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Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization

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Abstract

Conservation tillage systems (no-tillage, NT; and minimum tillage, MT) are being adopted in rainfed agroecosystems of the Mediterranean basin where water availability is the main limiting factor for crop productivity. We hypothesized that long-term adoption of conservation tillage systems would increase water use efficiency (WUE) and its response to N fertilizer additions due to improved soil water conservation.

A field experiment was established in 1996 on a loamy Xerofluvent Typic in the Ebro river valley (NE Spain). The experiment compared three nitrogen (N) fertilization levels (zero, 0 kg N ha⁻¹, medium, 60 kg N ha⁻¹, and high, 120 kg N ha⁻¹), under three tillage systems (CT, conventional tillage; MT and NT), annually cropped to barley (*Hordeum vulgare*, L.) as is usual in the region. Ten years after the experiment establishment, during four consecutive growing seasons, 2005-2006 to 2008-2009, we evaluated the response of soil water

content, soil nitrate, above-ground dry matter, grain yield and yield components to long-term (>10 years) tillage and N fertilization treatments.

The long-term sustainability of NT and MT was confirmed. Mean yield and WUE under long-term conservation tillage systems were 66% and 57% higher than under CT, respectively. This improvement was mainly attributed to improved soil water usage under conservation tillage, mainly due to reduced water use during the pre-anthesis period. However, in a wet year yield did not significantly differ among tillage systems. The improvement of WUE with N fertilization was confirmed under NT, which medium and high N fertilizer level increased 98% mean grain yield and 77% mean WUE compared to CT. The increased response of crop and yield to N fertilization under NT was due to improved soil water conservation and more available water for the crop. In this long-term experiment, CT accumulated higher amounts of mineral N on both unfertilized and fertilized plots because the lower yields and hence the lower N uptake compared to NT. Therefore, such soil N accumulation together with the lower water accumulation explained the lack of response to N fertilization under CT, even on a wet growing season (i.e., 2008-2009).

Long-term NT adoption was a sustainable practice for barley monoculture in the region, allowing for reduced costs and yield increase with N fertilizer additions. N fertilizer rates on rainfed Mediterranean croplands should be adjusted depending on the reduction of tillage intensity and rainfall of the year. In our system and as an example for this agroecosystems, N fertilizer rates should be kept at or below 60 kg N ha⁻¹, and should be further reduced on intensively cultivated soils.

Keywords: Dryland, winter cereal, soil mineral nitrogen, water productivity,
direct seeding, biomass.

Abbreviations

NT, no-tillage; MT, minimum tillage; CT, conventional tillage; ZN, zero nitrogen;
MN, medium level of N fertilization (60 kg N ha^{-1}); HN, high level of N
fertilization (120 kg N ha^{-1}); GWC, gravimetric water content; SWC, soil water
content; SN, soil nitrate N content; WU, water use; WU_{pre} , WU during pre-
anthesis period; WU_{post} , WU during post-anthesis period; WUE, water use
efficiency; WUE_{pre} , water use during pre-anthesis period; WUE_{post} , water use
during post-anthesis period; WUE_b , WUE of above-ground biomass production;
 WUE_y , of grain production.

1. Introduction

Dryland agriculture in the Mediterranean region is mostly water limited, and
yields vary markedly from year to year depending on the amount and
distribution of precipitation, which are both highly variable (Austin et al., 1998).
Water from precipitation must be captured and retained in soil and used
efficiently for optimum yield production. Adequate management practices, such
as conservation tillage and adequate N fertilization may increase water
productivity, and limit environmental problems as soil erosion and N losses.
Conservation tillage practices include reduced soil tillage systems, such as
minimum tillage (MT) and no-tillage (NT) systems, aimed at increasing the soil
cover with the crop residues from the previous crop (CTIC, 2010). Improved soil
surface cover usually improves water capture and retention (Unger et al., 1991).

NT is a promising practice for croplands on the Mediterranean basin, where it can improve water use efficiency (WUE) (Cooper and Gregory, 1987; Mrabet, 2000). NT and MT are mainly used for winter cereals, and the adoption in European Mediterranean countries is greater than in North African countries (Arrúe, 2006). In Spain, conservation tillage is adopted on over 4% of the surface and in some areas of Spain, it has been adopted over 80% of the surface and for more than 25 years (Cantero-Martínez et al., 2008).

Under semiarid Mediterranean conditions, N fertilization may also increase WUE by stimulating dry matter production (Latiri-Souki 1998), through a more rapid growth and improved transpiration efficiency. However, yields and WUE may be reduced when excessive N fertilizer is applied (Bladenopoulos and Koutroubas, 2003; Cantero-Martínez et al., 1995a). Moreover, N fertilization has to be adjusted because excessive N fertilization is an economical loss and leads to negative environmental consequences (Shepherd et al., 1993). In the Ebro river valley, as in other regions in the Mediterranean basin, N fertilizer rates for barley (*Hordeum vulgare*, L.) production has been usually applied between 100 and 200 kg of N ha⁻¹ without agronomical control in many cases (Cantero-Martínez et al., 2003). These rates must be reduced to reach equilibrium among cost, environment and productivity.

The study of soil and crop responses to N fertilization under different soil tillage systems is useful to understand the interaction between these two factors, and to define best practices for improved N fertilization. Conservation tillage systems may improve water capture and retention, thus increasing crop growth and N uptake. This may reduce the availability of soil mineral N and may require increased N fertilization (Malhi et al., 2001; McConkey et al., 2002). In

our Mediterranean dryland systems, a previous study in the area found that the interaction between these two practices in the short-term (1 to 3 years) was not significant and no additional fertilizer was needed when MT and NT were adopted. However long-term adoption (>10 years) may lead to a different response.

We hypothesized that long-term adoption of conservation tillage systems and reduced N fertilization would be a sustainable strategy in the region 10 years after their adoption, and that WUE and response to N fertilization would be increased under conservation tillage systems due to improved soil water conservation. Consequently, the objective of this study was to evaluate long-term effects of tillage and N fertilization on crop response and WUE in a rainfed Mediterranean agroecosystem.

2. Materials and methods

2.1. Site, tillage and N fertilization

A long-term experiment on tillage and N fertilization of winter-barley was initiated in 1996 in Agramunt (41° 48'N, 1° 07'E; Lleida, Spain) (Cantero-Martínez et al., 2003). The experiment consisted of a factorial combination of three levels of N fertilization (zero, ZN; medium -60 kg N ha⁻¹, MN; and high - 120 kg N ha⁻¹; HN), and three tillage systems with two conservation tillage systems (NT and MT) and one intensive tillage system (conventional tillage, CT). The experimental design was a randomized complete block design with three repetitions and a plot size of 50 m x 6 m. The mean annual rainfall in the area is 435 mm, and the soil was classified as Xerofluvent Typic (Soil Survey Staff, 1994). Main soil characteristics in the plough layer were the following: soil

pH was 8.5; sand, silt and clay content were 465, 417 and 118 g kg⁻¹, respectively; and soil organic carbon content (SOC) in the soil surface (0-5 cm) was around 16 g kg⁻¹ under NT, around 13 g kg⁻¹ under MT and around 8 g kg⁻¹ under CT, while SOC at deeper layers (10-25 cm) was similar among tillage systems, around 7 g kg⁻¹. Such increase in SOC at surface level under conservation tillage systems led to increased stock of C within the SOC (Morell et al., in press). Water storage capacity of the soil at the beginning of the experiment was 215 mm within the top 1 m soil depth (Cantero-Martínez et al., 2003).

