No-tillage reduces long-term yield-scaled soil nitrous oxide emissions in rainfed Mediterranean agroecosystems: a field and modelling approach

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Keywords

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Abstract

There is a strong need to identify agricultural management practices that maintain agronomic productivity while diminishing soil N_2O emissions. The yield-scaled N_2O emissions (YSNE) indicator can help to evaluate the adequacy of a given agricultural practice under both aspects. Long-term (18-yr) soil water and mineral N dynamics, crop biomass and yields, and 2011-2012 soil N_2O emissions and ancillary variables were measured on barley (*Hordeum vulgare* L.) production in a tillage (conventional tillage, CT; no-tillage, NT) and N rate (0, 60 and 120 kg N ha^{-1}) combination under rainfed Mediterranean conditions (NE Spain). Once evaluated, the STICS soil-crop model was used to simulate the 18-yr soil N_2O emissions of each tillage system under increasing N rates (0, 30, 60, 90 and 120 kg N ha^{-1}) in order to identify optimum management to reduce YSNE, being initialized with observed data. Cropping season precipitation was highly variable during the experiment, being a key regulating mechanism for crop yields and simulated soil N_2O emissions. Crop yield under NT with N outperformed CT in 11 years. STICS performed reasonably well when simulating cumulative N_2O emissions and ancillary variables with model efficiencies greater than 0.5. The 18-yr average simulated cumulative N_2O emissions were 0.50, 0.82 and 1.09 kg N_2O-N ha^{-1} yr^{-1} for CT-0, CT-60 and CT-120, respectively, and they were 0.53, 0.92 and 1.19 kg N_2O-N ha^{-1} yr^{-1} for their counterparts under NT. These averages mask a large variability between years, according to precipitation. The 18-yr mean yield-scaled N_2O emissions were 2.8 to 3.3 times lower under NT, compared to the corresponding CT treatments. Under CT, N application would increase YSNE in most years while YSNE would be more resilient to the application of increasing N rates under NT. Our work demonstrates that in rainfed

Mediterranean systems NT is a win-win strategy for the equilibrium between agricultural productivity and low soil N_2O emissions.

Abbreviations

CT, conventional tillage; EF, emission factor; greenhouse gases (GHG); NT, no-tillage; N_2O, nitrous oxide.

1. Introduction

Nitrous oxide (N_2O) is a powerful greenhouse gas (GHG) with a global warming potential 265 times greater than the reference gas, i.e. carbon dioxide (CO_2) (IPCC, 2013). Atmospheric concentration of N_2O has increased about 20% since the beginning of the industrial revolution, boosted after the invention of the Haber-Bosch process, and reaching a current value of 324.2 ppb (IPCC, 2013). Most of the emissions of N_2O are originated in soils treated with nitrogen (N) fertilizer as a result of the nitrification and denitrification processes (Butterbach-Bahl *et al*., 2013). These processes are the result of soil microorganism activities and are modulated by the amount of substrate (organic materials, mineral N) and environmental conditions (O_2, soil pH and temperature), which are modified, in turn, by a range of agricultural management practices. However, in agroecosystems, N is key for maintaining yield potential. Consequently, the increasing demand of food, feed and energy will probably raise significantly the emissions of N_2O from soils if agricultural management practices remain unchanged.

Rainfed Mediterranean agroecosystems are characterized by the low magnitude and high variability of precipitation and the high evapotranspiration rates, severely limiting crop yield potential. In these areas, winter cereals show a good adaptation given the partial synchrony of their water needs with the distribution of precipitation and the key contribution of the soil water recharge period (Lampurlanés *et al*., 2016; Plaza-Bonilla *et al*., 2017). In different rainfed Mediterranean areas of Spain reduced and no-tillage (NT) systems have been introduced during the last three decades aimed to reduce costs and mitigate soil erosion (Moreno *et al*., 2010). Under NT, crop residues are maintained at the soil surface enhancing water storage thanks to (i) reduced soil water evaporation, (ii) greater water infiltrability in soils prone to crusting, and (iii) improved soil water characteristics (Lampurlanés *et al*., 2016; Strudley *et al*., 2008). The usually higher water status in NT compared to conventional tillage (CT) soils has been claimed as a risk for greater N_2O production and emission to the atmosphere, worsening the C footprint of agroecosystems (e.g. Smith *et al*., 2001). However, the long-term use of NT greatly modifies soil physical properties with a greater proportion and connectivity of macropores (Strudley *et al*., 2008), due to soil fauna and roots activities, which, in turn, increases aeration, reducing the susceptibility to denitrification and N_2O production (van Kessel *et al*., 2013).

Nowadays, agricultural activities must fulfill consumer demands while avoiding environmental tradeoffs. A joint indicator of productivity and GHG emission such as the yield-scaled N_2O emissions (YSNE) (van Groenigen *et al*., 2010) provides a unique opportunity to evaluate the adequacy of a given agricultural practice under the productive and environmental points of view. Regarding to this, long-term field experiments represent an invaluable tool to assess the impact of crop management practices on agronomic and environmental variables with a high degree of confidence. Unfortunately, long-term measurement of soil N_2O emissions are time- and resource-consuming and, consequently, scarce in the literature. Simulation tools such as process-based models represent an interesting strategy to overcome this limitation (Abalos *et al*., 2016) and to help establish management decisions (Campbell *et al*., 2014; Ludwig *et al*., 2011), but provided that the models are well validated and produce robust and reasonably accurate results. Therefore, the objective of this work was to assess the long-term impact of different tillage systems and N rates on soil N_2O emissions and crop productivity in rainfed Mediterranean conditions with a combined experimental and simulation approach using long-term field data and the STICS model (Brisson *et al*., 1998, 2002, 2008). Our hypothesis was that long-term NT and adequate N fertilizer rates would lead to the best equilibrium between the environmental and agronomic components, as indicated by the yield-scaled N_2O emissions index (YSNE).

