ritchie, W.R., 1996. No-tillage Seeding. CAB International, Wallingford, UK, pp. 258.

Barbieri, P.A., Echeverria, H.E., Sainz Rozas, H.R., Andrade, F.H. 2008. Nitrogen use efficiency in maize as affected by nitrogen availability and row spacing. Agron. J. 100, 1094–1100.

Berenguer, P., Santiveri, P., Boixadera, J., Lloveras, J., 2009. Nitrogen fertilization of irrigated maize under Mediterranean conditions. Eur. J. Agron. 30, 163–171.

Bowman, W.D., Cleveland, C. C., Halada, L., Hresko, J., Baron, J.S., 2008. Negative impact of nitrogen deposition on soil buffering capacity. Nature Geoscience. 1, 767–770.

Cantero-Martínez, C., Angás, P., Lampurlanés, J., 2007. Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Ann. Appl. Biol. 150, 293–305.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Am J. Hum. Biol. 31, 132–140.

Cox, W.J., Kalonge, S., Cherney, D.J.R., Reid, W.S., 1993. Growth, yield, and quality of forage corn under different nitrogen management practices. Agron. J. 85, 341–347.

Cullum, R.F., 2012. Influence of tillage on maize yield in soil with shallow fragipan. Soil Tillage Res. 119, 1–6.

Dastane, N.G. 1978. Effective rainfall in irrigated agriculture. Irrigation and Drainage Paper 25. FAO, Rome.

Davidson, E.A., Suddick, E.C., Rice, C.W., Prokopy, L.S., 2015. More food, low pollution (Mo Fo Lo Po): A grand challenge for the 21st century. J. Environ. Qual. 44, 305–311.

Doran, J.W., 1980. Soil microbial and biochemical change associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765-771.

Fabrizzi, K.P., Garcia, F.O., Costa, J.L., Picone, L.I., 2005. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil Tillage Res. 81, 57-69.

Grassini, P.; Thorburn, J.; Burr, C.; Cassman, K.G. 2011. High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. Field Crops Research 120, 142-150.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods. SSSA Book, SSSA, Madison, Ser. 5, pp. 201–228.

Halvorson, A.D., Mosier, A.R., Reule, C.A., Bausch, W.C., 2006. Nitrogen and tillage effects on irrigated continuous corn yields. Agron J. 98, 63-71

Jones, D.B., 1941. Factors for converting percentages of nitrogen in foods and feeds into percentages of proteins. Circular No. 183. United States. Department of Agriculture. Washington, D.C.

Kitur, B.K., Smith, M.S., Blevins, R.L.,Frye, W.W., 1984. Fate of 15N-depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76, 240-242.

Lafond, G.P., 1994. Effects off row spacing, seeding rate and nitrogen on yield of barley and wheat under zero-till management. Can. J. Soil Sci. 74, 703–711.

Lamm, F.R., Aiken, R.M., Abou Kheira, A.A., 2009. Corn yield and water use characteristics as affected by tillage, plant density, and irrigation. Am. Soc. Agric. Biol. Eng. 52, 133-143.

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 Crops Res. 189, 59–67.

Martin, D.L., Watts, D.G., Mielke, L.N., Frank, K.D. Eisenhauer, D.E., 1982. Evaluation of nitrogen and irrigation management for corn production using water high in nitrate. Soil Sci. Soc. Am. J. 46, 1056–1062.

Martínez, E., Maresma, A., Biau, A., Cela, S., Berenguer, P., Santiveri, F., Michelena, A., Lloveras, J., 2017. Long-term effects of mineral nitrogen fertilizer on irrigated maize and soil properties. Agron J. 109, 1880–1890.

McConkey, B.G., Curtin, D., Campbell, C.A., Brandt, S.A., Selles, F., 2002. Crop and soil nitrogen status of tilled and no-tilled systems in semiarid regions of Saskatchewan. Can J Soil Sci. 82, 489–498.

Meijide, A., García-Torres, L., Arce, A., Vallejo, A., 2009. Nitrogen oxide emissions affected by organic fertilization in a non-irrigated Mediterranean barley field. Agric. Ecosyst. Environ. 132, 106–115

Morell, F.J., Lampurlanés, J., Álvaro-Fuentes, J., Cantero-Martínez, C., 2011. Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: long-term effects of tillage and N fertilization. Soil Tillage Res. 117, 76–84.