On average, rainfall has a bimodal distribution, with the major part occurring in autumn and late spring and little precipitation in winter and summer. However the pattern is highly variable and there is a high probability (25%) of low rainfall in the spring (< 50 mm). Barley is the main crop in the region, and it is widely adopted as a monoculture crop, with the growing season between November and June. Barley monoculture is the most extended cropping system in most of the areas within the region, where rotations with leguminous or other crops have demonstrated not feasible because the lack of economical benefits (Álvaro-Fuentes et al., 2009).

The CT treatment consisted of intensive tillage with a mouldboard plough to a depth of 25-30 cm with almost 100% of the residue incorporated in the soil. The mouldboard plough consisted of three bottoms of 0.50 m width. The MT treatment consisted of a cultivator pass to a depth of 10-15 cm with an incorporation of approximately 50% of the crop residue. The cultivator plough consisted of 5 rigid shanks spaced 20 cm apart and with a shank width of 5 cm. In the NT treatment, no soil disturbances occurred, and sowing was done by

direct drilling after spraying with herbicide. Tillage operations were annually conducted between the end of October and the beginning of November. Barley cv. Hispanic was annually sown at a rate of 450 seeds m⁻², in rows spaced 17 cm apart with a no-till disc drill.

N fertilizer was split into two applications, with one-third being broadcast before tillage as ammonium sulphate (21% N) and two-thirds at the beginning of tillering as ammonium nitrate (33.5% N). Split application between sowing and tillering, with a major portion at tillering, have shown to improve the recovery of the applied N under semiarid Mediterranean conditions (Ramos et al., 1995).

Harvesting was done by the end of June with a standard medium-sized combine. The straw was chopped and spread over the plots by the combine machine. The field was kept free of vegetation for three to four months each summer. Additional details of the experimental site and cropping practices are given in Angás et al. (2006) and Cantero-Martínez et al. (2003).

2.2. Measurements

This study was conducted over a 4-yr period, during the cropping seasons 2005-2006, 2006-2007, 2007-2008 and 2008-2009, hereafter referred to as 2006, 2007, 2008 and 2009, respectively, and after ten years of the initiation of the experiment. During the four cropping seasons under study, we evaluated the long-term effects of tillage and N fertilizer on above-ground growth and yield of barley and on water productivity. Additionally we determined the soil water content (SWC) at significant growth stages and residual soil nitrate content at sowing (SN).

2.2.1. Weather conditions and SWC

An automated weather station at the experimental site registered daily maximum and minimum temperatures, precipitation and air humidity.

In every cropping season, soil samples were collected at sowing, tillering, beginning of stem extension, anthesis and harvest for determinations of SWC.

The soil samples were taken using a 4 cm diameter soil auger. At each sampling, two samples per plot were taken at 25 cm increments to a depth of 100 cm. To reduce the effects of spatial variability on successive samplings, soil samplings were conducted on two regions of 10 m², 15 meters away from each end of the plot.

Gravimetric water content (GWC) was determined for every depth interval by drying a soil sub-sample in a forced-air oven at 105°C for 48 hours (Campbell and Mulla, 1990) in a % basis. SWC up to 1 m depth was computed from GWC and bulk density (BD) of each depth, assuming a 250 mm (25 cm) depth interval (Eq. 1)

$$SWC = \sum_{i=1}^4 GWC_i \times BD_i \times 250 \text{ [Eq. 1]}$$

2.2.2. Residual SN

Before sowing, the residual SN was determined on the same soil samples used for determinations of SWC. NO₃⁻ concentration was determined in the laboratory by Nitrachek® (reflectometry based instrument) on a solution of 100 g of soil in 100 ml of deionized water.

NH₄⁺ concentration was determined in a solution of 100 g of soil in 100 ml of 1M solution of potassium chloride at several growth stages in 2007 cropping season. RQflex® (reflectometry based instrument) measurements were corrected with periodic standard soil analysis of NH₄⁺.

Nitrachek[®] and RQflex[®] were used because they are faster and cheaper. Measurements of the instruments were corrected with periodic measurements with standard soil analysis of NO₃⁻ (Bremner, 1965). As in previous studies (Angás et al., 2006), the equipment were periodically calibrated in a certified laboratory, LAF-Applus+ laboratories, as well as measurements were calibrated with those obtained with official methods (colorimetric method with auto-analyzer) in the mentioned laboratory. R² of the calibrations were always higher than 0.98 and without any significant bias.

2.2.3. Above-ground growth and yield

Phenological stages were determined weekly following the BBCH scale (Lancashire et al., 1991). Crop biomass was sampled to quantify the total dry matter at the following developmental stages: tillering, beginning of stem extension, anthesis and maturity. Three samples per plot were taken by cutting the plants at the soil surface level on 50 cm along the seeding line. The samples were oven dried at 65-70° C for 48 hours, and then weighed. Yield components were determined at maturity. Ears were counted and, after oven drying, threshed to determine the number of grains per ear and the mean grain weight. In 2006, no samples of above-ground biomass at tillering and at beginning of stem extension were taken.

2.2.4. Water use and WUE

Water losses of due to runoff and leaching were assumed to be negligible (Cantero-Martínez et al., 1995b and 2003). Water use (WU) in mm, including soil water evaporation and crop transpiration, was calculated as the difference in SWC between two soil samplings plus the amount of rainfall during the interval of time. WU was calculated for the period between sowing and anthesis

(pre-anthesis period, WU_{pre}), the period between anthesis and harvest (post-anthesis period, WU_{post}), and for the whole growing season (WU_{total}), between sowing and harvest.

WUE, in $kg\ mm^{-1}\ ha^{-1}$, was calculated as the amount of either above-ground biomass (WUE_b) or grain yield (WUE_y) per mm of water used. WUE for the above-ground biomass was calculated for the pre-anthesis (WUE_{pre}) and the post-anthesis (WUE_{post}) periods considering the WU and above-ground biomass produced in those periods.

2.3. Statistical analysis

Statistical analysis were performed using the SAS software (SAS Institute, 1990). A global analysis of variance using the PROC GLM option was performed for SN, total above-ground biomass at maturity (M), yield and yield components, considering cropping season, tillage system and N fertilization level as the main factors, and the interaction terms. Secondly, analyses of variance were conducted for each cropping season and for each variable, including total above-ground biomass at tillering, stem extension and anthesis, and SWC at different growth stages. Means separation of the main effects and/or the interaction terms were conducted by the Tukey adjustment. Error bars, indicating the standard deviation of the means, were presented in the plots.

In 2008 cropping season, CT was not included in the statistical analyses of crop variables due to crop failure. Under MT we omitted data for one block due to patchy distribution of crop growth, and hence type III sums of squares and mean squares were used instead type I.

3. Results

3.1. Weather conditions

Precipitation during the growing seasons was 157, 307, 266 and 380 mm, in 2006, 2007, 2008 and 2009, respectively. Moreover the patterns of rainfall distribution greatly differed among seasons (Fig. 1).