2. Materials and methods

2.1. Site conditions, experimental design and crop management practices.

A field experiment was established in 1996 in Agramunt, NE Spain (41°48′ 36’’ N, 1°07′ 06’’ E, 330 m asl) to compare two tillage types (CT, conventional tillage; NT, no-tillage) and three mineral N rates (0, 60 and 120 kg N ha^{-1}). The area is representative of rainfed semiarid Mediterranean conditions with a mean annual precipitation of 401 mm, potential evapotranspiration (PET) of 855 mm, and annual temperature of 14.1 ºC (1984-2014). The 30-yr mean precipitation received during the soil water recharge period (September to January) reaches 201 mm (Lampurlanés *et al.*, 2016).

The experiment was based on a randomized complete block design with three replications which was run for 18 years until 2014. Individual plot was 6 m wide by 48 m long. Soil characteristics of the experiment are shown in Table 1.

Prior to the establishment of the experiment, the area was devoted to winter cereal production with summer fallow managed under intensive tillage and high rates of N which correspond to the high rate of the field experiment. Air temperature, moisture, and rainfall were recorded hourly using an automated weather station located in the experimental area. Daily solar radiation, wind speed and calculated Penman-Monteith potential evapotranspiration (PET) were obtained from the nearest (ca. 3 km far) meteorological station of the regional government.

The CT treatment consisted of one moldboard plough pass (25-30 cm depth) plus one or two cultivator passes (15 cm depth) before sowing, during September and October depending on soil moisture. In the NT treatment no soil tillage practices were carried out. Three to five days before sowing, the weeds were controlled by applying 1.5 L ha^{-1} of glyphosate [N-(phosphonomethyl)glycine]. In the region, NT has been progressively introduced with the aim of both reducing costs and either maintaining or increasing yields (Cantero-Martínez *et al*., 2003). Barley sowing (cv. Hispanic from 1996 to 2010 and cv. Cierzo from 2010 to 2014) was performed in November with the use of a commercial 3-m wide NT drill with disk openers at a rate of 450 seeds m^{-2} in rows spaced 17 cm apart. Continuous winter cereal production, mainly barley, represented the most common practice in the area, due to higher risks associated to alternative crops (Álvaro-Fuentes *et al*., 2009). N fertilization was split into two applications: one before sowing with a third of the rate which was surface broadcasted and incorporated with tillage in CT, and one as top-dressing, also broadcasted, with the other two thirds at the beginning of the tillering stage (i.e. between January and February depending on the year) using ammonium nitrate (33.5% N). Soil analysis for determining P and K levels was carried out each 3-4 years. Given the medium-high levels of available P and K, applications were oriented to satisfy crop needs at an equal rate for both tillage treatments: ca. 40-50 kg P_2O_5 ha^{-1} yr^{-1} and 90 kg K_2O ha^{-1} yr^{-1}. The grain was harvested using a commercial combine at the end of June or beginning of July, which chopped and spread uniformly crop residues over the soil surface. In the CT treatment, crop residues were incorporated into the soil with tillage operations. Under NT, crop residues were maintained on the soil surface throughout the study period.

2.2. Soil and crop sampling and measurements.

Two datasets were used to calibrate and evaluate the model: one related to N_2O emissions and ancillary variables (soil moisture, temperature, and ammonium and nitrate nitrogen) and the other related to yearly soil profile water and mineral N contents and biomass production. For the first, observed data reported in Plaza-Bonilla *et al*. (2014) were used to evaluate the ability of the STICS model in simulating soil N_2O emissions. Briefly, soil N_2O emissions were quantified during the 2011-2012 cropping season with the use of two static chambers per plot. Gas measurements were performed every two to three weeks, being more frequent during fertilizer applications. Cumulative N_2O-N losses were calculated with the trapezoid rule, taking into account the number of days between consecutive measurements. On every sampling date, the soil temperature (5 cm depth) was measured with a hand-held probe and a soil sample (0-5 cm depth) was taken for soil water and mineral N (ammonium, NH_4^+, and nitrate, NO_3^-) content determination. Soil water content (SWC) was quantified with the gravimetric method. Soil bulk density (0-5 cm depth) was also measured with the cylinder method (Grossman and Reinsch, 2002). Further information regarding soil N_2O emissions measurement and ancillary variables can be found in Plaza-Bonilla *et al*. (2014).

The second dataset comprised soil profile water and mineral N content and crop biomass and yield during the eighteen years covered by the experiment. Methods used are described by Angás *et al*. (2006) and Morell *et al*. (2011). Briefly, soil samples were taken prior to sowing, at flowering and after harvest in each cropping season studied. In each plot, two representative areas of 2 by 2 m were identified and three soil samples per area were taken using a mechanized soil corer, in 30-cm increments, up to a soil depth of 90 cm. The sub-samples were bulked for each depth and gravimetric moisture and ammonium and nitrate were quantified. Crop aboveground biomass was measured at physiological maturity by cutting the plants at soil level along a 0.5 m length of the seeding line in three locations per plot. Once in the laboratory, ears were separated and the stems and leaves were oven-dried at 65ºC during 48 h to estimate crop residues. Carbon and N concentration of the biomass was analyzed by dry combustion (LECO-2000 analyzer, LECO, St Joseph, MI, US). Crop yield was measured with a commercial combine, taking a sub-sample for grain moisture determination.

