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4 **Do no-till and pig slurry application improve barley yield and water**
5 **and nitrogen use efficiencies in rainfed Mediterranean conditions?**
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10 Daniel Plaza-Bonilla^{a*}, Carlos Cantero-Martínez^b, Javier Bareche^b, Jose Luis Arrúe^a,
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12 Jorge Lampurlanés^c and Jorge Álvaro-Fuentes^a
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21 ^a *Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de*
22 *Investigaciones Científicas (CSIC), POB 13034, 50080 Zaragoza, Spain*
23
24

25 ^b *Departamento de Producción Vegetal y Ciencia Forestal, Unidad Asociada EEAD-CSIC,*
26 *Agrotecnio, Universidad de Lleida, Av. Rovira Roure, 191, 25198. Lleida, Spain*
27
28
29

30 ^c *Departamento de Ingeniería Agroforestal, Unidad Asociada EEAD-CSIC, Agrotecnio,*
31 *Universidad de Lleida, Av. Rovira Roure, 191, 25198. Lleida, Spain*
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48 * Corresponding author: Daniel Plaza-Bonilla (PhD).
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50 E-mail address: dplaza.bonilla@gmail.com
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Abstract

Tillage and N fertilization strategies including mineral and organic sources need to be studied in combination given their importance on the production cost that farmers face and their potential interaction on crop performance. A four-year (2010-2014) experiment based on barley monocropping was carried out in NE Spain in a typical rainfed Mediterranean area. Two tillage treatments (CT, conventional tillage; NT, no-tillage) and three rates of N fertilization (0; 75 kg N ha⁻¹, applied at top-dressing; 150 kg N ha⁻¹, applied at pre-sowing and at top-dressing at equal rate), with two types of fertilizers (ammonium-based mineral fertilizer and organic fertilizer with pig slurry), were compared in a randomized block design with three replications. Different soil (water and nitrate contents) and crop (above-ground biomass, grain yield, yield components and N concentration in biomass and grain) measurements were performed. Water- and nitrogen use efficiencies (WUE and NUE) as well as other N-related indexes (grain and above-ground biomass N uptake; NHI, nitrogen harvest index; NAR, apparent nitrogen recovery efficiency) were calculated. Barley above-ground biomass and grain yield were highly variable and depended on the rainfall received on each cropping season (ranging between 280 mm and 537 mm). Tillage and N fertilization treatments affected barley grain yields. No-tillage showed 1.0, 1.7 and 6.3 times greater grain yield than CT in three of the four cropping seasons as a result of the greater soil water storage until tillering. Water scarcity during the definition of the number of spikes per m² under CT would have compromised the compensation mechanism of the other two yield components. Pig slurry application led to the same (3 of 4 years) or higher (1 of 4 years) grain yield than an equivalent rate of mineral N fertilizer. Regardless the N origin, barley yield did not respond to the application of 150 kg N ha⁻¹ split between pre-sowing and top-dressing compared to the 75 kg N ha⁻¹ rate applied as top-dressing. A significant nitrate accumulation in the soil over the experimental period was observed under CT. Greater barley water use efficiency for yield (WUEy), N uptake and grain N content were found under NT than CT in three of the four cropping seasons studied. Moreover, for a given N rate, the use of organic fertilization increased significantly the WUEy as an average of CT and NT. When CT was used, a greater NHI was observed when using pig slurry compared with mineral N as an average of the four years studied. However, the use of different N fertilization treatments (rates or types) under CT or NT did not increase the NUE compared with the control. Our study demonstrates that the use of NT and the application of agronomic rates of N as pig slurry leads to greater

barley yield and water- and nitrogen-use efficiencies than the traditional management based on CT and mineral N fertilization.

Abbreviations

CT, conventional tillage; HI, harvest index; NAR, apparent N recovery efficiency; NHI, nitrogen harvest index; NT, no-tillage; NUE, nitrogen use efficiency; WUE_b, water-use efficiency for biomass; WUE_y, water-use efficiency for yield.

1. Introduction

Rainfed Mediterranean cropping systems face a series of challenges related to different agronomic, environmental and socio-economic aspects. Crop productivity under Mediterranean conditions is highly dependent on the variable amount of precipitation received during the cropping season and the capacity of the soil to store water, leading to low yield potentials in many areas (Austin et al. 1998). Cropping intensity and crop diversification in the rainfed Mediterranean areas depends on the amount of water available. In the driest locations (i.e. < 350 mm of annual rainfall), the traditional cropping system is the winter cereal-fallow rotation. In wetter semiarid areas (i.e. 350-450 mm) cropping systems are mainly based on winter cereals, namely barley and wheat, usually grown in monoculture. Finally, under sub-humid conditions (i.e. > 450 mm and/or deeper soils) other crops such as grain legumes (e.g. vetch, peas, etc.) or canola are incorporated into the rotations.

Soil management and nitrogen (N) fertilization practices account for a great proportion of the production costs that farmers face (Cantero-Martínez et al. 1995) and have a wide margin for their improvement in semiarid areas such as the Mediterranean region (Carmona et al. 2015). Traditionally, soil management in the Mediterranean has been based on conventional tillage (CT) with soil inversion (i.e. based on moldboard plowing). Although inversion systems are still used in many areas, a significant proportion of farmers have turned to reduced tillage systems based on vertical implements (e.g. chisel-type plows) or less intensive inversion systems (e.g. disk plows). No-tillage (NT), which began to be experienced more than three decades ago, continues to be increasingly adopted, even though many farmers are still reluctant to make the switch (Cantero-Martínez and Gabiña, 2004; Kassam et al. 2012). However, different studies have shown the benefits of NT compared to CT in rainfed semiarid areas regarding different agronomic (e.g. higher and more stable yields, Hernanz and Sánchez-Girón, 1988; Mrabet, 2000), environmental (e.g. improving soil physical quality, Fernández-Ugalde et al. 2009) and economic aspects (e.g. Sánchez-Girón et al. 2004).

Low profitability of rainfed cropping systems drives the farmers towards the diversification of revenues. In the dryland Mediterranean systems of NE Spain that process has led to the establishment of intensive livestock production, mainly pig (*Sus scrofa*) farming (Clar and Pinilla, 2011; Yagüe and Quílez, 2013). Recent statistics

show that pig herd in NE Spain accounts for more than 13 million animals (MAGRAMA, 2013). The presence of that large swine production has led to a great availability of slurries that farmers spread on agricultural soils not always with the best synchronization with crop needs (Bosch-Serra et al. 2015). Furthermore, the need to empty the farm storage pits regularly and the costs of transporting large volumes of slurries with rather low N concentration per unit of volume have led to the contamination of groundwater with nitrates (Menció et al. 2016; Rebolledo et al. 2016). Traditionally, farmers of the area have tended to overdose the applications of N with mineral and/or organic fertilizers as a means to secure crop yields. This decision would be partly justified by the unpredictability of rainfall and water availability for the crops in rainfed Mediterranean areas. As a consequence, significant areas in NE Spain have been declared nitrate vulnerable zones according to the Nitrates Directive (91/676/EC) (European Union, 1991).

Previous works have evaluated the combined impact of tillage and mineral N fertilization on crop yields under rainfed Mediterranean conditions (López-Bellido et al. 1996; López-Bellido and López-Bellido, 2001; Angás et al. 2006; Lestingi et al. 2010; Cantero-Martínez et al. 2016; Seddaiu et al. 2016). Regarding to this point, Angás et al. (2006) stressed the need to reduce N applications due to their negative economic and environmental consequences independently of the type of tillage. In turn, Cantero-Martínez et al. (2016) pointed out the greater crop response to mineral N fertilizer under NT compared with CT. However, tillage x nitrogen fertilization experiments including the impact of organic fertilization are scanty since most have focused only on mineral N fertilizer.

Then, the aim of this experiment was to elucidate the impact of tillage and different sources and rates of nitrogen fertilization on cereal production and water and nitrogen use efficiencies under Mediterranean conditions. Our hypothesis was that the use of NT and medium rates of N fertilizer would led to greater productivities and resource use efficiencies.

2. Materials and Methods

2.1 Experimental site and treatments

A field experiment was established in 2010 in Senés de Alcubierre (NE Spain, 41° 54' 12'' N, 0° 30' 15'' W) in a rainfed area with a temperate continental Mediterranean climate. Soil and climatic characteristics of the site are shown in Table 1 and Fig. 1, respectively.