Precipitation during the summer-fallow periods was 84, 63, 31 and 50 mm in 2006, 2007, 2008 and 2009, respectively, and provided slight recharging of the soil water before sowing (Fig. 1). Monthly means of minimum and maximum temperatures of each growing season and means of the last thirty years are plotted in Figure 2.

3.2. Yield and yield components

Grain yields varied from 0 kg ha⁻¹ (due to crop failure in CT 2008) to 4500 kg ha⁻¹ in response to weather conditions and treatments (Table 1). Mean yields were 1075, 1519, 495 and 3680 kg ha⁻¹ for 2006, 2007, 2008 and 2009 cropping seasons, respectively. In contrast to the mean annual yield of the last 30 years in this area (2800 kg ha⁻¹), we had two years of low production (2006 and 2007), one extremely low (2008), and a final year with high production.

Over four cropping seasons, and under a range of conditions, mean yields during the study period were 2062 kg ha⁻¹ under NT, 1791 kg ha⁻¹, under MT, and 1155 kg ha⁻¹, under CT (Table 1). The improvement of grain yield with conservation tillage systems was greatest during the extremely dry year (i.e., 2008). In dry years (i.e., 2006 and 2007) yields were double under conservation tillage systems than under CT. In a wet year, grain yields did not significantly differ. N fertilization increased grain yields by 19% on average (Table 1), and it significantly interacted with tillage system and year (Table 2). The increase of

grain yield with increasing N fertilization was significant under NT, but not under MT or CT, and this response was significant in 2006, 2007 and 2009, but not in 2008 (Table 1).

The response of yield components to tillage systems depended on the cropping season (Tables 2 and 3). NT increased the number of ears on dry years (i.e., 2006 and 2007), but the opposite response occurred during the wettest year (i.e., 2009). The number of grains per ear tended to increase under NT, with significant increases in 2006 and 2009. The grain weight tended to be higher under NT, with a significant response in 2006. N fertilization increased the number of ears and the number of grains per ear (Table 3). The mean grain weight was also increased in response to N fertilization in 2009, but the opposite response occurred in 2006.

3.3. Above-ground growth

Dry matter production and its growth pattern varied among cropping seasons (Fig. 3). In 2006 and 2007, mean dry matter weights at maturity were similar, around 600 g m^{-2} , with different patterns of crop growth. Post-anthesis growth in 2006 was severely reduced due to the lack of rainfall, while in 2007, the crop growth was reduced during pre-anthesis period and high growth during post-anthesis period. In 2008, crop growth was 400 g m^{-2} on average under conservation tillage systems, and the crop failed to grow under CT. In 2009, crop growth was the greatest of all seasons, and mean weights at maturity were up to 1000 g m^{-2} .

Tillage systems significantly affected dry matter production in 2006, 2007 and 2008, but not in 2009, the wettest year (Fig. 3). N fertilization significantly increased dry matter production at several growth stages in 2006, 2007 and

2009, but not in 2008, the driest year. In 2008, the interaction between N fertilization and tillage system was significant at various growth stages. N fertilization usually increased crop growth under NT, by an average of 50% on ZN, while it did not lead to any response under CT.

3.4. SWC, WU and WUE

Total WU by the crop (WU_{total}) ranged between 255 and 460 mm (Table 4) and was related to the precipitation during the growing season. Differences on the distribution and quantity of rainfall led to differences on the pattern of water use between pre- and post-anthesis periods. On average, pre-anthesis WU (WU_{pre}) was 50 and 60% of WU_{total} in 2007 and 2009. However, WU_{pre} was 85% of the WU_{total} in 2006 due to the low precipitation during spring, and 31% of the WU_{total} in 2008 due to heavy precipitation during May.

Differences on SWC among tillage systems tended to occur at anthesis (Fig 4). This pattern of differences on SWC among tillage systems was also reflected in the pattern of water use in which increased WU_{pre} under CT (Table 4), thus leading to reduced amount of SWC at anthesis (Fig. 4).

SWC was slightly improved with long-term N fertilization (data not shown) which may have partly contributed to improving crop growth. This improvement of SWC with N fertilization can be related to greater soil cover with increased residue production. Improved SWC also led to slight increases of WU_{total} , such as in 2006 and 2009 when WU_{total} on HN was 16 and 23 mm more than that on ZN (Table 4).

WUE_b and WUE_y , were between 11.3 and 22.3 kg biomass $ha^{-1} mm^{-1}$, and between 1.2 and 9.7 kg grain $ha^{-1} mm^{-1}$ in all four years (Table 5). WUE_y was significantly affected by tillage system in the 2006 and 2007 seasons, when NT

doubled the efficiency compared to CT. In this study, the improvement of WUE_y under NT in dry years compared to CT was due to improved WUE_{pre} (Table 5). WUE_b was significantly increased by N fertilization in three out of the four seasons under study (i.e., 2006, 2007 and 2009), when WUE_b of MN and HN were between 30 and 40% greater than that of ZN. WUE_{pre} was greatest under NT in all the cropping seasons under study. WUE_y was also significantly affected by N fertilization level (Table 5). In 2007 and 2009, WUE_y was highest on MN where it ranged between 17 and 23% higher than that of ZN. But in 2006, it was highest on HN.

3.5. Residual soil mineral nitrogen

The quantity of nitrate N was between 150 and 1200 kg $N-NO_3^- ha^{-1}$ (Table 6). The main effects were consistent in different years (Table 6). In all the cropping seasons, SN was highest under CT, medium under MT and lowest under NT. The interaction between tillage system and N fertilization was not significant in any of the individual year, (close to the significance level in 2008; $P = 0.07$). However over the four years experimental period, a significant quantitative interaction occurred between tillage system and N fertilization (Table 2 and 6). Differences among N fertilization levels were higher under CT and MT than those under NT.

4. Discussion

4.1. Long-term effect of tillage

In this study and after ten years of the initiation of the experiment, there was a positive effect of NT on crop performance during most of the years. Furthermore, there were no detrimental effects of the NT system during wet

years, which is in contrast to that described in other semiarid regions (Azooz and Arshad, 1998; Moret et al., 2007), and in spite of increased soil strength and reduced root growth under NT (Morell et al., 2011).

The positive response of yield and crop growth to long-term conservation tillage systems contrasted with that observed during its early adoption, when crop growth and yields were slightly affected (Cantero-Martínez et al., 2003; López-Fando and Almendros, 1995). In our study, conservation tillage systems improved SWC and thus more water was available for crop growth leading to better WU, specially in the post-antesis period (WU_{post}). This effect was also shown by Bescansa et al., (2006) and Cantero-Martínez et al. (2007) under the same conditions. In semiarid Mediterranean conditions, the improvement on soil water conservation due to conservation tillage adoption is increased in the medium to long term. This could be related to the fact that crop residue production under semiarid conditions is low, and thus it may take a few cropping seasons for the soil cover to improve with conservation tillage. In subhumid Mediterranean environments or in wet years, crop residue production may be excessive. When excessive crop residues are produced, it may be appropriate to remove part of the residues to avoid problems when seeding or allelopaties.

Under NT, greater soil water available for crop growth resulted in higher biomass, ears per square meter and grains per ear compared to CT. Differences between tillage systems were higher as much drier was the year. Consequently, WUE in biomass and yield were improved, showing the more efficient use of water by the crop under conservation tillage systems.