Panettieri, M., Knicker, H., Berns, A.E., Murillo, J.M., Madejón, E., 2013. Moldboard plowing effects on soil aggregation and soil organic matter quality assessed by 13C CPMAS NMR and biochemical analyses. Agric. Ecosys. Env. 177, 48–57.

Pareja-Sánchez, E., Plaza-Bonilla, D., Ramos, M.C., Lampurlanés, J., Álvaro-Fuentes, J., Cantero-Martínez, C., 2017. Long-term no-till as a means to maintain soil surface structure in an agroecosystem transformed into irrigation. Soil Tillage Res. 174, 221-230.

Parry, M.A.J., Flexas, J., Medrano, H., 2005. Prospects for crop production under drought: research priorities and future directions. Ann. Appl. Biol. 147, 211–226.

Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J.L., Lampurlanés, J., Álvaro-Fuentes, J., 2017. Do no-till and pig slurry application improve barley yield and water and nitrogen use efficiencies in rainfed Mediterranean conditions?. Field Crops Res. 203, 74–85.

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.

Quemada, M., Baranski, M., de Lange, M.N,J., Vallejo, A., Cooper, J.M., 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agric. Ecosyst. Environ. 174, 1-10.

Salem, H.M., Valero, C., Muñoz, M.A., Rodríguez, M.G., Silva, L.L., 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma. 237, 60-70.

Salinas-García, J.R., Velázquez-García, J.D.J., Gallardo-Valdez, M., Díaz-Mederos, P., Caballero-Hernández F., Vargas, L.M., Rosales-Robles E., 2002. Tillage effects on microbial biomass and nutrient distribution in soils under rain-fed corn production in central-western Mexico. Soil Tillage Res. 66, 143-152.

Samuelson, L.J., Stokes T.A., Coleman M.D., 2007. Influence of irrigation and fertilization on transpiration and hydraulic properties of Populus deltoides. Tree Physiology. 27, 765-774.

Sanz-Cobena, A., Sanchez-Martín, L., García, L., Vallejo, A., 2012. Gaseous emissions of N_2O and NO and NO_3 leaching from urea applied with urease and nitrification inhibitors to a maize (Zea mays) crop. Agric. Ecosyst. Environ. 149, 64–73.

SAS Institute Inc, 2015. Using JMP® 12. Cary. SAS Institute Inc., NC.

Sisquella, M., Lloveras, J., Santiveri, P., Alvaro, J., Cantero, C., 2004. Técnicas de cultivo para la producción de maíz, trigo y alfalfa en regadíos del valle del Ebro. (Cropping management techniques for maize, wheat, and alfalfa production in the irrigated areas of the Ebro valley). Proyecto Trama-Life. ISBN: 84-688-7860-X. Lleida, pp. 105. (in Spanish).

Sims, A.L., J.S. Schepers, R.A. Olson, and J.F. Power. 1998. Irrigated corn yield and nitrogen accumulation response in a comparison of no-till and conventional till: Tillage and surface-residue variables. Agron. J. 90, 630–637.

Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC, pp 306.

Tokatlidis, I.S.; Koutroubas, S.D., 2004. A review of maize hybrids’ dependence on high plant populations and its implications for crop yield stability. Field Crops Research. 88, 103-114.

Unger, P.W., Stewart, B.A., Parr, J.F., Shingh, R.P., 1991. Crop residue management and tillage methods for conserving soil and water in semi-arid regions. Soil Tillage Res. 20, 219–240.

Figure captions

Fig. 1 Monthly precipitation and irrigation (orange and turquoise columns, respectively) and daily air temperature (continuous line), during the experimental period (April 2015 to November 2017). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and periods between crops in winter (2015-2016 and 2016-2017).