2.3. Overview of the STICS soil-crop model and its evaluation for N_2O emissions.

The soil and crop model STICS (Brisson *et al*., 1998, 2002, 2008) is a one-dimension daily-step model created to simulate a range of processes related to plant growth as well as water and N cycles over one or several growing seasons. The model requires soil and climate characteristics as well as management practices as input variables for the initialization of the simulation. In STICS, soil N_2O emission is simulated relying on the concepts described in Bessou et al. (2010). Nitrification and denitrification are simulated separately in the model, but coupled by nitrate production by nitrification, since it serves as substrate for denitrification. Nitrification is proportional to ammonium content and regulated by temperature and water-filled pore space (WFPS). Field experiment soil pH does not constrain nitrification rate as pH levels are in the high range. Soil N_2O emission as a result of nitrification represents a variable fraction of the nitrification rate depending on WFPS (Khalil *et al*., 2004). In turn, denitrification is the product of a soil dependent potential rate and nitrate concentration, soil temperature and SWC. The emission of N_2O associated to denitrification is then calculated as a variable fraction of the denitrification rate depending on pH and WFPS. A more detailed description of N_2O emission simulation by STICS can be found in Plaza-Bonilla *et al*. (2017).

Independent data from the two datasets obtained were used to calibrate the model. First, model calibration for N_2O emissions simulation was performed using the data obtained in the CT-60 and NT-60 treatments. Second, soil profile (i.e. 0-90 cm depth at 30-cm increments) water and mineral N contents and crop biomass production was calibrated with data obtained in the first three seasons (i.e. from 1996-1997 to 1998-1999), when more intensive crop biomass samplings were performed. The soil was divided in different layers according to the soil sampling depths established in the field experiment (i.e. 0-5, 5-30, 30-60 and 60-90 cm depth). Soil input variables were obtained from analysis, with the exception of gravimetric soil moisture at field capacity and permanent wilting point, which were initially estimated using a pedotransfer function (Saxton and Rawls, 2006). For each treatment, soil surface crop residues characteristics (i.e. amount, N concentration and C:N ratio) were introduced as crop management inputs. During the calibration process a poorer simulation of soil surface (0-5 cm depth) water dynamics on the high range of the values was detected under CT compared to NT. Therefore, field capacity was tuned as suggested by soil moisture measurements (0.179 and 0.206 g g^{-1} for CT and NT, respectively). Soil depth at which denitrification can take place was set at 0-20 cm depth. Potential denitrification rate was set at 3 kg N ha^{-1} d^{-1}, based on maximum N_2O peaks in the same field under irrigated conditions and the maximum N_2:N_2O ratio measured in the laboratory under controlled conditions (Klemedtsson *et al*. 1988).

The performance of the model to simulate soil N_2O emissions and its ancillary variables was evaluated by comparing the measured data obtained in the 2011-2012 season for the CT-0, CT-120, NT-0 and NT-120 treatments with the simulated values. In turn, the model performances to simulate soil profile (0-90 cm depth) water and mineral N contents and crop biomass dynamics was evaluated with data of the last 15 years of the experiments. The linear relationship between observed and simulated values (intercept, slope and coefficient of determination) and other statistical criteria were calculated: relative root mean square error (rRMSE), mean deviation or bias (MD) and model efficiency (ME):

Where:

n is the number of observations, S_i and O_i are the simulated and the observed values, respectively and

O

is the mean of the observed values.

Long-term simulation of N_2O emissions.

After evaluation, and judging a satisfactory performance, the model was used to simulate the emissions of N_2O of the eighteen years of differentiated tillage (CT and NT) and increasing N fertilization treatments (0, 30, 60, 90, and 120 kg N ha^{-1}), covered by the range compared experimentally (0 to 120 kg N ha^{-1}), to identify the impact of N rates on N_2O emissions, EF and YSNE for a given tillage treatment. Independent runs were initialized using the observed soil moisture and mineral N contents (at 0-30, 30-60 and 60-90 cm) for the 0, 60 and 120 kg N ha^{-1} treatments and interpolating the values for the 30 and 90 kg N ha^{-1} scenarios, and the actual management practices (Table S1) and climate inputs. This approach combining modelling and experimental results carrying out yearly independent simulations aimed at reducing the uncertainty of the N_2O simulated values.

For each tillage system the emission factor (EF) was calculated as the difference between simulated cumulative N_2O emission from a fertilized treatment (30, 60, 90 and 120 kg N ha^{-1}) and the non-fertilized control, divided by the amount of N fertilizer applied on each treatment. For each year, tillage and nitrogen rate combination, YSNE was calculated as the quotient between the cumulative annual N_2O emissions and grain yield (as dry matter). Since grain yield was only measured in 0, 60 and 120 kg N ha^{-1} treatments, a segmented regression (assuming a linear-plateau model) for each tillage x year combination was carried out to analyze grain yield response to N application and estimate grain yields under the 30 and 90 kg N ha^{-1} scenarios, using the non-linear platform of the JMP 12 statistical package (SAS Institute Inc, 2015).

An analysis of variance was performed for measured grain yield with tillage, N fertilization, year and their interaction as sources of variation. When significant, differences among treatments were identified at 0.05 probability level of significance by a LSD test. Grain yield data of the 2004-2005 season was excluded from the analysis due to lack of replicates (i.e. only one replicate was harvested due to extreme dry conditions during the season). A multiple linear regression was calculated to predict simulated cumulative N_2O emission based on observed key variables (i.e. cropping season precipitation, water deficit, amount of nitrate-N at the beginning of the season and crop residues returned to the soil). The simple and combined effects of the last variables on the fraction of N_2O emissions produced by denitrification were also analyzed. Data analysis was performed with the JMP 12 statistical package (SAS Institute Inc, 2015).