During the four years, soil mineral nitrogen showed high differences between tillage systems. The lower SN content in NT compared to CT did not limited crop yield. During the four years, in the NT treatment grain yields ranged between 1.3 and 4.4 Mg ha⁻¹ representing an uptake requirement of 80 kg N ha⁻¹. This uptake value is considerable lower than the amount of residual nitrogen observed in the study. Therefore, in our experiment, yields have been limited by soil water availability. Furthermore, under CT soil mineral nitrogen was greatly accumulated up to one meter soil depth. Two explanations could be given to this accumulation. Firstly, less water was available during the growing season and thus less N uptake was done. Secondly, leaching losses were negligible due to the non-percolate regimen trough the soil under such that lower rainfall conditions.

4.2. Long-term effect of N fertilization level

N fertilization did not considerably increase crop yield and biomass. Even a slightly reduction was observed in some years between high and medium levels.

Nevertheless, the increase of N fertilization significantly affected the soil mineral N content. However, the increase in SN did not affect crop yield and WUE in such a way. In our conditions, soil water continues being the most important limiting factor. Increases in SN could lead to higher biomass and thus WU in the pre-anthesis period. But this increase did not result in higher grain yield because water was mainly transpired and lost out of the grain-filling period when yield is produced. MN was better level of N fertilizer than HN which could decrease WUE_y, as observed in 2007 and 2009 (Table 5). Increased number of ears per unit area with increased N fertilization may be due to the increased

tiller survival at later stages (Ramos et al., 1995). Reduced grain weight with HN may be the responsible of the reduced yields (Herwaarden et al., 1998), as observed in 2006 (Table 1).

These results suggest that N fertilizer addition in the region should be kept at 60 kg N ha⁻¹ or below. Ramos et al. (1995), recommended 60 kg N ha⁻¹ rates for barley in southern Spain, with an even split application between sowing and tillering with the greater proportion applied at tillering. Similarly, in other semiarid Mediterranean conditions (e.g., Greece and Italy), high doses of N fertilization showed no positive responses of crop growth (Bladenopoulos and Koutroubas, 2003; De Giorgio and Montemurro, 2006) and 50 kg of N ha⁻¹ was found as the best compromise for the yield capacity of winter cereal production. Future fertilizer experiments in the region should also consider doses lower than 60 kg N ha⁻¹. However, the fertilizer recommendation may depend on the tillage system due to the observed significant interactions occurring in the long-term.

4.3. Tillage and N fertilization interaction

The tillage by N fertilization interaction was observed in above-ground dry matter (Fig. 3), yield and associated WUE (Table 1 and 5, respectively), and SN (Table 6). Crop growth and yield usually responded positively to N fertilization under NT, as well as under MT during the wettest year (i.e., 2009), but not under CT. The response to N fertilization under NT can be partly related to greater SWC under this system (Fig. 4) and to lower but not limiting SN content (Table 6). The lack of response under CT, even during a wet cropping season could be related to the accumulation of SN (Table 6). As commented in the Results section, in some sampling moments, soil nitrate content was higher

than 1000 kg N-NO₃ ha⁻¹. After more than 10 years with medium and high N fertilizer applications, this significant accumulation of SN was mainly attributed to: i) the accumulation of fertilizer exceeding the uptake by the crop; ii) the N mineralization from soil organic matter; and iii) the lack of leaching. It was assumed that in this experiment SN leaching was insignificant since the SWC (Fig. 4) plus rainfall (Fig. 1) slightly exceeded the soil water storage capacity of the soil in the top 1 m (215 mm approximated) only in certain moments. It is worth mentioning that in other experiments located in the same semiarid area we have found similar levels of soil mineral N (data not shown). Furthermore, high amount of mineral N in the top 1 m of the soil has been previously reported in another areas in the Mediterranean region with high levels of N fertilizer additions (Abad et al., 2004).

The quantity of ammonium N to one meter depth was around 15 and 20 kg N-NH₄⁺ ha⁻¹ with similar amounts on different treatments and through the season (data not shown; Margalef-Garcia, 2010). Soil samplings were performed at least 1 month after fertilizer applications. Consequently, applied ammonium in the ammonium sulphate and in the ammonium nitrate had been transformed to nitrate or volatilized before soil sampling. The ammonium fraction represented a small fraction of the soil mineral N (less than 3% in our soil) and showed practically no variation during the growing season, as observed in Vázquez et al. (2006), indicating that, under semiarid conditions, ammonium N is a low and rather stable fraction of the soil mineral N.

Reduced amounts of SN under conservation tillage systems could be mainly attributed to two reasons. First, the increase of SOC stock under NT (Morell et al., in press) and the concomitant increase of organic N stored in the soil

organic matter, which may account of up to 500 kg of N stored in soil organic matter with the increase of 4 Mg ha⁻¹ of the SOC stock under NT. Second, increased exportation of N with the grain under conservation tillage systems due to increased yields (Table 1). As a rough estimation, given a mean increase of 600 kg ha⁻¹ of yield under NT compared to CT and with a 2% of N in the grain, the N exportation with grain under NT over the 14 years period may be of up to 170 kg of N.

Mediterranean agroecosystems are characterized by poorly developed soils prone to erosion and reduced available water, and hence low yields and crop residue production, which are leading to soil degradation and economical limitations. The present study demonstrates an increase of the benefits of conservation tillage systems over the long-term. For this reason, conservation tillage adoption, and especially NT, should be encouraged in other semiarid Mediterranean countries, where NT is in its early stage of adoption (Derpsch et al., 2010). Our results show that the long-term adoption of NT and adjustment of N fertilization improve productivity and reduces the risk of desertification in the area.

Conclusions

In Mediterranean dryland agroecosystems, long-term adoption of conservation tillage systems is an agronomical sustainable strategy to improve soil water conservation that leads to increase yields and improve WUE. Long-term addition of N fertilizer only under NT improves WUE and grain yield. Application of N fertilizer under CT leads to the accumulation of high amounts of nitrate in the soil. Long-term adoption of NT with adjusted N fertilization improves the

agronomical and economical sustainability of cereal based rainfed agroecosystem under Mediterranean conditions.

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Figure captions

Figure 1. Precipitation. Bars indicate monthly rainfall during the four cropping
seasons under study: 2006, 2007, 2008 and 2009, starting in July (J), after
harvest of the previous year. Continued line with vertical ticks indicates average
monthly rainfall (30 years) (line).

Figure 2. Air temperature. White triangles indicate monthly mean of the daily
minimum (dotted line) and maximum (continued line) temperatures. Black
triangles indicate average monthly mean of minimum (dotted line) and

maximum (continued line) temperatures over the last 30 years. Small vertical arrows indicate sowing (by mid November, N) and harvest (by the end of June, J) dates on each cropping season.

Figure 3. Total above-ground biomass production in 2005-2006, 2006-2007, 2007-2008 and 2008-2009 cropping seasons, for different tillage systems, no-tillage (NT), minimum tillage (MT) and conventional tillage (CT), and different N fertilization levels: zero N –ZN- (no fertilizer application); medium N -MN- (60 kg N ha⁻¹), and high N –HN- (120 kg N ha⁻¹), at different periods: beginning of stem extension (E), anthesis (A) and crop maturity (M). Error bars indicate standard deviation of the means. C.f., crop failure. In each cropping season and each period significant differences of the means according to Tukey's adjustment (P<0.05) are indicated with different letters.