The experimental design consisted of the combination of two tillage practices (CT, conventional tillage; NT, no-tillage) and three N fertilization rates (0, 75 and 150 kg N ha⁻¹) based on two different types of fertilizer (mineral N and organic N with pig slurry) in a randomized block design with three replications. Since the 1970s soil management at the site was based on the use of a subsoiler and a chisel. Four years before the establishment of the experiment (i.e. 2006) soil management was switched to NT. The cropping system during the experiment consisted of a barley (*Hordeum vulgare* L., cv. Meseta) monoculture. The CT treatment consisted of one pass of disk plow (15 cm depth) followed by a cultivator. However, due to the dry conditions of soil in 2011 two passes of chisel were used. A non-selective herbicide (1.5 L 36% glyphosate per hectare) was applied before sowing in the NT treatment. Sowing was carried out with a no-till seeder equipped with disk type furrow openers set to 2-4 cm depth. The combination of fertilizer types and N rates led to five fertilization treatments: 0, control, 75 Min and 75 Org, 75 kg N ha⁻¹ with mineral and organic N at the beginning of tillering, respectively, and 150 Min and 150 Org, 150 kg N ha⁻¹ with mineral and organic N applied at equal rates before sowing and at the beginning of tillering. For the mineral N treatments ammonium sulphate (21% N) and ammonium nitrate (33.5% N) were used before sowing and at the beginning of tillering, respectively. Mineral N applications were performed manually. The organic fertilization treatment consisted on the application of slurry from fattening pigs of a commercial farm close to the site. The application was carried out spreading the slurry with a commercial vacuum tanker fitted with a splashplate (Beguer mod. 12500, Barbastro, Spain) as it is common in the area. Previously to each application pig slurry was analyzed for its N content and the tanker was calibrated accordingly to apply the precise N rate. Composition of the pig slurry applied in the organic fertilization treatments is shown in Table 2. Harvest of the plots was carried out with a commercial medium-sized combine which chopped and spread over the soil surface the crop residues. Plot size was 40 m x 12 m in the organic

fertilization treatments and 40 m x 6 m in the mineral N fertilization and control treatments. Daily air temperature and rainfall data were recorded with the use of an automated weather station located in the site and equipped with a datalogger. This study focuses on the first four cropping seasons after the establishment of the experiment (2010-2011, 2011-2012, 2012-2013 and 2013-2014).

2.2 Soil and crop samplings and analyses

Within each plot, two sampling areas were defined. In each season, soil water and nitrate contents for the entire profile were quantified at two depth intervals (0-30 and 30-60 cm depth) at four stages: before sowing (i.e. mid-October), at the barley tillering stage (i.e. end of January-beginning of February), at anthesis, and after harvest (i.e. mid-June to beginning of July). A composite sample of a minimum of 3-4 subsamples per sampling area and depth was obtained. Once in the laboratory, water and nitrate contents were determined. Gravimetric water content was quantified by drying the samples at 50° C during 48 h to avoid the dehydration of the significant content of gypsum in the soil of the experiment (Porta, 1988). Soil nitrate was determined by extracting 50 g of fresh soil with 100 mL of 1M KCl. Soil ammonium was considered negligible, given the high oxidative conditions of this dryland area, where NH_4^+ concentrations are usually very low (i.e. < 2% of total soil mineral N) (Angás et al. 2006). The extracts were analyzed by hydrazine reduction with the use of a continuous flow analyzer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). Concentration values were transformed to mass-based values using soil bulk densities determined by the soil core method (Grossman and Reinsch, 2002).

Right before grain harvest a biomass sampling was carried out by cutting a variable number of plants at the soil surface level along 0.5 m of the seeding line at three locations per plot. Once in the laboratory, ears were separated from the rest of the above-ground biomass of the plant. Both fractions were oven-dried at 65 °C during 48 h. Afterwards, the ears were counted, threshed and the grain counted and weighed. The rest of above-ground biomass (i.e. leaves and stems) was also weighed. These determinations allowed calculating the total above-ground biomass and the harvest index (HI) as well as barley yield components: number of spikes per square meter, number of grains per spike and thousand kernels weight (TKW). Grain yield was quantified by harvesting each plot with a commercial combine and weighing the grain.

Yield values are reported at a grain moisture content of 10%. Nitrogen concentration of the grain and of the rest of above-ground biomass (i.e. stems and leaves) was determined by dry combustion (Dumas method) with a LECO-2000 analyzer (LECO, St Joseph, MI, US). Then, N content of the grain and the rest of the plant was calculated by multiplying the biomass of each fraction by its N concentration. Total N uptake was calculated by the sum of N content in both fractions. Barley grain protein concentration was calculated by multiplying the grain N concentration by 5.83 (Merrill and Watt, 1973).

2.3 Calculations and data analysis

2.3.1 Water and nitrogen-related indicators

Water-use efficiency for above-ground biomass (WUE_b) and yield (WUE_y) was calculated as follows:

$$WUE_b = \frac{\text{Aboveground biomass}}{WU}$$

$$WUE_y = \frac{\text{Grain yield}}{WU}$$

where WU is the water use calculated as the difference in soil water content (SWC) between sowing and harvest plus the rainfall received between both dates. In this simplified water balance runoff and deep drainage were considered negligible due to the (i) low slope gradient of the site (<1%) and the (ii) highly unusual rainfall conditions for leaching of the area, which occurs once every 7-10 years (Angás et al. 2006).

For each fertilizer treatment the apparent N recovery efficiency (NAR) was calculated as:

$$NAR = \frac{N \text{ uptake} - N \text{ uptake}_{0N}}{N \text{ fertilizer}}$$

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

The N harvest index (NHI) was calculated as:

$$NHI = \frac{N \text{ grain}}{N \text{ uptake}}$$

where $N \text{ grain}$ is the content of N in barley grain and $N \text{ uptake}$ is the above-ground N uptake.

Soil nitrogen mineralization was estimated using data from the control treatment of each tillage system as:

$$\begin{aligned} \text{Soil N mineralization} &= \\ &= \sum_{i=n}^n \frac{(SMN_{i+1} - SMN_i) + N \text{ uptake}_{0N}}{\text{Number of days between consecutive sowings}} \times 365 \end{aligned}$$

where SMN_{i+1} and SMN_i is the soil mineral nitrogen content (0-60 cm depth) at sowing of year $i+1$ and i , respectively.

Barley nitrogen use efficiency (NUE) was calculated as:

$$NUE = \frac{\text{Grain yield}}{N \text{ use}}$$

where $N \text{ use}$ is the sum of the amount of mineral N (0-60 cm depth) available at sowing, the N fertilizer applied and the N mineralized.

2.3.2 Data analysis

Data were checked for normality by plotting a normal quantile plot. Log-transformation was used to normalize soil nitrate and NUE data. Analyses of variance were performed for SWC, soil nitrate, above-ground biomass, yield and yield components with tillage, N fertilization, year or sampling date and their interaction as sources of variation. When significant, differences among treatments were identified at

0.05 probability level of significance using a Tukey HSD test. Least squares linear regression was used to evaluate relationships between grain yield and yield components and between grain yield and grain protein concentration. The slopes of the regressions were tested for differences between tillage and N fertilization treatments. Entire data analysis was performed with the JMP 12 statistical package (SAS institute, Inc, 2015).

3. Results

3.1 Weather characteristics of the study period

During the experiment duration, air temperature showed the typical Mediterranean pattern of cold winters (7 °C) and hot summers (23 °C) with intermediate values during spring (16 °C) and autumn (11 °C) (Fig. 1). All the cropping seasons showed similar temperatures except the spring of 2012-2013 which presented lower values than the spring of the other three cropping seasons (14 °C vs 16 °C). In the different seasons most of the rain occurred during the autumn and spring months as it is common in the Mediterranean climate. However, rainfall was highly variable between cropping seasons. Total July to June rainfall ranged between 280 mm and 537 mm (Fig. 1). Growing season (i.e. sowing to harvest) precipitation was 243 mm, 219 mm, 336 mm and 278 mm for the 2010-2011, 2011-2012, 2012-2013 and 2013-2014 seasons, respectively. The 2010-2011 cropping season presented a great peak in rainfall in March during the stem elongation of the crop. The 2011-2012 cropping season was characterized by a long drought which affected the entire autumn soil water recharge period. Contrarily, the 2012-2013 cropping season was characterized by a much greater annual rainfall (i.e. 537 mm), which represents receiving about 60% more rainfall than the average. However, the rainfall was not well distributed throughout the growing season, since most of it (i.e. 212 mm) occurred in October, with 108 mm registered in a single event (i.e. on October 20, 2012). Finally, the 2013-2014 cropping season showed the closest distribution of rainfall to the 30-yr average, with autumn and spring periods slightly wetter than the historical average for the site.