Fig. 2 Maize grain yield and above-ground biomass as affected by N fertilization treatments (0, 200 and 400 kg N ha^{-1}) in three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. For each experiment, different lowercase letters indicate significant differences between N fertilization treatments for a given year at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 3 Maize grain yield, above-ground biomass, yield components (thousand kernels weight, TKW and plants populations) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. Different lowercase letters indicate significant differences between tillage treatments for a given year at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 4 Soil water content (SWC) (0–90 cm depth) dynamics as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) in a long-term field experiment (LTE) during three consecutive maize growing seasons (2015, 2016 and 2017). For a given date, different lowercase letters indicate significant differences between treatments at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 5 Maize water-use efficiency for yield (WUE_Y), above-ground N uptake (N uptake) and N use efficiency (NUE) as affected by tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rates (0, 200 and 400 kg N ha^{-1}) during three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term experiment (LTE). Different lowercase letters indicate significant differences between tillage for a given N fertilization treatments at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 6 Water-use efficiency for biomass (WUE_B) and yield (WUE_Y), above-ground N uptake, grain N content and N use efficiency (NUE) as affected N fertilization treatments (0, 200 and 400 kg N ha^{-1}). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. For each experiment, different lowercase letters indicate significant differences between N fertilization treatments for a given years at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 7 Nitrogen apparent recovery efficiency (NAR) as affected by tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rates (0, 200 and 400 kg N ha^{-1}) during three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term experiment (LTE). For a given year, different lowercase letters indicate significant differences between tillage and N fertilization treatments at $P < 0.05$. Vertical bars indicate standard deviation.

Table 1. Analysis of variance (*P*-values) of maize grain yield, above-ground biomass, plant population (plants m^{-2}), thousand kernels weight (TKW) and grain protein as affected by tillage, N fertilization, year and their interactions in a long-term (LTE) and a short-term (STE) field experiment.

Experiment	**Source of variation**	**Grain yield**	**Above-ground biomass**	**Plants m^{-2}**	**TKW**	**Grain protein**
LTE	**Tillage (Till)**	<0.001	<0.001	<0.001	ns	<0.001
	N fertilization (Fert)	<0.001	0.001	ns	<0.001	<0.001
	Year	<0.001	<0.001	<0.001	0.005	ns
	Till*Fert	<0.001	ns	ns	0.01	0.03
	Till*Year	0.01	ns	<0.001	0.003	ns
	Fert*Year	<0.001	0.03	ns	ns	ns
	Till*Year*Fert	ns	ns	ns	ns	ns
STE	**Tillage (Till)**	ns	ns	ns	ns	0.01
	N fertilization (Fert)	<0.001	0.003	ns	<0.001	<0.001
	Year	ns	<0.001	<0.001	ns	0.003
	Till*Fert	ns	ns	ns	0.03	ns
	Till*Year	ns	0.003	ns	ns	ns
	Fert*Year	0.004	0.002	ns	ns	ns
	Till*Year*Fert	ns	ns	ns	ns	ns

ns, non-significant

Table 2. Analysis of variance (*P*-values) of soil water content (SWC), soil nitrate content (SNC) (0-90 cm depth), maize water use (WU), water-use efficiency for above-ground biomass (WUE$_B$), water-use efficiency for yield (WUE$_Y$), above-ground N uptake (N uptake), grain N content, N use efficiency (NUE), N harvest index (NHI), N apparent recovery fraction (NAR) as affected by tillage, N fertilization, year or date (year/date) and their interactions in a long-term (LTE) and a short-term (STE) field experiment.

Experiment	**Source of variation**	**SWC**	**SNC**	**WU**	**WUE$_B$**	**WUE$_Y$**	**N uptake**	**Grain N content**	**NUE**	**NHI**	**NAR**
LTE	**Tillage (Till)**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001
	N fertilization (Fert)	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	<0.001
	Year/Date	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
	Till*Fert	<0.001	0.005	0.002	ns	0.001	<0.001	<0.001	<0.001	<0.001	ns
	Till*Year/Date	<0.001	0.001	<0.001	0.006	0.006	0.005	0.004	ns	ns	0.004
	Fert* Year/Date	0.007	0.004	ns	0.002	<0.001	<0.001	<0.001	0.01	0.003	ns
	Till* Year/Date *Fert	ns	ns	ns	ns	ns	ns	0.01	ns	0.003	0.03
STE	**Tillage (Till)**	0.002	ns	ns	ns	ns	ns	ns	ns	ns	ns
	N fertilization (Fert)	0.008	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001	ns	0.007
	Year/Date	<0.001	<0.001	<0.001	<0.001	ns	0.01	ns	<0.001	<0.001	<0.001
	Till*Fert	0.03	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Till* Year/Date	ns	ns	0.01	ns	ns	ns	ns	ns	ns	ns
	Fert* Year/Date	ns	<0.001	ns	0.003	0.002	0.04	0.008	<0.001	ns	ns
	Till* Year/Date *Fert	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns, non-significant

Fig. 1 Monthly precipitation and irrigation (orange and turquoise columns, respectively) and daily air temperature (continuous line), during the experimental period (April 2015 to November 2017). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) and periods between crops in winter (2015-2016 and 2016-2017).