3. Results

3.1. Weather characteristics during the experimental period

The precipitation from July (year y) to June (year y+1) was highly variable during the study period, ranging between 244 mm in the 2004-2005 cropping season to 702 mm in the 2009-2010 cropping season (Figure 1). Of the eighteen years that covered the experiment, 9 received an amount of precipitation below the 30-year average, i.e. 401 mm. Annual temperature ranged between 12.8 ºC in the 2007-2008 season and 14.7ºC in the 2000-2001 and 2011-2012 seasons (Figure 1). The yearly dynamics of air temperature followed the typical Mediterranean pattern (with a continental trend) being the winters mild to cold and the summers very hot with hourly temperatures well-above 35 ºC. Of the 18 years a total of 168 days presented a mean daily temperature below 0 ºC, being a 6%, 44%, 32%, 15% and 3% in November, December, January, February and March, respectively.

3.2. Tillage and nitrogen effects on barley grain yield.

Mean grain yields of the 1996-2014 period were 1455, 1532, and 1590 kg ha^{-1} for the CT-0, CT-60 and CT-120 treatments and 1601, 2248 and 2426 kg ha^{-1} for the NT-0, NT-60 and NT-120 treatments, respectively. Under CT, the highest yields were registered in 2009-2010 with 3737 kg ha^{-1} without differences between N rates. Under NT, the highest yield was registered in 2008-2009, with 3973 kg grain ha^{-1} when applying 60 kg N ha^{-1}. The lowest yields were observed in 2004-2005, when a complete failure of the crop occurred under CT and only 606 kg grain ha^{-1} were obtained under NT as an average of N rates.

Barley grain yield was significantly affected by the tillage x nitrogen x year interaction (p = 0.004). Significant differences between treatments were observed in 17 out of the 18 years that covered the experiment, since the 2004-2005 season was not included in the analysis. In the first two years of experiment CT led to greater grain yields than NT (Figure 2). Differently, from the third year of experiment onwards, greater yields were observed under NT compared to CT in the treatments with 60 and 120 kg N ha^{-1} in 13 cropping seasons. The exceptions were observed in the rainy 2003-2004 and 2009-2010 seasons, when no differences between tillage systems were found at a given N rate different from the control. Crop yield response to N application was severely affected by the type of tillage performed. In this line, no grain yield response to the application of 60 kg N ha^{-1} was observed under CT, while greater grain yields than the control treatment were observed in 11 occasions under NT. The application of further 60 kg N ha^{-1} under NT (i.e. a rate of 120 kg N ha^{-1}) only increased grain yield in three cropping seasons (1997-1998, 1999-2000, and 2000-2001) while reduced grain yield in the 2009-2010 cropping season.

3.3. Model evaluation.

Model efficiency was greater than 0.5 for all the ancillary variables with the exception of soil nitrate at soil surface (0-5 cm) since the exceptionally high observed values in the CT-120 treatment led to an underestimation by the model (Figure 3, Table 2). STICS performed reasonably well when simulating the dynamics of soil moisture at soil surface (0-5 cm) with some overestimated values in the CT treatment (Figure 3). The fluctuation of surface soil (5 cm) temperature was well simulated by the model, independently of the treatment, with a good agreement between observed and simulated values (Table 2). The model adequately responded to the application of fertilizer with an increase in soil ammonium (0-5 cm) levels similar than the observed (Figure 3).

Observed and simulated soil N_2O emissions were similar, with observed and simulated values ranging from -2.7 to 9.7 g N_2O-N ha^{-1} d^{-1} and from 0 to 15.3 g N_2O-N ha^{-1} d^{-1}, respectively. Measured cumulative N_2O emission during the 2011-2012 barley growing season was calculated at 0.09, 0.40, 0.09 and 0.22 kg N_2O-N ha^{-1} for the CT-0, CT-120, NT-0 and NT-120 treatments, respectively, while the corresponding simulated values were in the same range with 0.08, 0.34, 0.10 and 0.30 kg N_2O-N ha^{-1}. The agreement between observed and simulated cumulative N_2O values was very good, with a ME of 0.83 and rather low MD and rRMSE, although simulated values presented a slight underestimation (i.e. slope of 0.84).

In the 2000-2014 period, measured soil moisture of the rooting depth (0-90 cm) ranged from 78 to 235 mm and 76-218 mm for CT and NT, respectively. Comparatively, the corresponding simulated values ranged from 82 to 240 and 69-234 mm, respectively. The model showed a good performance with a low rRMSE (17.6%) and a ME and slope of the regression of 0.62 and 1.09, respectively (Table 2). The model simulated better the amount of soil nitrate in the first 30 cm soil depth and in the whole rooting depth (0-90 cm) than in the soil surface (0-5 cm) in the 2011-2012 barley cropping season (Table 2). For the 0-90 cm soil depth, the agreement between observed and simulated values led to a ME of 0.74 and a slope close to 1 (i.e. 0.92). However, the rRMSE reached a 44.8%. Barley above-ground biomass and grain yield were highly variable during the experimental period (Figure 4). In the CT-0, CT-60 and CT-120 treatments observed biomass ranged from 0.5 to 10.6 Mg ha^{-1}, 0.7-11.7 Mg ha^{-1} and 0.3-11.3 Mg ha^{-1}, respectively. In NT-0, NT-60 and NT-120 observed biomass ranged from 1.5 to 11.8 Mg ha^{-1}, 2.3-12.6 Mg ha^{-1}, 3.3-13.3 Mg ha^{-1}, respectively, corresponding to the same cropping seasons (Figure 4). The model was relatively able to simulate the great temporal variability on crop growth and grain yield, although the ME was lower than 0.25 for both variables (Figure 4; Table 2).