3.2 Tillage and N fertilization treatment effects on soil water and nitrate content dynamics

The use of different tillage systems led to significant differences in SWC and soil nitrate content dynamics, as shown by the tillage x sampling date interaction in Table 3. Soil water content dynamics followed a similar pattern in the 2010-2011, 2012-2013 and 2013-2014 cropping seasons, with a soil water recharge during the autumn-winter period and a soil water depletion during the period of greater water consumption by the crop (i.e. from start of February to end of May) (Fig. 2A). In contrast, the 2011-2012 season showed low SWC values in the four sampling dates. The NT treatment presented greater SWC at tillering in the last three out of the four cropping seasons

studied, with 36, 45 and 37 mm of water more than CT in 2011-2012, 2012-2013 and 2013-2014, respectively (Fig. 2A). Similarly, greater SWC was also found under NT compared with CT before sowing in 2012-2013 and after harvest in 2013-2014.

Soil nitrate content (0-60 cm depth) ranged between 43 and 547 kg N ha⁻¹ under CT and between 49 and 202 kg N ha⁻¹ under NT (Fig. 2b). A significant nitrate accumulation in the soil over the study period was observed under CT. Contrarily, the NT treatment showed similar values during the entire duration of the experiment. Despite the expected differences in magnitude, the high variability found in soil nitrate content values only led to significant differences between tillage systems in four sampling dates, with CT showing greater values than NT in all the cases (Fig. 2b). Significant differences on soil nitrate content were also found between N fertilization treatments and the interaction between N fertilization and tillage systems (Table 3). The use of increasing rates of mineral fertilizer under CT led to greater soil nitrate content as an average of the different sampling dates covered by the experiment (i.e. 168, 215 and 433 kg N ha⁻¹ for the 0, 75 Min and 150 Min treatments, respectively). Contrarily, the application of pig slurry under CT or NT did not led to significant differences with the control treatment, as an average of the different sampling dates (Table 3).

3.3 Tillage and N fertilization treatment effects on barley grain yield, biomass, yield components and grain protein concentration

Barley grain yield was significantly affected by tillage and N fertilization and by their interaction with the year (Table 4). Significant differences between CT and NT occurred in 2010-2011, 2012-2013 and 2013-2014, with NT showing 1.0, 1.7 and 6.3 times greater yield than CT, respectively (Fig. 3). In 2012-2013 and 2013-2014 significant differences between N fertilization treatments were found. In 2012-2013 the organic N treatments led to the greater yields than the mineral N and control treatments. In 2013-2014, no significant differences were found between N fertilization types for a given N rate. (Fig. 3)

Barley above-ground biomass was significantly affected by tillage and nitrogen and their interaction, by year and by the interaction between tillage and year (Table 4). Greater above-ground biomass was observed under NT than CT in the 2010-2011, 2012-2013 and 2013-2014 seasons (Fig. 3). No response to the application of fertilizer on barley above-ground biomass was observed when CT was used. Differently, the

1 application of 150 kg organic N ha⁻¹ under NT led to greater above-ground biomass
2 production than the control as an average of the four cropping seasons studied (Table 4).

3 Of the three yield components studied (spikes m⁻², grains spike⁻¹ and TKW),
4 only TKW was affected significantly by the interaction between tillage and N
5 fertilization (Table 4). When using CT, the 150 Org treatment showed greater TKW
6 than the control (Table 4), with 35 g and 27 g, respectively, as an average of the four
7 cropping seasons studied. The tillage x year interaction affected significantly the three
8 yield components studied (Table 4). Regarding to this point, greater number of spikes
9 m⁻², grains spike⁻¹ and TKW was observed under NT than CT in the 2013-2014 season
10 (Fig. 3). The N fertilization x year interaction only affected significantly the TKW
11 (Table 4 and Fig. 3) with greater values under the 150 Org treatments compared to the
12 mineral N and control treatments in the 2013-2014 cropping season. Furthermore, the
13 three yield components studied showed a significant linear relationship with barley
14 grain yield (Fig. 4). However, in the cases of number of grains per spike and TKW, the
15 slope of the relationship was significantly greater under NT than CT (Fig. 4b and Fig.
16 4c).

17 The interaction between tillage and N fertilization treatments led to significant
18 differences in barley HI (Table 4). When NT was used, no differences between N
19 fertilization treatments were observed in HI. Contrarily, when CT was used, the 150
20 Org treatment showed greater HI than the control and the 75 Min (0.44 vs. 0.31 and
21 0.30) and the 75 Org treatment showed greater HI than its counterpart with mineral N
22 (i.e. 75 Min) (0.40 vs. 0.30). The HI was also affected by the interaction of year with
23 tillage and N fertilization treatments (Table 4). As shown in Fig. 3, in the 2013-2014
24 season the use of NT led to greater HI than CT. Moreover, in the same season the use of
25 75 and 150 kg of organic N led to greater HI compared with the application of 75 kg
26 mineral N ha⁻¹.

27 The concentration of protein in the grain was significantly affected by tillage and
28 N fertilization simple effects on this variable, and by the interaction between tillage and
29 year of sampling (Table 4). In this regard, greater grain protein concentration was found
30 under CT compared with NT in the 2010-2011, 2012-2013 and 2013-2014 seasons (Fig.
31 3). As an average of the four cropping seasons studied, the application of mineral N at
32 75 and 150 kg N ha⁻¹ led to greater grain protein concentration compared with the use of
33 pig slurry at the same rate (Table 4). The concentration of protein decreased 1.4 units
34 per each Mg of increase in grain yield ($R^2 = 0.50$, $P < 0.001$).

3.4 Tillage and N fertilization treatment effects on barley water and nitrogen use efficiency indexes

Water use (WU) was similar between tillage systems with slight differences in 2010-2011 and 2012-2013 (Fig. 5). The analysis of variance revealed significant effects of tillage, N fertilization treatments, year, tillage x year and nitrogen fertilization x year interactions on WUE_b and WUE_y (Table 5). NT showed larger WUE_b and WUE_y than CT in two and three cropping seasons, respectively (Fig. 5). The tillage x N fertilization interaction only affected significantly WUE_b with significant differences between N fertilization treatments under NT. Regarding N fertilization, the use of 150 kg mineral N ha^{-1} and the two rates of pig slurry (75 Org and 150 Org) led to greater WUE_y than the control treatment. Moreover, for a given N rate, the use of organic fertilization increased significantly the WUE_y of barley (Table 5).

Barley above-ground N uptake and grain N content were significantly affected by tillage, N fertilization, year and the interaction between tillage and year. Barley grain N content was also affected by the interaction between N fertilization and year (Table 5). Greater above-ground N uptake and grain N content was observed under NT than CT in 2010-2011, 2012-2013 and 2013-2014, with a mean 85% increase for the above-ground N uptake and 168% for the grain N content.

Soil N mineralization was estimated at 67 and 41 kg N $ha^{-1} yr^{-1}$ for the CT and NT treatments, respectively. The NHI and NUE were affected by tillage, N fertilization, year, and by the tillage x N fertilization and the tillage x year interactions (Table 5). Greater NHI and NUE were observed under NT than CT as an average of the four seasons studied (Table 5). When CT was used, for a given N rate (75 or 150 kg N ha^{-1}) greater NHI was observed when using pig slurry compared with mineral N as an average of the four years studied. With the exception of 150 Org under CT, the use of different N fertilization treatments did not increase the NUE compared with the control (Table 5). Under CT, the use of pig slurry at 150 kg N ha^{-1} led to greater NUE than the application of the same rate with mineral N. Finally, the apparent N recovery efficiency (NAR) was significantly affected by tillage and the interaction between tillage and N fertilization (Table 5). The use of NT led to a 62% increase in NAR, as an average of the four cropping seasons (Table 5).