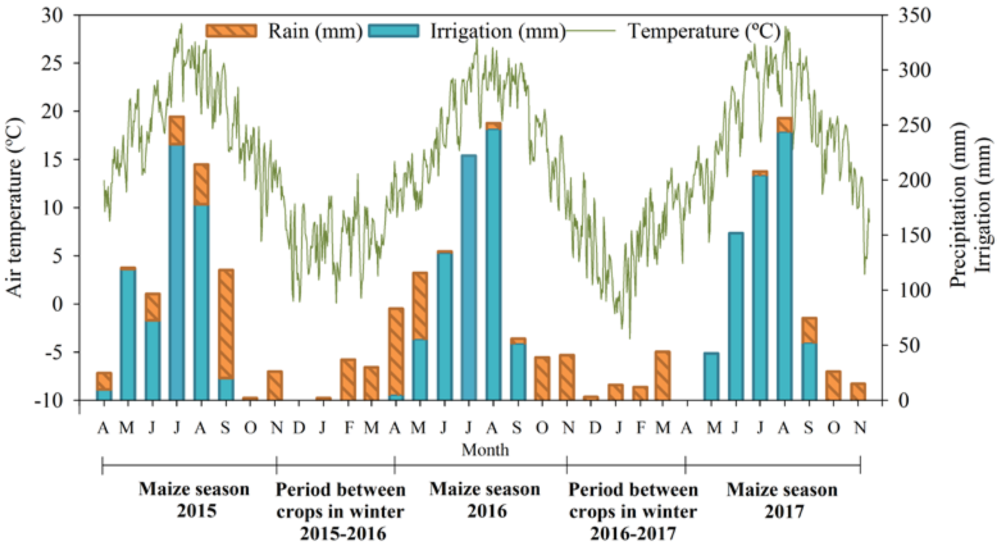

Fig. 2 Maize grain yield and above-ground biomass as affected by N fertilization treatments (0, 200 and 400 kg N ha^{-1}) in three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. For each experiment, different lowercase letters indicate significant differences between N fertilization treatments for a given year at *P*< 0.05. Vertical bars indicate standard deviation.

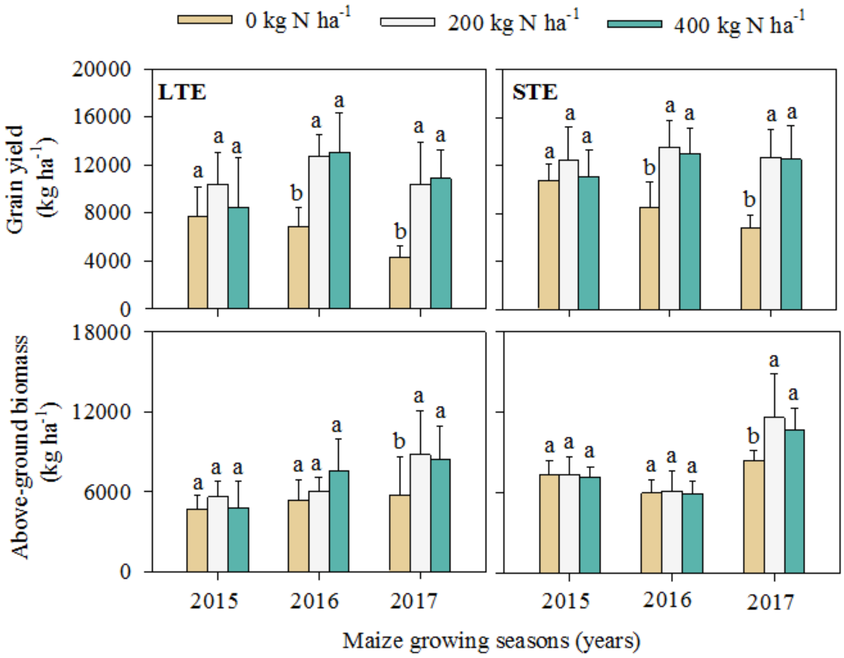

Fig. 3 Maize grain yield, above-ground biomass, yield components (thousand kernels weight, TKW and plants populations) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. Different lowercase letters indicate significant differences between tillage treatments for a given year at $P< 0.05$. Vertical bars indicate standard deviation.