3.4. Predicting long-term tillage and increasing N rates impact on N_2O emissions, yield-scaled N_2O emissions, and emission factor.

Simulated annual cumulative N_2O emissions were 0.50, 0.67, 0.82, 0.98 and 1.09 kg N_2O-N ha^{-1} yr^{-1} for the CT-0, CT-30, CT-60, CT-90, and CT-120 treatments, respectively, as an average of the 1996 to 2014 period. Slightly greater average annual values were simulated for the same N rates under NT, with 0.53, 0.73, 0.92, 1.07, and 1.19 kg N_2O-N ha^{-1} yr^{-1}, respectively (Table 3). A great variability between years on cumulative N_2O emissions was also simulated by the model, with coefficients of variation greater than 50% for the different treatments. The lowest value (0.07 kg N_2O-N ha^{-1} yr^{-1}) was obtained under NT-0 in the 2002-2003 season, while the highest (2.95 kg N_2O-N ha^{-1} yr^{-1}) was simulated under NT-120 in 2010-2011. The fraction of N_2O derived from denitrification ranged between 0.42 and 0.81, with an average of 0.66 and being very similar between tillage treatments. For a given tillage treatment, slight greater values were simulated at greater N rate, as an average of the 18 years of the experiment (Table 3).

The simulated N_2O EF was about 0.57% in average of the 18 years, with values of 0.56, 0.53, 0.54, 0.50, 0.65, 0.65, 0.65, 0.60, and 0.55 for the CT-30, CT-60, CT-90, CT-120, NT-30, NT-60, NT-90, and NT-120 treatments, respectively, with coefficients of variation between 44% and 73% (Table 4). This emission factor of N_2O only exceeded 1% in 2 situations under CT and in 9 situations under NT out of the 18 years crossed with 8 tillage x N rate combinations (144 situations) (Table 4).

In general, for a given tillage treatment, YSNE increased when increasing the N rate, being the lowest values found in the control treatment (0 kg N ha^{-1}) in most of the year x tillage combinations (Figure 5). However, that increase was of a greater magnitude under CT compared to NT, being YSNE of NT less responsive to the application of increasing N rates. Regarding to this, as an average of the eighteen cropping seasons studied, the yield-scaled N_2O emissions (YSNE) were 1.25, 1.40, 1.58, 1.88, and 2.11 g N_2O-N kg^{-1} grain under CT-0, CT-30, CT-60, CT-90 and CT-120, respectively. In turn, under NT the values were 0.45, 0.52, 0.56, 0.59, and 0.63 g N_2O-N kg^{-1} grain, for the NT-0, NT-30, NT-60, NT-90, and NT-120 treatments, respectively (Figure 5). In most of the cases, greater YSNE were observed under CT compared to NT for a given N rate (Figure 5). Exceptions were observed in the first two cropping seasons (1996-1997 and 1997-1998) when lower yields occurred under NT, and in 2010-2011. Yield-scaled N_2O emissions were highly variable among years, with coefficients of variation above 100% in all the treatments, except NT-90 and NT-120. Independently of the treatment, the lowest YSNE values were found in the one of the highest yielding cropping seasons, i.e. 1997-1998. Differently, the highest YSNE was observed in CT-120 in the 2007-2008 season, with 15.2 g N_2O-N kg^{-1} grain. Under NT the greatest value was 2.69 g N_2O-N kg^{-1} grain, for NT-60 in 2007-2008 (Figure 5). A linear relationship was found between precipitation and the quotient between NT YSNE and CT YSNE for all N rates (excluding three cropping seasons) (Fig. S1, supplementary material). According to this relationship, YSNE values would be higher in NT than CT in years with precipitation above 608 mm.

A multiple linear regression was calculated to predict cumulative N_2O emissions based on different dependent variables. Cumulative N_2O emissions (kg N_2O-N ha^{-1}) were significantly explained (P<0.001; R^2=0.31) by the combination of seasonal precipitation (PPT, mm), water deficit (as seasonal precipitation minus potential evapotranspiration, mm), crop residues of the previous season (Mg DM ha^{-1}) and the amount of soil nitrate at 0-30 cm soil depth at the beginning of the season (kg NO_3^--N), being the four variables significant predictors of cumulative N_2O emissions. The resulting linear multiple variables model was as follows:

Cumulative N_2O emissions = 0.0061 (PPT) – 0.0046 (Water deficit) + 0.1650 (Crop residues) + 0.0012 (Soil Nitrate-N) – 5.45.

In the CT treatment, the amount of crop residues incorporated to the soil in the previous season was negatively related to the fraction of N_2O emitted due to denitrification (N_2O_{den}), following the relationship: N_2O_{den} = 0.71 – 0.024 (Crop residues). No significant relationship was found between N_2O_{den} and precipitation, water deficit, and soil nitrate (0-30 cm).

4. Discussion

4.1. Long-term tillage and N fertilization effects on barley yields

As an average of the 18 years of experiment, NT increased grain yield by a 10, 47 and 53% compared to CT when applying 0, 60 and 120 kg N ha^{-1}, respectively. Under semiarid rainfed Mediterranean conditions NT increases the amount of water stored in the soil proportionally to the aridity of the site, increasing crop yields (Lampurlanés *et al*. 2016), with differences between tillage systems being larger in drier years. The impact of soil water availability on NT performance would be confirmed by the lack of differences between tillage systems when applying 60 or 120 kg N ha^{-1} in the 2003-2004 and 2009-2010 seasons, when rainfall was above than the average. The long-term data also showed differences between tillage systems on grain yield response to N fertilization. The application of 60 kg N ha^{-1} led to greater yields than the control without N in 11 occasions (i.e. years) under NT. The grain yield response to the highest N rate (120 kg N ha^{-1}) was uncommon, being only observed in 3 occasions out of 18 under NT. Differently, no response to N fertilizer was observed under CT. Grain yield response to N fertilization under NT would be the consequence of greater amount of water available for the crop, being modulated by soil mineral N availability and the aridity of the site (Cantero-Martínez *et al*., 2016). The aridity of the site would play a major role, since the differential response of yields to N fertilization depending on the tillage system has not been observed in wetter rainfed Mediterranean environments such as Central Italy (Seddaiu *et al*., 2016).