Figure 4. Soil water content in 2006-2005, 2006-2007, 2007-2008 and 2008-2009 cropping seasons, for different tillage systems, no-tillage (NT), minimum tillage (MT) and conventional tillage (CT), at sowing (S), tillering (T), anthesis (A) and crop maturity (M). Error bars indicate standard deviation of the means. C.f., crop failure. In each cropping season and each period significant differences of the means according to Tukey's adjustment (P<0.05) are indicated with different letters.

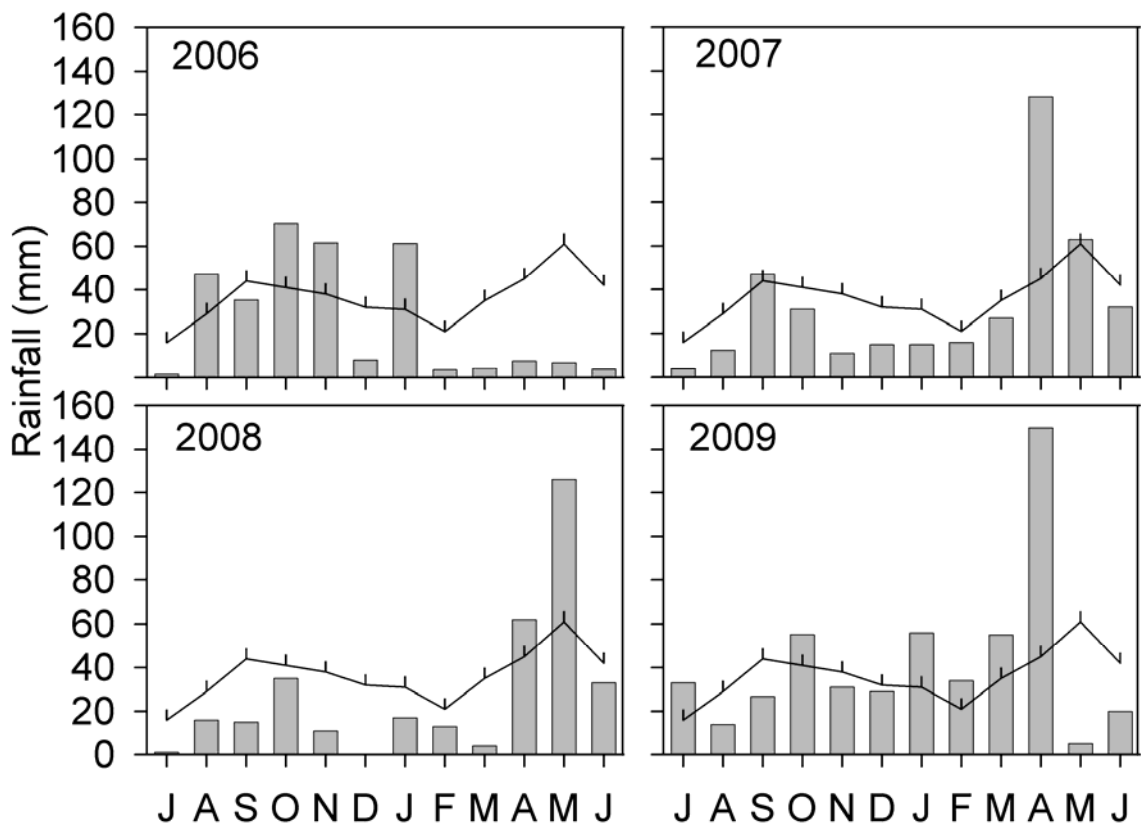


Figure 1.

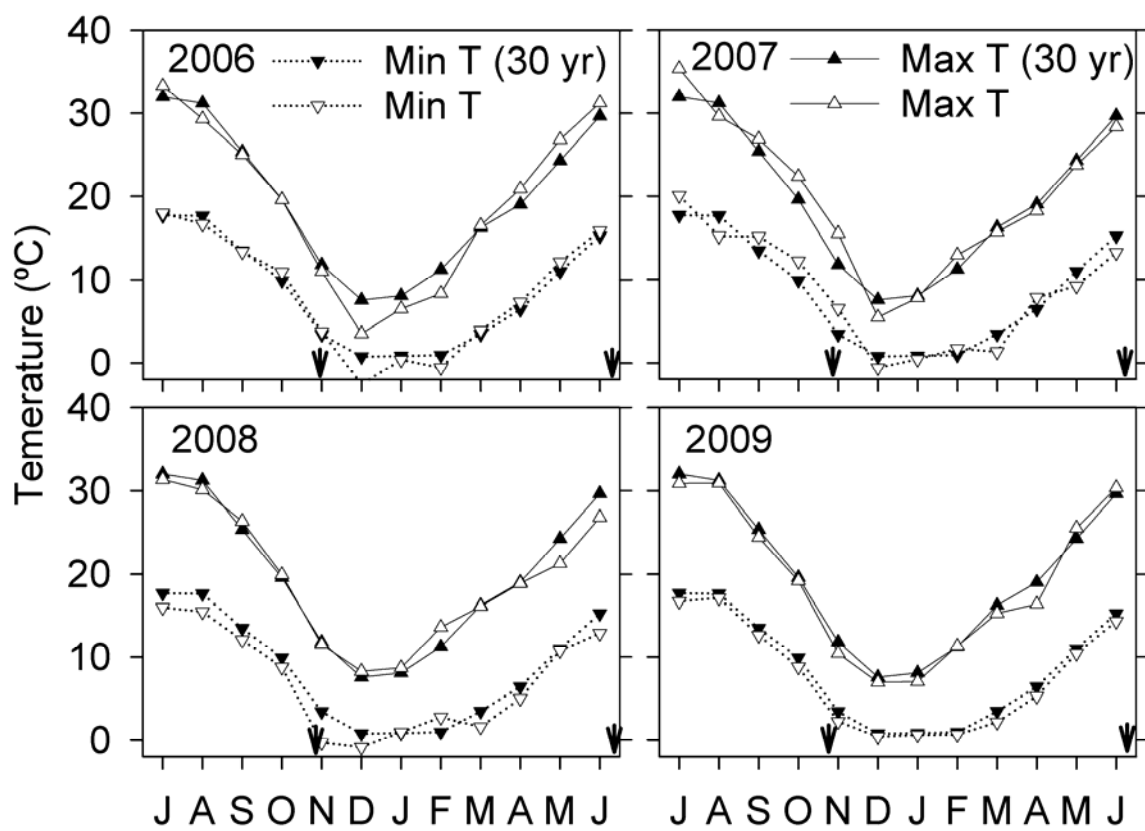
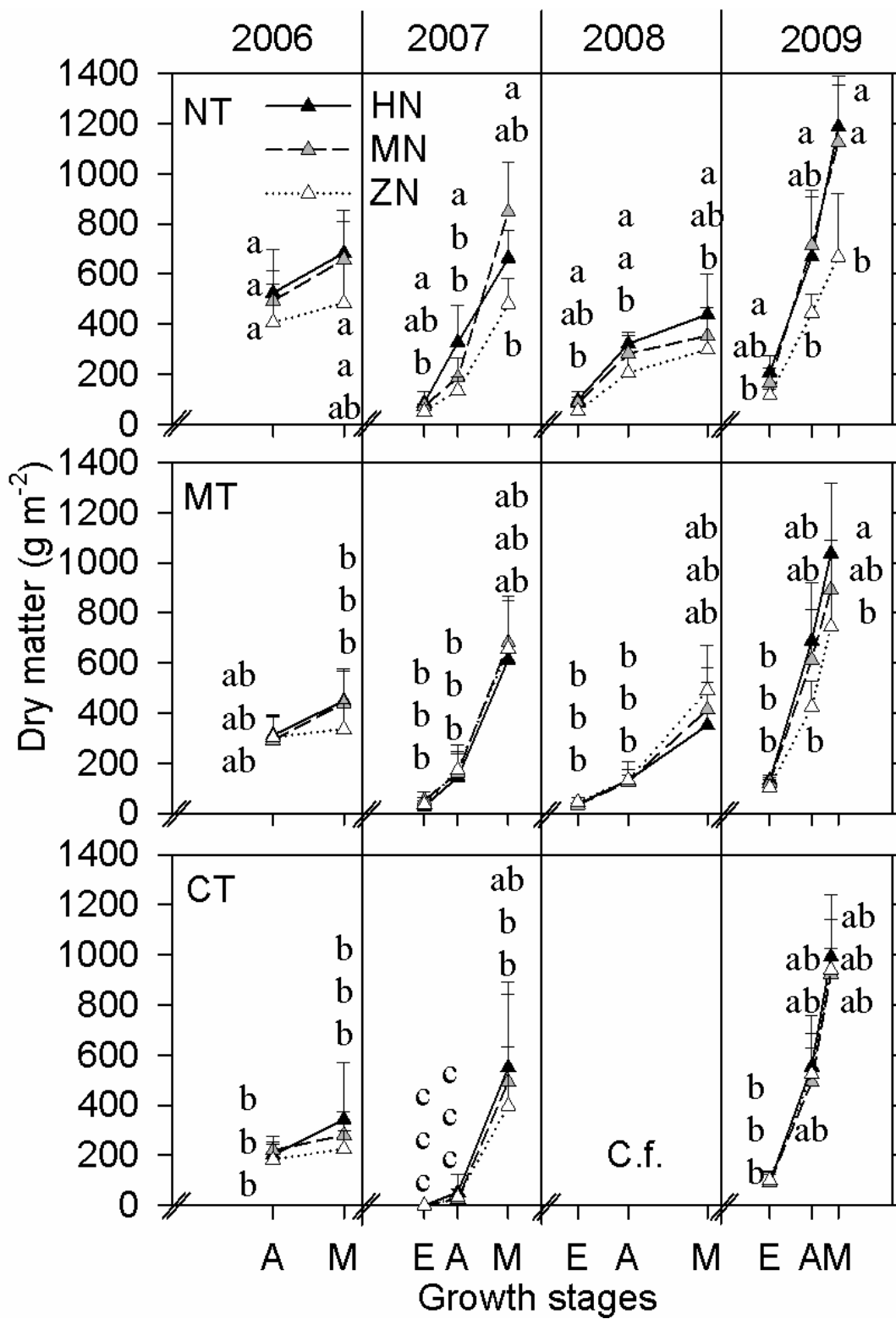