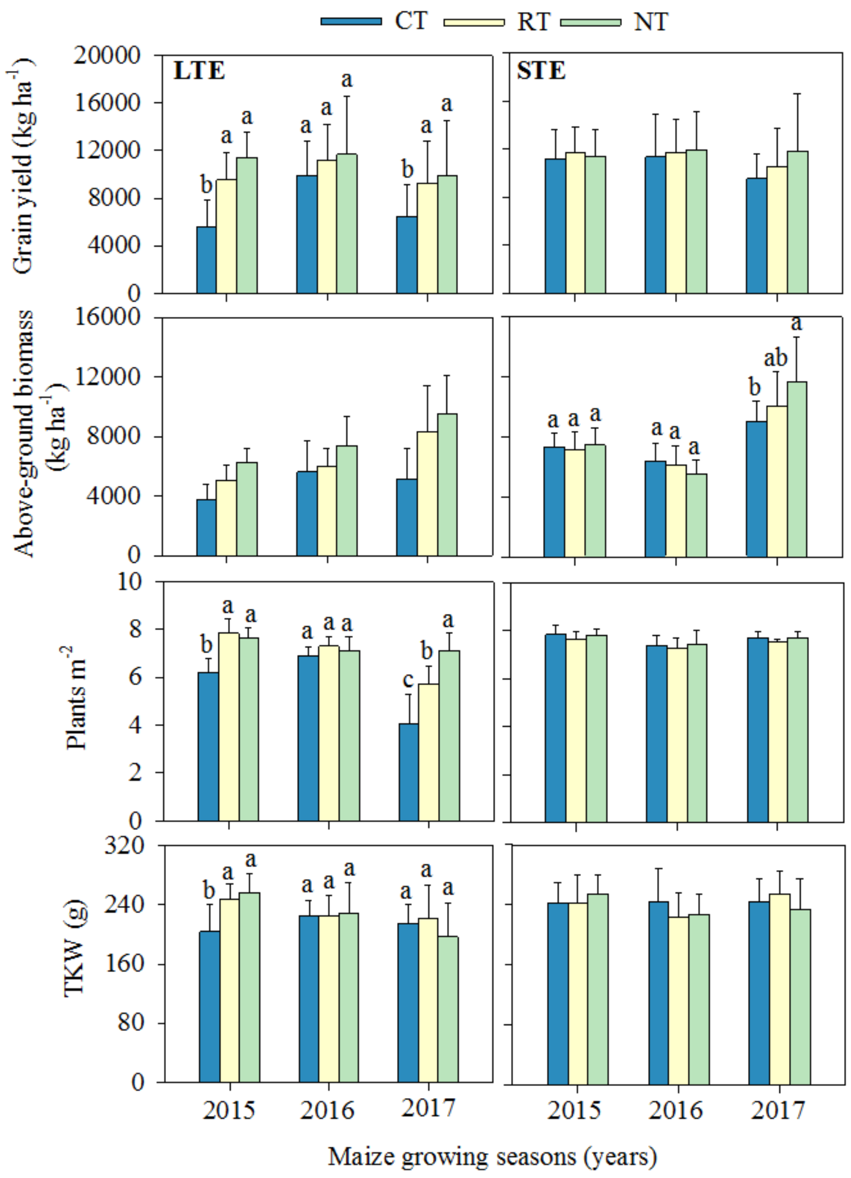

Fig. 4 Soil water content (SWC) (0–90 cm depth) dynamics as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) in a long-term field experiment (LTE) during three consecutive maize growing seasons (2015, 2016 and 2017). For a given date, different lowercase letters indicate significant differences between treatments at *P*< 0.05. Vertical bars indicate standard deviation.