Yields declined in the first 2 years after the implementation of no-tillage, which corresponded to rainy seasons with 582 and 460 mm in 1997-1998 and 1998-1999. In a recent meta-analysis Pittelkow *et al*. (2015) reported similar yields between NT and CT

1 or 2 years after NT implementation, but never greater under NT. Moreover, as an average of all studies covered by the meta-analysis, they reported a 12% decline in yields when using NT without N fertilizer applications. Both aspects differ from our results, pointing out the need to take into account the local component (i.e. specific pedoclimatic conditions and agricultural management practices) to evaluate the performance of NT on crop yields in a given location. The lag period of 2 years until NT reached greater yields than CT would be the consequence of the time required for the improvement on soil hydraulic properties, related to the amount of soil organic matter and soil aggregate stability, which are greatly influenced by NT duration (Álvaro-Fuentes *et al*., 2014; Pittelkow *et al*., 2015; Plaza-Bonilla *et al*., 2013).

4.2. Model evaluation, and magnitude and temporal variation of simulated N_2O emissions.

We used an approach that links long-term observed field data with model retrospective simulation to assess the long-term impact of different tillage systems and increasing N rates on soil N_2O emissions and crop productivity in rainfed Mediterranean conditions. The main aim of the approach followed was to reduce the uncertainty associated to the predictions, similarly than Ludwig *et al*. (2011).

According to the results obtained from the different statistical tests used, the STICS model performed relatively well when simulating the different soil N_2O emission ancillary variables, i.e. soil moisture, temperature, and ammonium and nitrate nitrogen. Coucheney *et al*. (2015) reported a good overall accuracy when using STICS to simulate soil water and N and plant biomass in a wide range of pedoclimatic conditions in France under 15 different crops, highlighting the versatility of the model to accurately simulate under different conditions.

The agreement between observed and simulated soil nitrate at 0-30 and 0-90 cm depth, indicated by the rRMSE, was similar than the one reported by Coucheney *et al.* (2015). In our study, the prediction of the magnitude and dynamics of cumulative N_2O emissions was accurate, in line with those reported by Plaza-Bonilla et al. (2017) when using STICS to simulate the cumulative emission of N_2O under durum wheat and faba bean in low-input cropping systems of SW France. However, it must be taken into account that the non-continuous measurements of N_2O emissions under field conditions may underestimate the actual N_2O-N losses (Campbell *et al*., 2014). The model was also able to accurately simulate the dynamics of SWC and nitrate N and crop above-ground biomass and grain yield during the duration of the field experiment under different tillage systems and N rates. Soil water and crop growth have a great influence on the amount of N susceptible to be nitrified and/or denitrified. These aspects justify the implementation of STICS as a tool to estimate soil N_2O emissions, given the high year-to-year variability of water availability and crop performance under Mediterranean conditions (Flower *et al*., 2017; Lampurlanés *et al*., 2016; Seddaiu *et al*., 2016).

Interestingly, throughout the simulation period (1996-2014), the model predicted a high year-to-year variability of soil N_2O emissions under rainfed Mediterranean conditions independently of the mineral N rate applied, according to the irregularity of precipitations as shown by Plaza-Bonilla *et al.* (2017). According to the model, denitrification would play a slightly greater role than nitrification on soil N_2O emissions. Similarly, Meijide *et al*. (2007) reported greater relative importance of denitrification over nitrification on soil N_2O emissions under Mediterranean conditions. The magnitudes of the annual emissions simulated were in agreement with the ones reported in the literature for similar Mediterranean environments and cropping systems. Values as low as 72 g N_2O-N ha^{-1} yr^{-1} were reported by Tellez-Rio *et al*. (2017) from a

NT wheat in Central Spain. Garcia-Marco *et al*. (2016) reported cumulative emissions between 183 and 1110 g N_2O-N ha^{-1} in a triticale cropping season (i.e. from September to June) in SW Spain. Menéndez et al. (2008) measured N_2O emissions during wheat fertilization events in a rainfed area of southern Spain, quantifying values as high as and 2378 g N_2O-N ha^{-1}. Similarly, in Central Italy, Bosco et al. (2015) observed N_2O cumulative emissions ranging between 827 and 2340 g N_2O-N ha^{-1} in a durum wheat season when applying 0 and 170 kg N ha^{-1}, respectively.

Cumulative N_2O emissions were partly explained by the combination of seasonal precipitation, water deficit, crop residues of the previous season and the amount of soil nitrate at 0-30 cm soil depth at the beginning of the season. Soil water availability plays a major role regulating the nitrification and denitrification rates, being a key soil N_2O controlling mechanism under Mediterranean conditions (Plaza-Bonilla *et al*., 2017). In turn, release of C after crop residues incorporation provides the energy for microbial denitrification (Ábalos *et al*., 2013), while nitrate acts as electron acceptor during denitrification. The high year-to-year variability of N_2O emissions under Mediterranean conditions would consequently be explained by the variability in the last variables.

4.3. Long-term tillage and N fertilization effects on N_2O emissions, and yield-scaled N_2O ratio.

The STICS model predicted that in rainfed Mediterranean systems cumulative N_2O emissions would be greatly affected by N rate, with a minor impact of tillage systems, coinciding with the findings of Plaza-Bonilla *et al*., (2014) and Bosco *et al*., (2015) in tillage and N fertilization combination experiments.