Figure 2.



686

687 Figure 3.

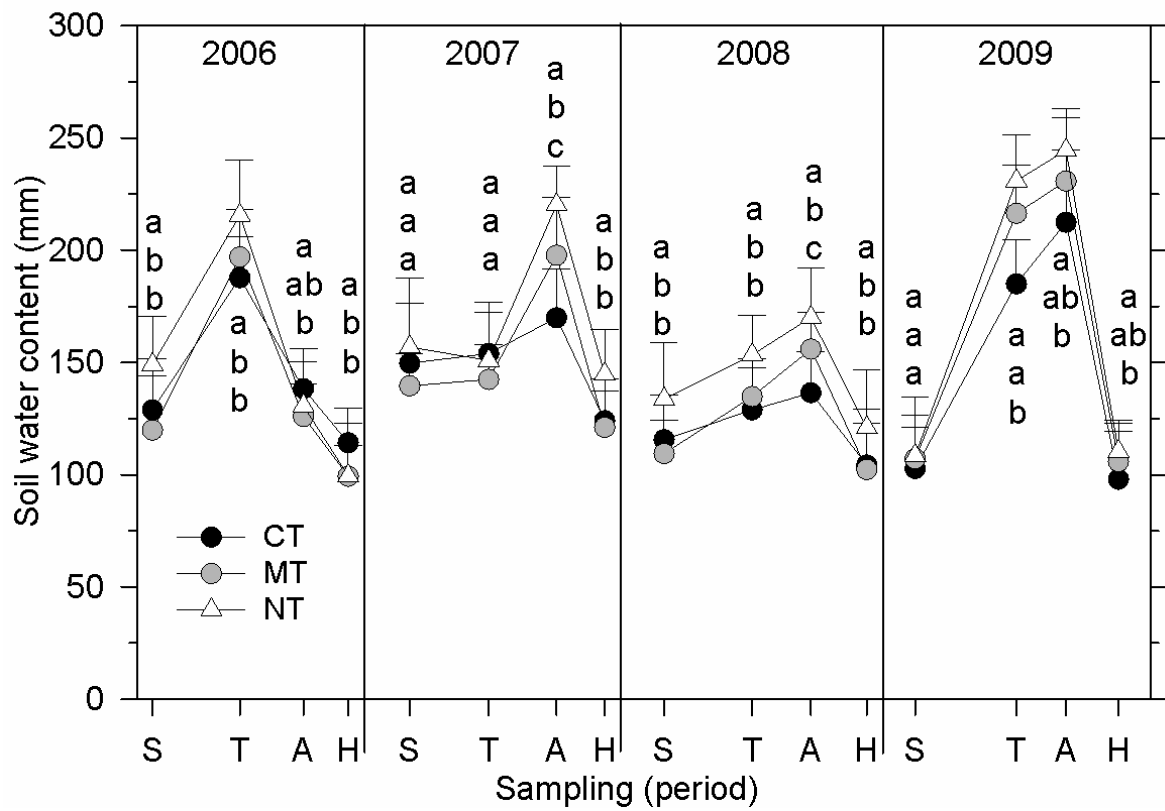


Figure 4.