4. Discussion

4.1 Tillage effects on barley production and water and nitrogen use efficiency

The results of our study showed an important reduction in the yield of barley when using CT under the harsh conditions of the experimental area, which is characterized by very low water availability for the crop. The positive response of barley to NT under the semiarid rainfed conditions of our experiment is of a greater magnitude than the upper threshold of crop yield response to NT reported in the recent meta-analysis of Pittelkow et al. (2015). Under dryland Mediterranean conditions, the use of NT leads to a greater soil water storage than CT during the water recharge period as observed in our experiment and elsewhere (Lampurlanés et al. 2016). The soil water recharge takes place between the previous crop harvest (i.e. July) and the tillering stage of the subsequent cropping season (i.e. February), being more accused during the beginning of autumn-to-tillering sub-period (i.e. October-January) (Cantero-Martínez et al. 2007). In the Mediterranean climate this period is characterized by low water needs by the crop (low ET_c) and major rainfall events (Turner and Asseng, 2005). Then, the greater availability of water under NT would explain the increase in crop above-ground biomass and grain yield under this treatment.

According to the results of the regressions tested between barley yield components and grain yield, it could be hypothesized that the great differences between tillage systems on the production of spikes m⁻² could have played a major role when defining the potential yield under each system. In this regard, Blum and Pnuel (1990) pointed out the major importance of the number of spikes when defining the potential yield of cereals in Mediterranean environments. The difference in the number of spikes m⁻² between tillage systems (i.e. 51% greater under NT than CT as an average of N fertilization treatments and years) would be related to the differences in the soil water recharge explained above which would have influenced the water available for the crop in relatively early growth stages affecting tiller survival. Tiller production may have a direct influence on all other following traits of cereal development (García del Moral et al. 2003). Despite the plasticity of winter cereals such as barley, the significantly lower number of spikes per surface unit found under CT would also have reduced the yield compensation capacity of the other two yield components. This explanation would be supported by the significantly lower slopes of the linear relationships between the

number of grains per spike and TKW and grain yield under CT compared with NT found in our experiment.

The water stored in the soil was used more efficiently to produce above-ground biomass and grain yield and allowed a more efficient use of N (NUE) under NT than CT. That aspect also compromised both the accumulation of N in the grain and the NHI. The same finding has been reported for a range of field crops in other semi-arid environments (e.g. Hansen et al. 2012). Then, the similar values of WU between tillage systems seem to indicate that more water is lost (i.e. not used for crop transpiration) under CT than NT. Given the high PET of the area, soil water evaporation appears to be the most plausible process explaining these losses. It has been reported that in semiarid areas a significant amount of soil water is lost during tillage operations (Moret et al. 2006; Schwartz et al. 2010). Moreover, the lack of crop residues covering the soil surface and the lower shading by barley leaves could have increased water loss by evaporation under CT as has been reported in other studies (e.g. Passioura, 2006; Unger et al. 1991).

In the calculations performed in our work we considered negligible water drainage below 0.6 m, similarly to that done by Angás et al. (2006) in a similar rainfed Mediterranean environment. This assumption has implications in the calculation of N efficiency indexes since N losses as leaching are assumed to be nil/negligible. According to the soil characteristics of the experiment and using the soil water characteristic estimates of Saxton and Rawls (2006), the SWC at field capacity was estimated to be 221 mm. This last value is well above to all the SWC measurements taken along the experiment, thus supporting the hypothesis of a nil water drainage. Moreover, the fine texture of the soil, with around 60% of silt and less than 10% of sand in the 0-30 and 30-60 cm depths would suggest that other water loss processes such as water ponding (and concomitant evaporation) could be more important than drainage in our conditions when high intensity storms occur.

Soil N mineralization was estimated at 67 and 41 kg N ha⁻¹ yr⁻¹ for CT and NT treatments, respectively. These results are in line with the 47 kg N ha⁻¹ yr⁻¹ reported by Cantero-Martínez et al. (2016) who used the CropSyst model to estimate N mineralization for the same area. Our results also showed a 62% improvement in NAR when using NT (0.42) compared with CT (0.26). Values under NT were in the low range of those reported from a long-term wheat experiment carried out under rainfed Mediterranean conditions in Australia by Dalal et al. (2011). Contrary results were

found on a wheat monocropping by López-Bellido and López-Bellido (2001) under Mediterranean conditions in southern Spain. This disagreement could be explained by the high values of rainfall received during their experimental period (ranging between 833 and 1009 mm) and the soil type of their experiment (deep Vertisol), which could have counteracted the relative importance of the soil water conservation effect under NT.

A lack of enough water for crop N uptake and further N remobilization during barley grain filling led to a significant accumulation of nitrates in the soil (0-60 cm) in the CT treatment over the whole experiment duration. Nitrate leaching risk in this rainfed area is rather low due to high evapotranspiration and low rainfall, although occasional rainfall events of great magnitude could lead to nitrate losses to groundwater (Angás et al. 2006; Salmerón et al. 2010). Then, the use of NT in these water-limited areas might represent an environmentally sound practice to limit the potential losses of nitrogen.

Interestingly, the yield reduction associated to the CT treatment was already observed in the first year of the experiment when the plots were established in a site that had been managed with NT the previous four years. Currently, there is a great interest to analyze the impact of occasional tillage (termed strategic tillage) on NT farming-systems, as a way to overcome some of the issues that could be posed by the use of NT. Dang et al. (2015) reviewed the impact of strategic tillage on crop yields, concluding that it was negligible in most of the studies analyzed, a finding different from our first year results. In our experiment, the loss of soil water associated with CT could have compromised the establishment of the crop under this treatment. However, the drivers for the adoption of strategic tillage use are broad and dependent on the specific conditions of each farm (e.g. herbicide resistance, soil compaction, etc.) (Kirkegaard et al. 2014).

4.2 Fertilization strategy effects on barley production and water and nitrogen use efficiency

Regardless the type of fertilizer used, barley yield did not respond to the application of 150 kg N ha⁻¹ split between pre-sowing and top-dressing compared to the 75 kg N ha⁻¹ rate entirely applied as top-dressing. Two interesting aspects can be inferred from that result. First, it indicates that the application of N fertilizer before

sowing is not a sound agronomic practice in semiarid rainfed Mediterranean systems, given the low N needs during the first stages of cereal growth (Garabet et al. 1998). Second, in line with results of other studies in the same region, it demonstrates that N application rates can be reduced to half of the rate traditionally used by farmers without yield losses (Cantero-Martínez et al. 1995; Cantero-Martínez et al. 2016).

The use of organic fertilizer as pig slurry did not decrease the yield of barley compared to the use of the same rate of N as mineral fertilizer. In the year with the greatest rainfall (2012-2013) barley production was higher when using pig slurry compared with mineral N. Furthermore, water use efficiency for yield (WUE_y) was also higher for pig slurry than for mineral N fertilizer at a given N rate and as an average of the four years analyzed. Pig slurries usually show slightly lower N availability than mineral N fertilizers as a result of their organic N content and due to soil immobilization processes that can affect the short-term release of mineral N (Morvan et al. 1997; Jensen et al. 2000; Sørensen and Amato, 2002). Then, a lower N availability when applying slurries would represent a useful mechanism to satisfy crop needs at a better synchrony in years with enough water available at late crop growth stages. However, other organic products with a lower proportion of readily available N than slurries, such as manures or composts, can affect the performance of the subsequent crop (Montemurro, 2009). As a consequence, to reach the same yield levels the application of solid organic fertilizers must be compensated by long-term carry-over effects and/or additional mineral N applications at key stages. In our experiment, the improvement in water and N use efficiency for yield (WUE_y and NUE) when using pig slurry could be explained by its diverse mineral composition (Maltas et al. 2013). Unfortunately, some farmers are reluctant to apply slurries as top-dressing adducing risk of leaf burn, which could be true in some situations such as overdosing these products under very dry conditions. However, our results do not point out any negative effect of slurry application on barley productivity when compared with the traditional application of mineral N at the tillering stage and regardless of the year.