In general, the use of NT led to greater crop yields and similar cumulative N_2O emissions than CT, resulting on lower (-66%) YSNE in most cropping seasons.

According to the data of 15 out of 18 cropping seasons studied, YSNE would only be greater under NT compared to CT in years with precipitation above 600 mm. In most of the cropping seasons YSNE would increase when increasing the N rate under CT. Differently to CT, under NT, YSNE would be more resilient to the application of increasing N fertilizer rates, providing the farmers and stakeholders more versatility when using or establishing a recommended N rate in the rainfed Mediterranean area. Regarding to this, in the case-study covered here, the recommended rate would range between 30 and 60 kg N ha^{-1}. This range would optimize barley grain yield while maintaining YSNE at low values, close to the obtained when applying no N fertilizer. Kim and Giltrap (2017) stressed the need to increase our knowledge in the response of YSNE to N input in different cropping systems and pedoclimatic conditions, given the current lack of data. The YSNE permits to identify the best strategy in terms of emissions of N_2O per production unit for a given pedoclimatic and cropping system content. For instance, in less water-limited environment of Upper Midwest USA, Venterea *et al*. (2011) observed lower corn (*Zea mays* L.) grain yields under NT, which resulted in yield-scaled N_2O emissions with NT being more than 50% greater than CT. In the climatic conditions of last authors study lower soil temperature in spring under NT delay crop growth, affecting yields negatively. Contrarily, in rainfed Mediterranean agroecosystems the lower YSNE and greater grain yields under NT should be seen as a win-win strategy for the relationship between agricultural productivity and environmental sustainability. Moreover, in these areas it could be expected that a wider assessment of the GHG footprint of the cropping system would equally be favorable to NT, given the potential of this system to sequester soil organic carbon, at least, during the first decade after its implementation (Álvaro-Fuentes *et al*., 2014).

The slightly greater soil N_2O emissions found under NT when compared to CT at a given N rate could be explained by the greater amount of water stored in the soil under NT (Lampurlanés *et al*., 2016), which would increase the nitrification rate and/or reduce the air-filled porosity boosting denitrification during rainy periods. However, the long-term maintenance of NT is also related to a soil structure improvement, mainly as a result of greater water-stability of soil macroaggregates (Plaza-Bonilla *et al*., 2013), which may offset the impact of soil moisture on N_2O emissions under non-tilled soils (van Kessel *et al*., 2013). Unfortunately, most models ignore the dynamic nature of soil structure and the impact of soil management on its temporal evolution (Vereecken *et al*., 2016). Different works have been performed to study the impact of tillage practices on soil N_2O emissions under field crops cultivation in rainfed Mediterranean conditions. Lower cumulative N_2O emissions in NT compared to CT have been found in Spain under wheat (Tellez-Rio *et al*., 2017), and triticale (Garcia-Marco *et al*., 2016) cultivation, and in south-eastern Australia (Li *et al*., 2016) in a canola crop. Other authors have reported no differences between CT and NT (Bosco *et al*., 2015; Menéndez *et al*., 2008; Tellez-Rio *et al*., 2015a, 2015b). Contrasting results depending on the amount of years since NT implementation on barley cultivation were observed by Plaza-Bonilla *et al*. (2014) with greater soil N_2O emissions under NT compared to CT in the short-term (3-yr) and the contrary results in the long-term experiment covered by the present work.

Average EF for the CT-60, CT-120, NT-60 and NT-120 treatments ranged between 0.50 and 0.65. These values were in the high range of the EF reported by a recent meta-analysis of N_2O emissions from Mediterranean rainfed cropping systems (Cayuela *et al*., 2017). The pioneering work of Bouwman (1996) led to the establishment of the IPCC Tier 1 value that was subsequently updated to 1% (IPCC, 2006).

5. Conclusions

Overall, STICS showed a satisfactory performance when simulating soil N_2O emission and ancillary variables such as biomass and nitrogen and water dynamics budgets in the water-limited rainfed Mediterranean agroecosystem studied. According to our approach including retrospective model simulations and long-term field measurements the use of long-term NT and medium N fertilizer rates (30-60 kg N ha^{-1}) supposes a win-win strategy to maximize barley grain yield while maintaining low yield-scaled N_2O emissions in rainfed Mediterranean agroecosystems. Similar than grain yields, soil N_2O emissions would present a very high year-to-year variability, according to the simulations, being modulated by precipitation and water deficit, soil nitrate and the amount of crop residues. Increasing N fertilization under CT would led to an increase in the magnitude of N_2O emissions and YSNE, given the lack of enough water in the soil restricting crop response to mineral N application. Finally, our work gives some evidence that the EF is almost half of the proposed by IPCC in such semi-arid Mediterranean conditions, which needs to be taken into account when evaluating the contribution of agriculture to GHG emissions.

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Figure captions

Fig. 1 Mean monthly precipitation (black columns), potential evapotranspiration (PET, red empty columns) and air temperature (grey line) at Agramunt: 30-yr average values (in italics) and 1996 to 2014 cropping seasons (i.e. shown from July to June). For each season mean temperature and total precipitation are reported. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2 Measured barley grain yield under different tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (0, 60 and 120 kg N ha^{-1}) treatments. Within each season, different letters indicate significant differences between treatments at 0.05 probability level according to a Tukey HSD test.Vertical bars correspond to the standard error.