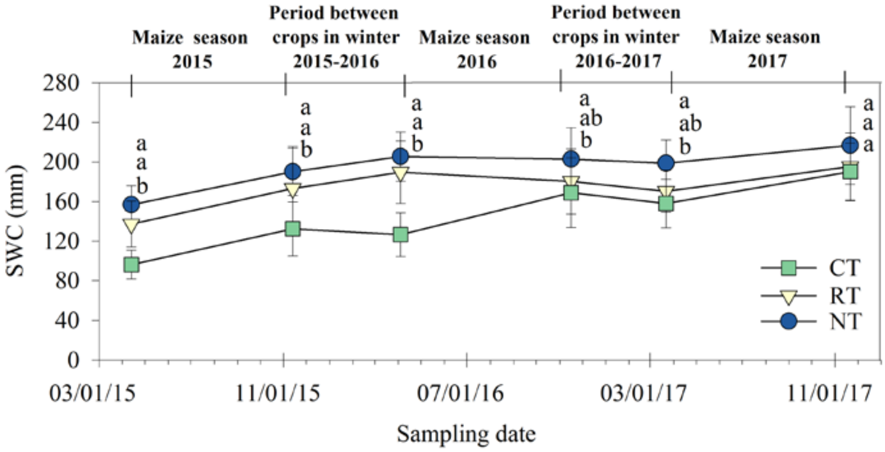

Fig. 5 Maize water-use efficiency for yield (WUE$_Y$), above-ground N uptake (N uptake) and N use efficiency (NUE) as affected by tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rates (0, 200 and 400 kg N ha^{-1}) during three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term experiment (LTE). Different lowercase letters indicate significant differences between tillage for a given N fertilization treatments at P< 0.05. Vertical bars indicate standard deviation.

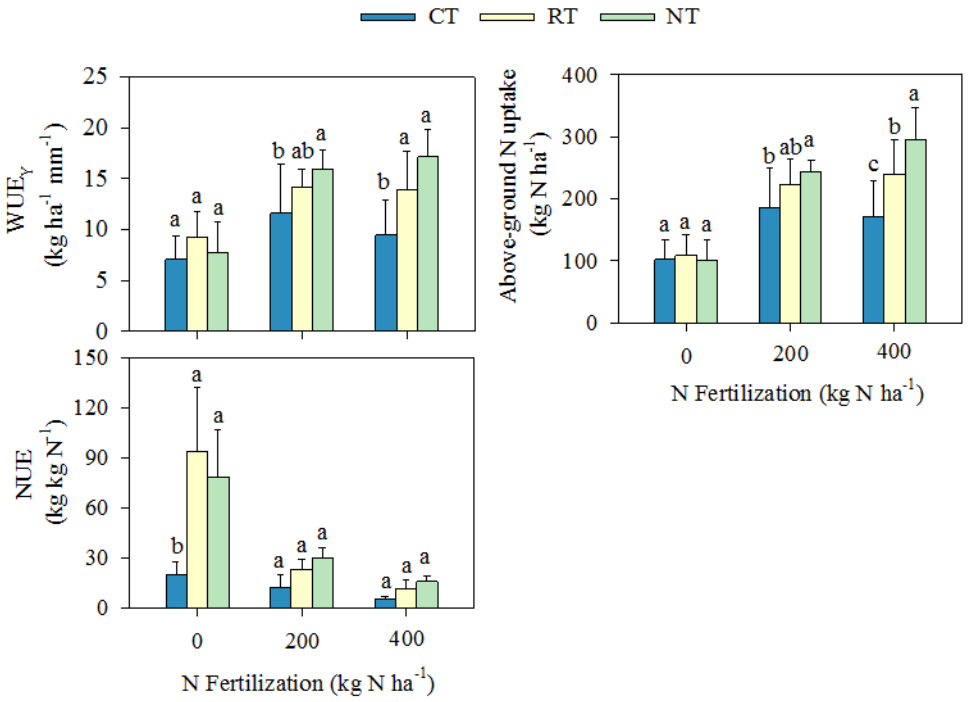

Fig. 6 Water-use efficiency for biomass (WUE_B) and yield (WUE_Y), above-ground N uptake, grain N content and N use efficiency (NUE) as affected N fertilization treatments (0, 200 and 400 kg N ha^{-1}). Values correspond to three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term (LTE) and a short-term (STE) field experiment. For each experiment, different lowercase letters indicate significant differences between N fertilization treatments for a given years at P< 0.05. Vertical bars indicate standard deviation.