4.3 Tillage and N fertilization interaction effects on barley production and water and nitrogen use efficiency

A significant interaction was found between tillage and N fertilization treatments on barley above-ground biomass and WUE_b . As explained above, the lack of enough

1 available water under CT would partly explain the lack of significant response to any N
2 fertilization treatment on above-ground biomass production and WUE_b compared with
3 the control. Another process explaining this finding would be the accumulation of
4 nitrate N in the soil under CT (i.e. for a given N fertilization treatment, soil nitrate levels
5 were always higher under CT than under NT) that would have restricted the response to
6 further N application. Similar findings have been reported by Morell et al. (2011) when
7 working in a slightly wetter area than our experimental site in the Ebro valley (NE
8 Spain). The last authors did not observe any response to the application of increasing
9 mineral N fertilizer rates even in a wet growing season (i.e. sowing to harvest
10 precipitation of 380 mm) where CT based on moldboard plow was used. In our
11 experiment, the application of 150 kg N ha⁻¹ with pig slurry under NT was the unique
12 treatment that showed greater above-ground biomass at harvest than the control, being
13 also significantly different from the application of 75 kg N ha⁻¹ of the same product.
14 However, that increase in above-ground biomass did not result in greater grain yield or
15 significant changes in the HI. That result would confirm the inadequacy of pre-sowing
16 N fertilizer applications. The presence of nitrogen when water is available at the first
17 crop stages often leads to an increase in vegetative growth at great expense of water
18 used by transpiration. That overuse of water could compromise water availability for the
19 crop at reproductive stages. It has been suggested that it is more efficient to partition
20 growth directly into ears and grain than retranslocating assimilates to the grain from
21 plant vegetative organs (Loss and Siddique, 1994).
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5. Conclusions

The greater accumulation of water in the soil during most of the experimental period led from the first year of the study to a significant crop yield response and greater water and N use efficiencies when using no-tillage (NT) compared with conventional tillage (CT). Contrarily, the lack of enough water available under CT reduced N uptake and led to a significant accumulation of nitrate in the soil, thus enhancing the potential losses of N to the environment. According to the results of the yield components, water scarcity during the first stages, when the number of spikes per unit of surface is defined, significantly compromised the potential yield under each tillage system, especially under CT. Our study confirmed the inadequacy of pre-sowing N applications under rainfed Mediterranean conditions regardless of the type of fertilizer and tillage system. Pig slurry application led to the same (3 of 4 years) or higher (1 of 4 years) production than an equivalent rate of mineral N fertilizer. The use of pig slurry also increased water use and nitrogen use efficiencies for yield on average for the four years analyzed. Our study demonstrates that in Mediterranean systems the use of NT and the application of agronomic rates of N as pig slurry leads to greater barley yield and water- and nitrogen-use efficiencies than the traditional management based on CT and mineral N fertilizers.

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Figure captions

Fig. 1 Monthly precipitation (bars) and air temperature (solid black line) at the experimental site: (A) historical (30-year) average and (B) 2010-2011, (C) 2011-2012, (D) 2012-2013 and (E) 2013-2014 cropping seasons. Total annual precipitation during the season is shown in italics. Note the break of the Y-axis in sub-figure D.

Fig. 2 Soil water content (A) and nitrate content (B) (0-60 cm depth) dynamics as affected by tillage (CT, conventional tillage; NT, no-tillage) during the cropping seasons studied (2010-2011, 2011-2012, 2012-2013 and 2013-2014). *Indicates significant differences between tillage treatments for a given date at $P < 0.05$. Grey bars indicate standard deviation.

Fig. 3 Barley grain yield, above-ground biomass, yield components (spikes m^{-2} , grains spike $^{-1}$, thousand kernels weight, TKW), harvest index (HI) and grain protein concentration as affected by tillage (CT, conventional tillage; NT, no-tillage) and N fertilization treatments (0, control; 75 Min and 150 Min, 75 kg N ha^{-1} and 150 kg N ha^{-1} with mineral N fertilizer; 75 Org and 150 Org, 75 kg N ha^{-1} and 150 kg N ha^{-1} with organic fertilizer based on pig slurry) in the 2010-2011, 2011-2012, 2012-2013 and 2013-2014 cropping seasons. *Indicates significant differences between tillage treatments for a given cropping season at $P < 0.05$. Different lower-case letters indicate significant differences between N fertilization treatments for a given cropping season at $P < 0.05$. Vertical bars indicate standard deviation.

Fig. 4 Barley water use (WU), water-use efficiency for biomass (WUE_b) and yield (WUE_y), N uptake, grain N content, nitrogen harvest index (NHI), nitrogen use efficiency (NUE) and apparent N recovery efficiency (NAR) as affected by tillage (CT, conventional tillage; NT, no-tillage) and N fertilization treatments (0, control; 75 Min and 150 Min, 75 kg N ha^{-1} and 150 kg N ha^{-1} with mineral N fertilizer; 75 Org and 150 Org, 75 kg N ha^{-1} and 150 kg N ha^{-1} with organic fertilizer based on pig slurry) in the 2010-2011, 2011-2012, 2012-2013 and 2013-2014 cropping seasons. *Indicates significant differences between tillage treatments for a given cropping season at $P < 0.05$. Different lower-case letters indicate significant differences between N fertilization

1 treatments for a given cropping season at $P < 0.05$. Vertical bars indicate standard
2 deviation.

3 **Fig. 5** Linear relationship between grain yield and spikes m^{-2} (a), grains spike $^{-1}$ (b) and
4 thousand kernel weight (TKW) (c) for the tillage treatments compared (CT,
5 conventional tillage, in black circles and continuous regression line; NT, no-tillage, in
6 white circles and short-dashed regression line). Data corresponds to the 2010-2011,
7 2011-2012, 2012-2013 and 2013-2014 cropping seasons. * and *** indicate significant
8 relationships at $P < 0.05$ and $P < 0.001$, respectively.
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Table 1 General and soil (0-30 cm) characteristics of the field site. Soil properties were measured at the beginning of the experiment (October 2010).

Site and soil characteristic	
Elevation (masl)	395
Annual precipitation (mm)	327
Mean annual air temperature (°C)	13.4
Annual PET (mm)	1197
Soil classification¶	Typic calcixerept
pH (H ₂ O, 1:2.5)	8.0
EC _{1.5} (dS m ⁻¹)	1.04
Organic C (g kg ⁻¹)	15.6
Organic N (g kg ⁻¹)	1.4
Particle size distribution (%)	
Sand (2000-50 µm)	6.2
Silt (50-2 µm)	63.3
Clay (< 2 µm)	30.5

PET, potential evapotranspiration.

¶ According to the USDA classification (Soil Survey Staff, 2014).

Table 2 Pig slurry composition used in the 75 Org and 150 Org treatments in the four cropping seasons studied (2010-2011, 2011-2012, 2012-2013 and 2013-2014).

Cropping season	Time of application	Pig slurry composition*				
		Dry matter	Kjeldahl N [†]	Ammonium N	P	K
2010-2011	Pre-sowing	45.0	34.2	44.5	18.7	22.6
	Top-dressing	94.0	23.6	33.0	19.3	18.2
2011-2012	Pre-sowing	19.0	29.8	104.9	16.9	77.4
	Top-dressing	19.5	34.2	15.5	17.1	81.5
2012-2013	Pre-sowing	56.0	24.2	36.4	16.8	27.9
	Top-dressing	138.0	23.6	42.5	18.7	26.5
2013-2014	Pre-sowing	54.4	23.7	36.4	22.5	29.6
	Top-dressing	40.5	25.6	65.7	18.6	54.0

* Dry matter is expressed in g kg⁻¹ fresh weight and the rest of variables in g kg⁻¹ dry weight.

[†] Values of the dry residue.

Table 3 Analysis of variance of soil water content (SWC) (mm) and soil nitrate content (kg NO₃⁻ -N ha⁻¹) (0-60 cm depth) as affected by tillage (CT, conventional tillage; NT no-tillage), fertilization treatment (0, control; 75 Min and 150 Min, mineral N at 75 and 150 kg N ha⁻¹; 75 Org and 150 Org, organic N with pig slurry at 75 and 150 kg N ha⁻¹) and sampling date and their interactions. Data between brackets correspond to standard deviation.