691

		Grain yield (kg ha ⁻¹)			FNT
		NT	MT	CT	
2006	ZN	1348 b	1101 b	306 d	919 b
	MN	1653 ab	1041 b	490 d	1061 b
	HN	1964 a	1103 b	669 cd	1246 a
	TIL	1655 a	1082 b	488 c	
2007	ZN	1563 b	1944 ab	638 c	1382 b
	MN	2521 a	1972 ab	708 c	1734 a
	HN	2091 ab	1792 ab	443 c	1442 ab
	TIL	2058 a	1903 a	596 b	
2008	ZN	480	462	c.f.	314 a
	MN	685	544	c.f.	410 a
	HN	861	609	c.f.	490 a
	TIL	675 a	539 a	c.f.	
2009	ZN	2970 b	3346 ab	3646 ab	3321 b
	MN	4415 a	4089 a	3529 ab	4011 a
	HN	4195 a	3497 ab	3434 ab	3709 a
	TIL	3860 a	3644 a	3536 a	
2006-2009	ZN	1590 bc	1714b	1148 c	1484 b
	MN	2319 a	1912 b	1182 c	1804 a
	HN	2278 a	1751 b	1137 c	1722 a
	TIL	2062 a	1792 b	1155 c	

692

693 Table 1. Yields (kg ha⁻¹) in 2006, 2007, 2008 and 2009 cropping seasons.

694 Comparison of N fertilization levels: zero N –ZN- (no fertilizer application);

695 medium N -MN- (60 kg N ha⁻¹), and high N –HN- (120 kg N ha⁻¹), under different

696 tillage systems, no-tillage (NT), minimum tillage (MT) and conventional tillage

697 (CT). C.f., crop failure. Significant differences of the means according to

698 Tukey's adjustment (P<0.05) are indicated with different letters.

699

	SWCs	SWCt	SWCa	SWCh	SN	M	Ears	GpE	Gw
YEAR	<0.001	<0.001	<0.001	<0.001	n.s.	<0.001	<0.001	<0.001	0.003
TIL	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.03	<0.001	<0.001
YEAR*TIL	0.05	<0.001	<0.001	<0.001	n.s.	0.002	<0.001	<0.001	n.s.
FNT	0.004	0.001	n.s.	n.s.	<0.001	<0.001	0.017	<0.001	n.s.
YEAR*FNT	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<0.001
TIL*FNT	n.s.	n.s.	<0.001	0.007	0.013	0.009	0.018	n.s.	0.026
YEAR*TIL*FNT	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<0.001
	HI	Yield	WUpre	WUpost	WUtotal	WUEpre	WUEpost	WUEb	WUEy
YEAR	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.02	<0.001	<0.001
TIL	<0.001	<0.001	<0.001	<0.001	n.s.	<0.001	n.s.	<0.001	<0.001
YEAR*TIL	0.017	<0.001	<0.001	n.s.	<0.001	<0.001	0.03	0.004	<0.001
FNT	n.s.	<0.001	0.005	n.s.	0.002	0.003	n.s.	0.003	0.002
YEAR*FNT	0.044	0.014	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.02
TIL*FNT	n.s.	<0.001	n.s.	n.s.	n.s.	0.01	n.s.	0.01	<0.001
YEAR*TIL*FNT	n.s.	n.s.	n.s.	n.s.	0.04	n.s.	n.s.	n.s.	n.s.

701

702 Table 2. Probability of significance of main factors (YEAR, cropping seasons,
703 TIL, tillage system and FNT, N fertilization level) and their interaction at the
704 global analyses of variance of: soil water content (SWC) at sowing (s), tillering
705 (t), anthesis (a), and harvest (h); soil nitrate (SN); on above-ground biomass at
706 maturity (M); yield components (number of ears unit area, Ears, number of
707 grains per ear, GpE, mean weight of grain, Gw); yield and harvest index (HI);
708 water use (WU) during different periods: WU_{pre} , WU in the pre-anthesis period;
709 WU_{post} , WU in the post-anthesis period; and WU_{total} , WU for the whole growing
710 season; and water use efficiency (WUE) during different periods: WUE_{pre} , WUE
711 of total biomass in the pre-anthesis period; WUE_{post} , WUE of the total biomass
712 in the post-anthesis period; WUE_b , WUE on the whole growing season and total
713 above-ground biomass; and WUE_y , WUE on grain yield. n.s., non-significant
714 effect at $P>0.05$.

		Ears (m ⁻²)				FNT	GpE				FNT	Gw (mg)				FNT
		NT	MT	CT			NT	MT	CT			NT	MT	CT		
2006	ZN	354	317	316	329 b		13.9	11.5	8.9	11.4 a		41.5	39.2	35.8	38.8 a	
	MN	474	390	321	395 a		14.8	12.2	9.8	12.3 a		39.1	38.0	33.7	36.9 ab	
	HN	490	394	393	426 a		14.5	12.8	9.4	12.2 a		37.2	36.5	36.3	36.7 b	
	TIL	440 a	367 b	343 b			14.4 a	12.2 b	9.3 c			39.3 a	37.9 a	35.3 b		
2007	ZN	609	753	366	576 b		9.8	11.6	12.5	11.3 a		38.8	37.2	33.7	36.6 a	
	MN	954	789	419	721 a		12.2	12.1	12.9	12.4 a		36.5	32.9	34.2	34.6 a	
	HN	745	640	473	619 ab		12.4	13.6	12.6	12.9 a		34.4	33.7	33.6	33.9 a	
	TIL	769 a	727 a	419 b			11.5 a	12.4 a	12.7 a			36.6 a	34.6 a	33.8 a		
2008	ZN	502	827	C.f.	665 a		6.9	8.5	C.f.	7.5 a		32.0	35.1	C.f.	33.2 a	
	MN	488	629	C.f.	559 a		7.9	8.3	C.f.	8.1 a		39.4	33.0	C.f.	36.9 a	
	HN	558	655	C.f.	607 a		9.9	8.1	C.f.	9.2 a		36.7	29.4	C.f.	33.8 a	
	TIL	516 b	704 a				8.2 a	8.3 a				36.0 a	32.5 a			
2009	ZN	481 b	749 ab	1065 a	765 b		14.5	13.1	12.9	13.5 c		29.0 b	34.1 ab	38.3 ab	33.8 a	
	MN	751 ab	856 a	994 a	868 ab		17.2	13.9	13.4	14.8 b		47.7 a	37.7 ab	33.0 ab	39.5 ab	
	HN	783 ab	992 a	980 a	919 a		17.8	15.0	14.9	15.9 a		47.5 a	41.5 ab	34.7 ab	41.2 b	
	TIL	672 c	866 b	1014 a			16.5 a	14.0 b	13.7 b			41.4 a	37.8 a	35.3 a		

715

716 Table 3. Average of yield components. Comparison among N fertilization levels: zero (ZN), medium (MN), and high (HN);
717 under different tillage systems: no-tillage (NT), minimum tillage (MT), and conventional tillage (CT); at four cropping
718 seasons: 2006, 2007, 2008, and 2009. C.f., crop failure. HI, harvest index; Ears, number of ears per square meter; GpE,
719 grains per ear; and Gw, mean grain weight. Different letters indicate significant differences among means on each
720 cropping season (P<0.05). Means of all treatments are separated with different letters when interaction effect was
721 significant (P<0.05).