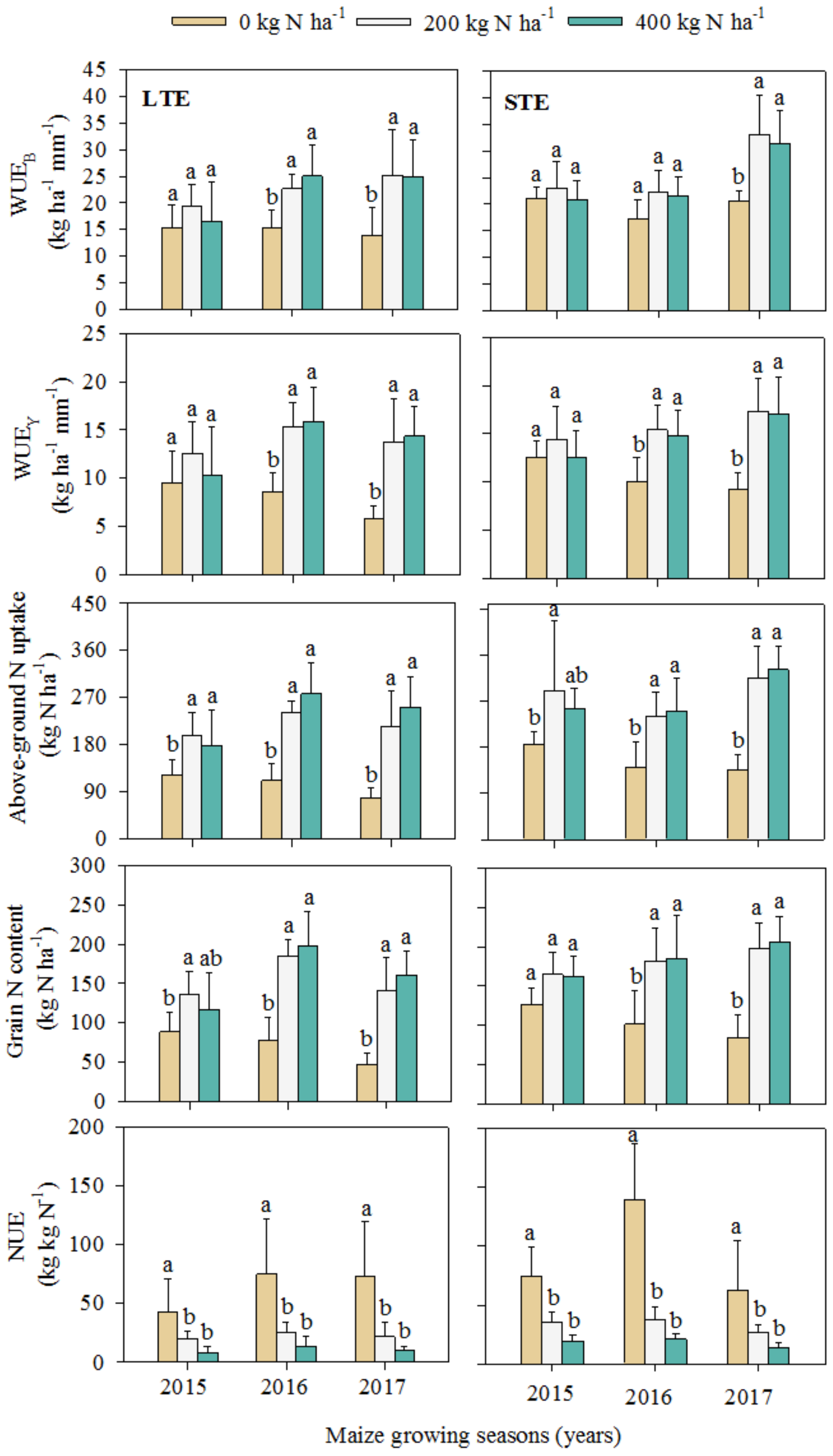

Fig. 7 Nitrogen apparent recovery efficiency (NAR) as affected by tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and N fertilization rates (0, 200 and 400 kg N ha^{-1}) during three consecutive maize growing seasons (2015, 2016 and 2017) in a long-term experiment (LTE). For a given year, different lowercase letters indicate significant differences between tillage and N fertilization treatments at $P < 0.05$. Vertical bars indicate standard deviation.