Treatments	SWC	Soil nitrate
CT	102 (24) b¶	261 (231) a
NT	119 (30) a	141 (130) b
0	108 (29)	146 (121) cd
75 Min	108 (29)	235 (223) b
150 Min	112 (29)	306 (279) a
75 Org	111 (29)	147 (138) d
150 Org	112 (26)	171 (120) bc
CT-0	98 (25) e	168 (120) cd
CT-75 Min	99 (25) e	215 (254) ab
CT-150 Min	111 (28) bcd	433 (323) a
CT-75 Org	102 (22) cde	198 (139) bc
CT-150 Org	100 (18) de	190 (130) bcd
NT-0	118 (30) ab	122 (118) ef
NT-75 Min	116 (30) ab	153 (150) def
NT-150 Min	113 (31) bc	180 (142) bc
NT-75 Org	120 (32) ab	95 (118) f
NT-150 Org	125 (28) a	152 (107) cde
<i>ANOVA (p-values)</i>		
Tillage (Till)	<0.001	<0.001
N fertilization (Fert)	0.086	<0.001
Sampling date (Date)	<0.001	<0.001
Till x Fert	<0.001	0.004
Till x Date	<0.001	<0.001
Fert x Date	0.982	0.970
Till x Fert x Date	0.999	0.988

¶ Different lower-case letters indicate significant differences between treatments at $P < 0.05$.

Table 4 Analysis of variance of barley grain yield, above-ground biomass, yield components (spikes m⁻², grains spike⁻¹ and thousand-kernel weight, TKW), harvest index (HI) and grain protein concentration as affected by tillage (CT, conventional tillage; NT no-tillage), fertilization treatment (0, control; 75 Min and 150 Min, mineral N at 75 and 150 kg N ha⁻¹; 75 Org and 150 Org, organic N with pig slurry at 75 and 150 kg N ha⁻¹) and year and their interactions. Data corresponds to the mean of 2010-2011, 2011-2012, 2012-2013 and 2013-2014 seasons. Values between brackets correspond to standard deviation.

Treatments	Grain yield [†] (kg ha ⁻¹ ; 10% moisture)	Above-ground biomass (Mg ha ⁻¹)	Spikes m ⁻²	Grains spike ⁻¹	TKW (g)	HI	Grain protein (g 100 g ⁻¹)
CT	1108 (953) b¶	4.5 (3.2) b	308 (208) b	14 (9) b	30 (15) b	0.36 (0.19) b	14.8 (2.7) a
NT	3126 (1520) a	8.2 (4.0) a	623 (243) a	17 (6) a	38 (8) a	0.47 (0.12) a	12.0 (2.8) b
0	1389 (1184) d	4.4 (3.2) c	363 (287)	13 (9) b	33 (16) ab	0.41 (0.21) ab	11.7 (2.6) d
75 Min	1818 (1522) cd	5.9 (3.8) bc	420 (268)	15 (10) ab	32 (15) b	0.38 (0.19) b	13.4 (3.0) ab
150 Min	1972 (1506) bc	6.8 (4.1) ab	477 (280)	17 (8) ab	32 (13) b	0.39 (0.17) ab	15.4 (2.7) a
75 Org	2528 (1862) ab	6.3 (3.8) b	477 (265)	16 (6) ab	37 (12) a	0.45 (0.15) a	12.5 (3.4) cd
150 Org	2879 (1657) a	8.2 (4.8) a	591 (248)	18 (6) a	36 (8) ab	0.39 (0.17) a	13.2 (2.6) bc
CT-0	506 (404)	3.1 (2.8) d	221 (191)	11 (9)	27 (19) cd	0.31 (0.24) de	13.4 (1.8)
CT-75 Min	751 (831)	3.5 (2.8) d	207 (174)	13 (13)	26 (17) d	0.30 (0.21) e	15.0 (2.3)
CT-150 Min	1009 (698)	5.1 (3.4) cd	314 (222)	14 (8)	29 (16) bcd	0.35 (0.20) cde	16.4 (2.8)
CT-75 Org	1303 (953)	5.2 (4.0) cd	356 (249)	15 (7)	33 (14) abc	0.40 (0.16) bcd	14.5 (2.8)
CT-150 Org	1972 (1128)	5.4 (2.7) cd	441 (126)	18 (6)	35 (9) ab	0.44 (0.10) abc	14.1 (2.8)
NT-0	2272 (1032)	5.8 (3.0) bcd	505 (304)	15 (9)	39 (8) a	0.51 (0.12) a	10.5 (2.4)
NT-75 Min	2886 (1291)	8.3 (3.0) ab	633 (143)	17 (5)	38 (9) a	0.46 (0.13) ab	12.3 (3.0)
NT-150 Min	2935 (1497)	8.5 (4.2) ab	641 (239)	20 (6)	34 (8) abc	0.44 (0.14) abc	14.3 (2.2)
NT-75 Org	3753 (1754)	7.5 (3.4) bc	597 (232)	16 (4)	41 (8) a	0.51 (0.11) ab	10.5 (2.7)
NT-150 Org	3786 (1641)	11.0 (4.9) a	740 (254)	19 (6)	37 (7) ab	0.44 (0.12) abc	12.4 (2.3)
<i>ANOVA (p-values)</i>							
Tillage (Till)	<0.001	<0.001	<0.001	0.035	<0.001	<0.001	<0.001
N fertilization (Fert)	<0.001	<0.001	0.061	0.016	0.003	0.005	<0.001
Year	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Till x Fert	0.190	0.027	0.492	0.462	0.001	<0.001	0.152
Till x Year	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fert x Year	<0.001	0.062	0.524	0.096	0.002	0.026	0.218
Till x Fert x Year	0.276	0.382	0.934	0.573	0.133	0.014	0.075

¶ Different lower-case letters indicate significant differences between treatments at $P < 0.05$.

† Grain yield was quantified with the use of a medium-sized combine.

Table 5 Analysis of variance of barley water use (WU), water-use efficiency for biomass (WUE_b) and yield (WUE_y), above-ground N uptake, grain N content, nitrogen harvest index (NHI), nitrogen use efficiency (NUE) and apparent N recovery efficiency (NAR) as affected by tillage (CT, conventional tillage; NT no-tillage), fertilization treatment (0, control; 75 Min and 150 Min, mineral N at 75 and 150 kg N ha⁻¹; 75 Org and 150 Org, organic N with pig slurry at 75 and 150 kg N ha⁻¹) and year and their interactions. Data corresponds to the mean of 2010-2011, 2011-2012, 2012-2013 and 2013-2014 seasons. Values between brackets correspond to standard deviation.

Treatments	WU (mm)	WUE _b (kg ha ⁻¹ mm ⁻¹)	WUE _y (kg ha ⁻¹ mm ⁻¹)	N uptake (kg N ha ⁻¹)	Grain N content (kg N ha ⁻¹)	NHI	NUE (kg kg N ⁻¹)	NAR
CT	333	13.0 (7.8) b¶	3.3 (2.6) b	61 (37) b	26 (20) b	0.41 (0.14) b	3.1 (2.6) b	0.26 (0.25) b
NT	328	25.7 (13.4) a	9.5 (3.7) a	104 (49) a	60 (25) a	0.58 (0.15) a	12.1 (7.2) a	0.42 (0.34) a
0	331	13.3 (8.8) c	4.4 (3.9) d	50 (29) c	25 (19) c	0.48 (0.18) b	8.7 (8.4) ab	-
75 Min	327	18.9 (14.0) b	5.5 (4.2) cd	82 (50) ab	37 (26) b	0.45 (0.19) b	6.6 (6.4) b	0.37 (0.39)
150 Min	332	20.4 (10.5) ab	5.8 (3.7) bc	99 (53) a	47 (31) b	0.45 (0.14) b	4.9 (4.1) b	0.33 (0.28)
75 Org	333	19.2 (11.4) b	7.5 (5.1) ab	71 (31) bc	46 (28) b	0.57 (0.20) a	9.8 (8.7) a	0.27 (0.33)
150 Org	328	24.6 (15.7) a	8.7 (4.4) a	107 (52) a	60 (27) a	0.54 (0.12) a	8.2 (5.1) a	0.38 (0.21)
CT-0	330	8.7 (6.1) e	6.1 (1.7)	38 (24)	12 (10)	0.36 (0.15) cd	2.6 (2.0) e	-
CT-75 Min	327	10.5 (8.1) e	8.1 (2.4)	54 (42)	18 (20)	0.31 (0.14) d	2.4 (2.5) e	0.21 (0.35) c
CT-150 Min	332	15.0 (7.4) de	7.4 (3.2)	77 (44)	27 (18)	0.38 (0.15) cd	2.1 (1.8) e	0.26 (0.24) bc
CT-75 Org	340	14.1 (7.2) e	7.2 (3.6)	59 (30)	29 (17)	0.42 (0.13) bc	3.5 (2.4) de	0.29 (0.26) bc
CT-150 Org	334	16.5 (8.7) de	8.7 (5.6)	78 (31)	44 (21)	0.53 (0.08) b	4.7 (3.3) cd	0.27 (0.11) bc
NT-0	331	17.8 (9.0) cde	9.0 (7.1)	63 (30)	39 (16)	0.57 (0.14) ab	14.8 (7.9) ab	-
NT-75 Min	327	27.4 (13.8) ab	13.8 (8.7)	111 (42)	56 (15)	0.54 (0.17) ab	10.8 (6.4) ab	0.56 (0.38) a
NT-150 Min	332	25.9 (10.6) bc	10.6 (8.4)	122 (53)	68 (27)	0.51 (0.09) b	7.7 (3.9) bc	0.40 (0.31) bc
NT-75 Org	326	24.3 (12.8) bcd	12.8 (11.3)	85 (28)	63 (26)	0.73 (0.11) a	16.0 (8.3) a	0.25 (0.41) bc
NT-150 Org	323	33.6 (17.1) a	17.1 (11.7)	136 (54)	75 (24)	0.55 (0.15) ab	11.6 (6.4) ab	0.49 (0.23) ab
<i>ANOVA (p-values)</i>								
Tillage (Till)	0.091	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
N fertilization (Fert)	0.741	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.261
Year	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.098
Till x Fert	0.297	0.019	0.065	0.087	0.237	<0.001	0.010	0.042
Till x Year	<0.001	<0.001	<0.001	0.047	<0.001	<0.001	<0.001	0.771
Fert x Year	0.875	0.006	0.076	0.283	0.001	0.144	0.384	0.318
Till x Fert x Year	0.199	0.335	0.084	0.338	0.088	0.193	0.464	0.087