		WU _{pre}			FNT	WU _{post}			FNT	WU _{total}			FNT
		NT	MT	CT		NT	MT	CT		NT	MT	CT	
2006	ZN	217 b	199 b	209 b	208 b	43	40	31	38 a	259	239	240	246 b
	MN	240 ab	207 b	206 b	218 ab	44	39	35	40 a	284	246	241	257 ab
	HN	248 a	225 ab	206 b	226 b	37	31	37	35 a	285	257	243	262 a
	TIL	235 a	210 b	207 b		41 a	37 a	34 a		276 a	247 b	241 b	
2007	ZN	190	181	209	194 a	170	176	147	164 a	360	357	356	358 a
	MN	175	169	235	193 a	172	185	129	162 a	347	354	364	355 a
	HN	173	205	224	201 a	173	157	150	160 a	346	362	374	360 a
	TIL	180 b	185 b	223 a		171 a	173 a	141 b		351 a	358 a	365 a	
2008	ZN	102	101	131	102 a	190	209	193	197 a	292 b	309 ab	323 ab	308 a
	MN	102	88	112	95 a	224	222	189	212 a	326 a	313 ab	301 ab	313 a
	HN	116	87	124	102 a	210	207	192	203 a	326 a	306 ab	316 ab	316 a
	TIL	107 b	93 b	122 a		208 a	213 a	191 b		315 a	309 a	313 a	
2009	ZN	270	290	308	289 a	180	152	154	162 a	450	442	462	451 b
	MN	270	272	298	280 a	186	179	163	176 a	456	451	461	456 b
	HN	288	303	301	297 a	177	185	167	176 a	465	488	469	474 a
	TIL	276 b	288 ab	302 a		181 a	171 a	161 a		457 a	460 a	464 a	

722

723 Table 4. Water use (WU) in mm, in response to different N fertilization levels: zero (ZN), medium (MN), and high (HN);
724 under different tillage systems: no-tillage (NT), minimum tillage (MT), and conventional tillage (CT); at four cropping
725 seasons: 2006, 2007, 2008, and 2009. WU_{pre}, WU in the pre-anthesis period; WU_{post}, WU in the post-anthesis period; and
726 WU_{total}, WU for the whole growing season. C.f., crop failure. Different letters on each year indicate significant differences
727 among means for the main effects (P<0.05). Means of all treatments are separated with different letters when interaction
728 effect was significant (P<0.05).

		WUE _{pre}			FNT	WUE _{post}			FNT
		NT	MT	CT		NT	MT	CT	
2006	ZN	14.9	15.6	9.4	15.1 a	42.9	5.1	6.4	18.2 a
	MN	21.9	12.8	10.3	15.0 a	48.9	28.3	21.5	32.9 a
	HN	22.0	14.2	9.3	13.3 a	61.1	43.5	48.6	51.1 a
	TIL	19.6 a	14.2 b	9.7 c		51.0 a	26.5 a	25.5 a	
2007	ZN	7.7 b	10.0 b	2.2 c	6.6 b	18.2	29.4	26.2	24.6 a
	MN	12.4 ab	11.0 b	1.5 c	8.3 ab	36.2	30.2	42.8	36.4 a
	HN	23.2 a	8.7 b	3.2 c	11.7 a	18.1	25.4	38.0	27.2 a
	TIL	14.4 a	9.9 b	2.3 c		24.2 a	28.3 a	35.7 a	
2008	ZN	22.1	10.7	C.f.	16.7 a	7.4	24.1	C.f.	15.0 a
	MN	30.8	9.8	C.f.	20.6 a	5.4	19.2	C.f.	11.6 a
	HN	29.4	12.7	C.f.	21.4 a	9.0	13.4	C.f.	10.5 a
	TIL	27.4 a	11.7 b	C.f.		7.3 b	17.4 a	C.f.	
2009	ZN	16.7	15.0	16.5	16.1 b	14.2	9.8	29.5	17.8 a
	MN	25.5	23.2	15.9	21.5 a	26.5	16.8	28.9	24.1 a
	HN	23.1	21.6	18.0	20.9 ab	30.7	19.7	27.6	26.0 a
	TIL	21.8 a	19.9 ab	16.6 b		23.8 a	15.4 a	28.7 a	
		WUE _b			FNT	WUE _y			FNT
		NT	MT	CT		NT	MT	CT	
2006	ZN	17.2	11.9	9.0	12.7 b	5.3 b	4.6 b	1.3 c	3.7 b
	MN	22.5	15.5	10.7	16.2 ab	5.7 ab	4.3 b	1.9 c	4.0 b
	HN	24.4	17.4	14.9	18.9 a	7.0 a	4.0 b	2.9 c	4.6 a
	TIL	21.4 a	14.9 b	11.3 b		6.0 a	4.3 b	2.1 c	
2007	ZN	12.6	19.5	12.1	14.7 a	4.1 b	5.4 ab	1.9 c	3.8 b
	MN	24.0	20.4	16.5	20.3 a	7.1 a	5.4 ab	1.9 c	4.8 a
	HN	20.1	15.5	17.2	17.6 a	5.7 ab	4.8 a	1.2 c	4.1 ab
	TIL	18.9 a	18.5 a	15.3 a		5.7 a	5.2 a	1.8 b	
2008	ZN	11.7	18.7	C.f.	14.7 a	1.6	2.3	C.f.	1.7 a
	MN	12.5	16.0	C.f.	13.8 a	2.0	2.7	C.f.	2.2 a
	HN	16.0	10.4	C.f.	12.8 a	2.7	3.1	C.f.	2.7 a
	TIL	13.4 a	14.1 a	C.f.		2.1 a	2.3 a	C.f.	
2009	ZN	15.4	13.2	21.3	16.6 b	6.7 b	7.4 b	8.0 ab	7.4 b
	MN	26.0	20.5	19.9	22.1 a	9.7 a	9.2 a	7.7 ab	8.7 a
	HN	25.6	20.2	20.5	22.1 a	9.0 a	6.9 b	7.5 b	7.8 b
	TIL	22.3 a	17.9 b	20.6 ab		8.5 a	7.9 a	7.7 a	

730

731 Table 5. Water use efficiency (WUE) in kg mm⁻¹, under different N fertilization
732 levels: zero (ZN), medium (MN), and high (HN); under different tillage systems: no-
733 tillage (NT), minimum tillage (MT), and conventional tillage (CT); at four cropping

seasons: 2006, 2007, 2008, and 2009. WUE_{pre} , WUE of the total biomass in the pre-anthesis period; WUE_{post} , WUE of the total biomass in the post-anthesis period; WUE_b , WUE on the whole growing season and total above-ground biomass; and WUE_y , WUE on grain yield. C.f., crop failure. Different letters on each year indicate significant differences among means for the main effects ($P < 0.05$). Means of all treatments are separated with different letters when interaction effect was significant ($P < 0.05$).

		SN (kg N-NO ₃ ha ⁻¹)			FNT
		NT	MT	CT	
2006	ZN	184	287	603	358 b
	MN	317	307	752	459 b
	HN	578	554	1264	799 b
TIL		360 b	383 b	873 a	
2007	ZN	134	274	630	346 b
	MN	351	382	913	549 ab
	HN	425	757	1065	749 a
TIL		303 b	471 b	869 a	
2008	ZN	172	262	514	316 b
	MN	230	458	838	508 b
	HN	276	843	1126	748 a
TIL		226 c	521 b	826 a	
2009	ZN	91	136	498	241 b
	MN	227	581	921	576 a
	HN	256	694	1097	682 a
TIL		191 c	470 b	839 a	
2006-2009	ZN	145 f	240 ef	561 cd	315 b
	MN	281 ef	432 de	856 b	523 ab
	HN	384 de	712 bc	1138 a	745 a
TIL		270 c	461 b	852 a	

Table 6. Soil nitrate content (SN). Comparison among N fertilization levels: zero (ZN), medium (MN), and high (HN); under different tillage systems: no-tillage (NT), minimum tillage (MT), and conventional tillage (CT); at four cropping seasons:

746 2006, 2007, 2008, and 2009. Different letters indicate significant differences among
747 means on each cropping season ($P < 0.05$). Means of all treatments are separated
748 with different letters when interaction effect was significant ($P < 0.05$).
749