¶ Different lower-case letters indicate significant differences between treatments at $P < 0.05$.

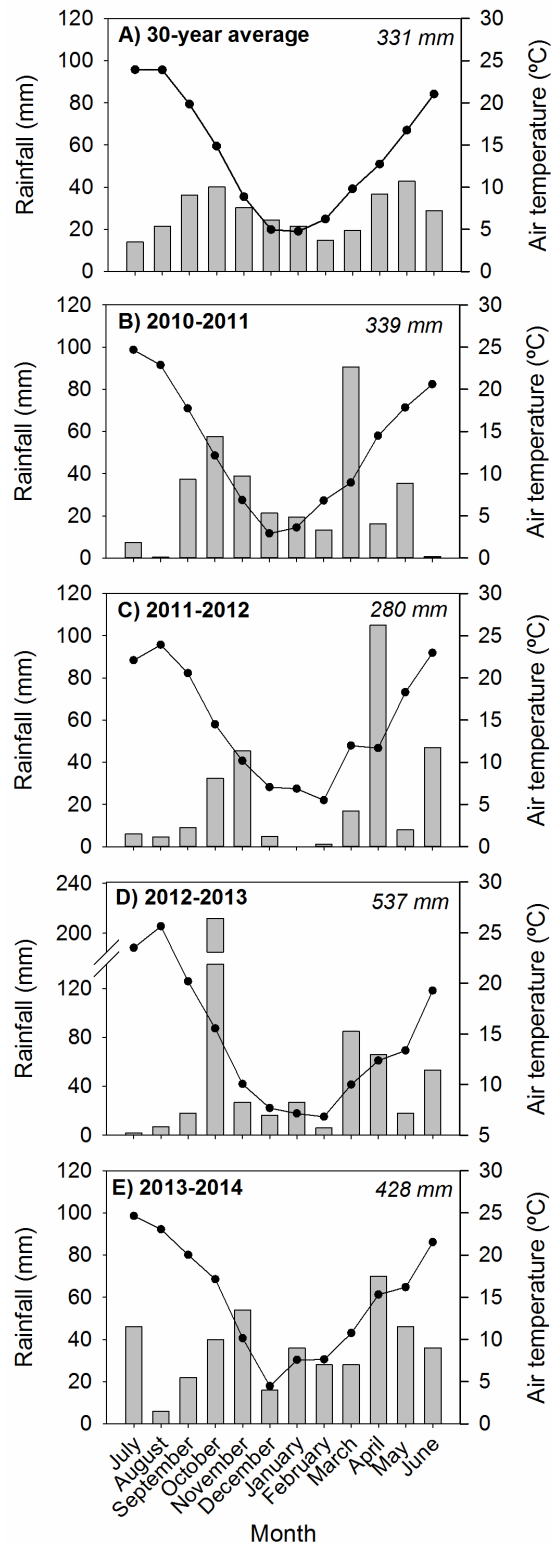


Fig. 1

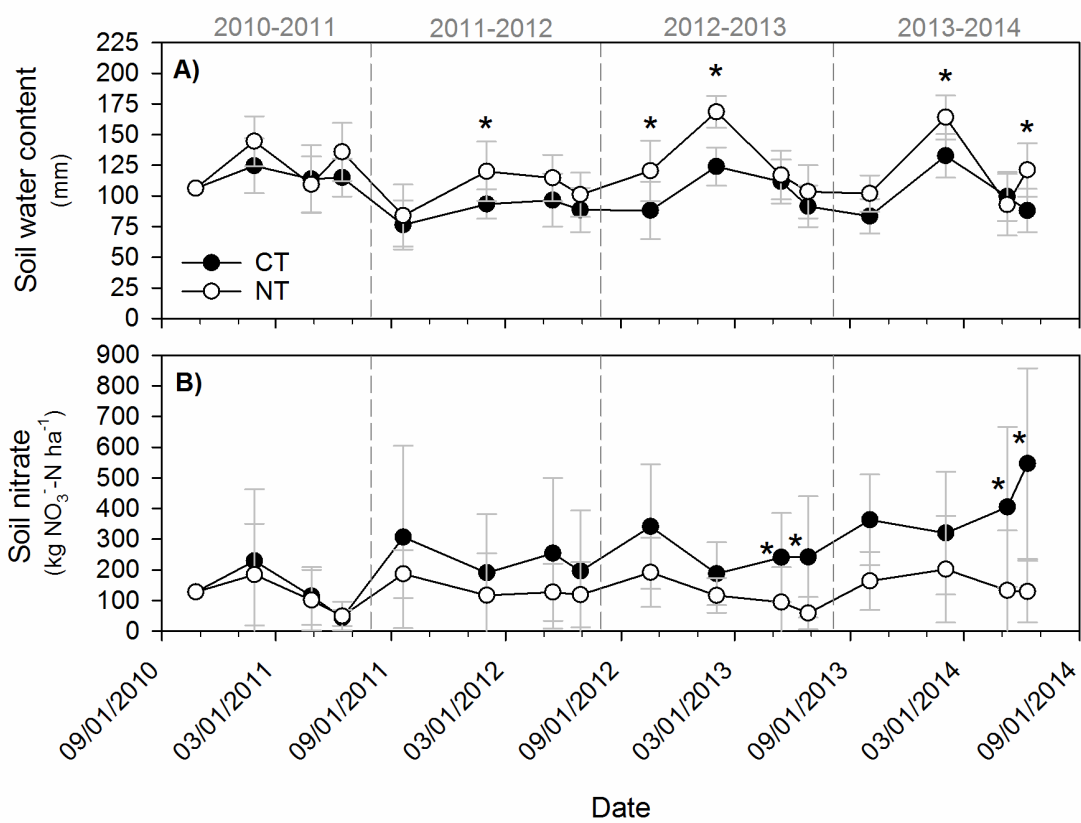


Fig. 2

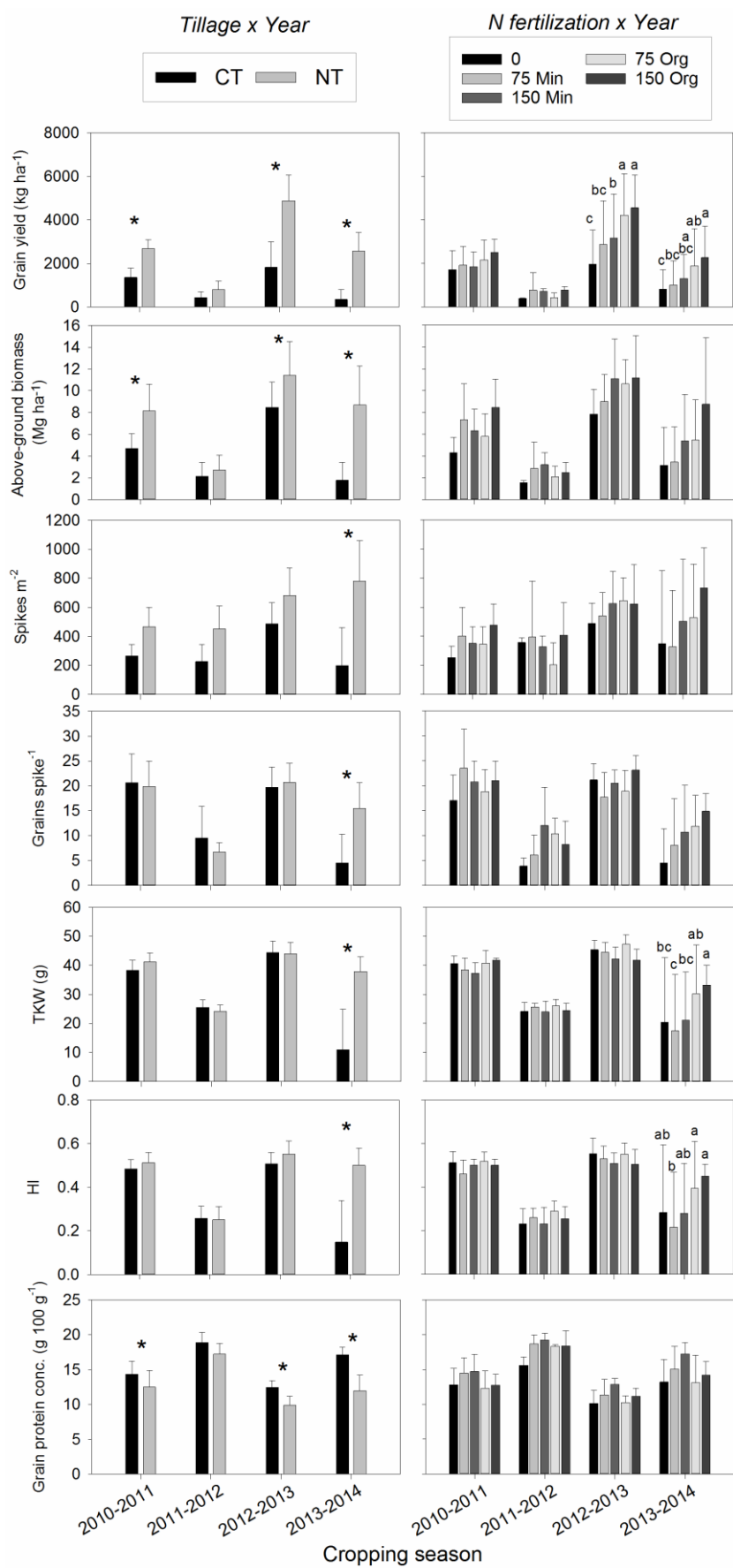


Fig. 3

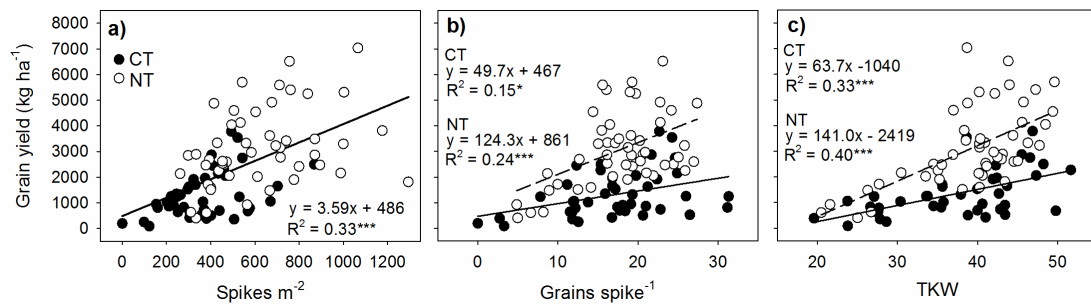


Fig. 4

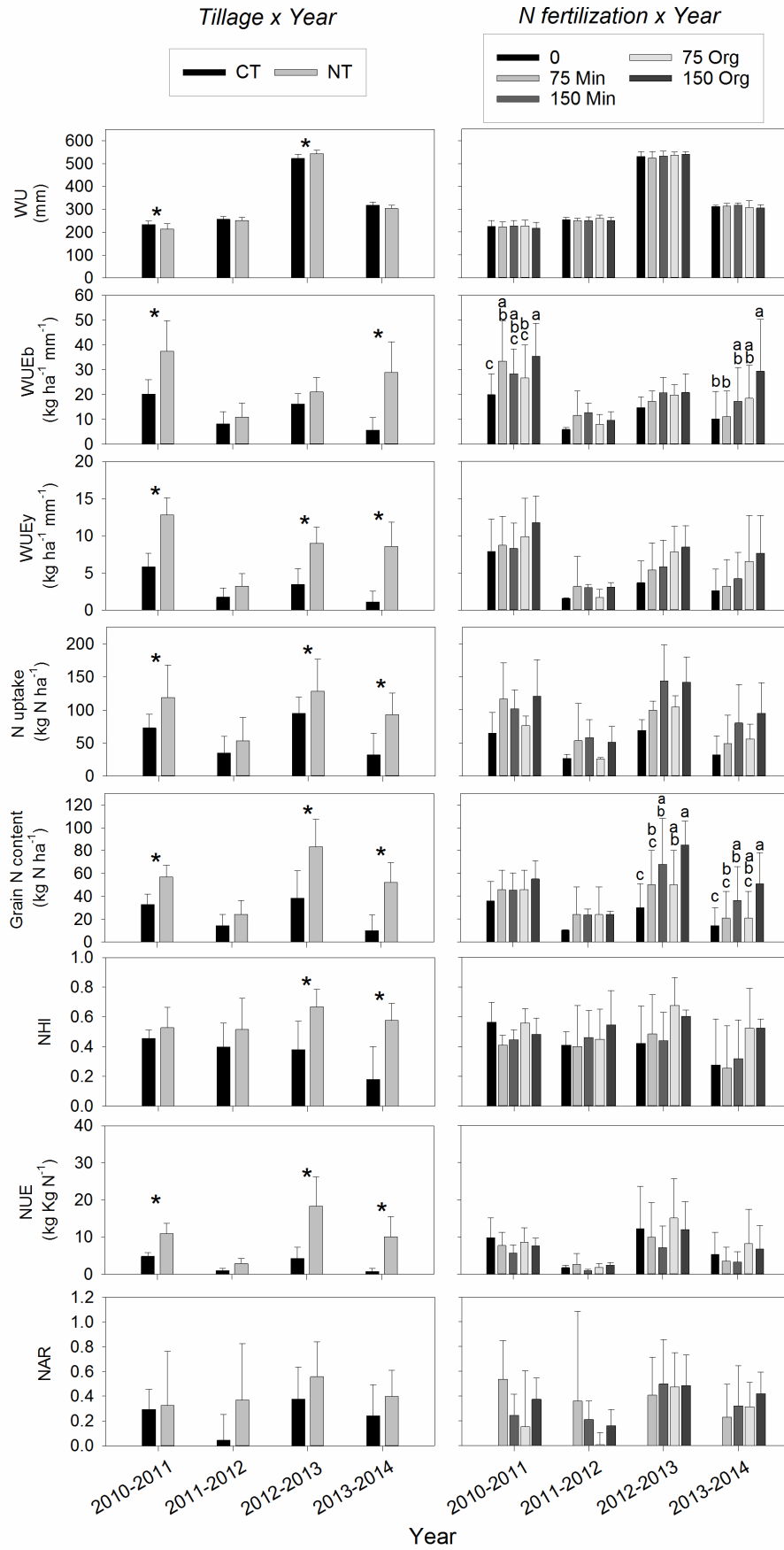


Fig. 5