Fig. 3 Dynamics of soil moisture (0-5 cm), soil temperature (5 cm), soil nitrate and soil ammonium (0-5 cm), soil N_2O flux and cumulative N_2O-N loss in the 2011-2012 barley season under different types of tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (0, control; 120, 120 kg N ha^{-1}) used for STICS evaluation. Simulated and observed values are shown by continuous lines and circles, respectively. Vertical bars correspond to the standard error. Arrows indicate N fertilizer applications.

Fig. 4 Barley above-ground biomass and grain yield as affected by tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (0, 60 and 120 kg N ha-1 yr-1) during the 1996-2014 period. Simulated and observed values are shown by continuous lines and circles, respectively. Vertical bars correspond to the standard error.

Fig. 5 Yield-scaled N_2O emissions calculated as the quotient between simulated cumulative soil N_2O emissions and grain yield (dry matter) as affected by tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (0, 30, 60, 90, and 120 kg N ha^{-1} yr^{-1}) in a rainfed barley cropping system during the eighteen cropping seasons of the 1996-2014 period. n.d., not-determined. For each sub-figures row, the Y-axis scale corresponds to the sub-figure in the left.

Table 1. Soil characteristics of Ap horizon (0-28 cm) at the beginning of the field experiment (1996).

Soil characteristic	
Soil classification[a]	Typic Xerofluvent
pH (H_2O, 1:2.5)	8.5
$EC_{1,5}$ (dS m^{-1})	0.15
Organic C (g kg^{-1})	7.6
Organic N (g kg^{-1})	0.76
$CaCO_3$ eq. (%)	40.0
Particle size distribution (%)	
Sand (2000-50 µm)	46.5
Silt (50-2 µm)	41.7
Clay (< 2 µm)	11.8

[a] According to the USDA classification (Soil Survey Staff, 2014).

Table 2. Statistical criteria showing the performance of the STICS model when simulating different variables related to (i) soil N_2O emissions and (ii) other agronomic soil and crop variables. For soil N_2O emissions data corresponds to the conventional- and no-tillage treatments without N fertilization and with 120 kg N ha^{-1} of the 2011-2012 season in Agramunt. For agronomic soil and crop variables data corresponds to the conventional- and no-tillage treatments without N fertilization and with 60 and 120 kg N ha^{-1} of the 2000-2014 period in Agramunt.

Type of data	Variable	Soil depth (cm)	n	ME	MD	rRMSE (%)	Intercept	Slope	r^2
Soil N_2O emissions-related	Soil moisture	0-5	46	0.58	1.7 g 100 g^{-1}	30.9	7.05	0.57	0.69
	Soil temperature	5	64	0.93	0.6 ºC	20.8	1.38	0.92	0.94
	Soil nitrate	0-5	46	-0.33	-44.4 kg NO_3^--N ha^{-1}	141.0	4.15	0.09	0.16
	Soil ammonium	0-5	46	0.78	-0.3 kg NH_4^+-N ha^{-1}	67.5	-0.44	1.04	0.83
	Cumulative N_2O-N	-	4	0.83	0.006 kg N_2O-N ha^{-1}	25.8	0.038	0.84	0.84
Agronomic soil and crop variables	Soil moisture	0-90	264	0.62	3.1 mm	17.6	-9.91	1.09	0.76
	Soil nitrate	0-30	222	0.67	-3.2 kg NO_3^--N ha^{-1}	82.4	2.78	0.95	0.59
		0-90	222	0.74	-22.7 kg NO_3^--N ha^{-1}	44.8	3.49	0.92	0.77
	Above-ground biomass	-	226	0.24	1.7 Mg ha^{-1}	76.1	2.49	0.78	0.59
	Grain yield	-	87	0.16	0.4 Mg ha^{-1}	52.2	1.23	0.52	0.35

n, number of pairs; ME, model efficiency; MD, mean difference; rRMSE, relative root mean square error.

Table 3 Simulated cumulative soil N_2O emissions and fraction of total N_2O emission corresponding to denitrification (between brackets) as affected by tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (0, 30, 60, 90, and 120 kg N ha^{-1} yr^{-1}) in a rainfed barley cropping system during the eighteen cropping seasons of the 1996-2014 period.

Cropping season	Cumulative N_2O-N emission ($kg\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$)									
	CT-0	CT-30	CT-60	CT-90	CT-120	NT-0	NT-30	NT-60	NT-90	NT-120
1996-1997	1.05 (0.69)	1.08 (0.68)	1.17 (0.69)	1.29 (0.70)	1.42 (0.72)	1.05 (0.69)	1.08 (0.68)	1.16 (0.69)	1.30 (0.71)	1.43 (0.72)
1997-1998	0.12 (0.65)	0.18 (0.60)	0.23 (0.57)	0.28 (0.54)	0.32 (0.52)	0.15 (0.65)	0.18 (0.60)	0.24 (0.59)	0.34 (0.61)	0.49 (0.64)
1998-1999	0.11 (0.56)	0.15 (0.55)	0.22 (0.50)	0.28 (0.48)	0.34 (0.48)	0.24 (0.57)	0.26 (0.60)	0.28 (0.60)	0.38 (0.59)	0.49 (0.61)
1999-2000	1.11 (0.63)	1.38 (0.66)	1.60 (0.68)	1.82 (0.70)	2.01 (0.71)	1.08 (0.64)	1.29 (0.67)	1.50 (0.69)	1.90 (0.72)	2.20 (0.74)
2000-2001	0.34 (0.67)	0.46 (0.67)	0.67 (0.70)	1.02 (0.74)	1.20 (0.74)	0.39 (0.71)	0.64 (0.75)	0.80 (0.75)	0.96 (0.75)	1.05 (0.75)
2001-2002	0.21 (0.65)	0.46 (0.68)	0.63 (0.69)	0.69 (0.68)	0.74 (0.66)	0.25 (0.66)	0.61 (0.74)	0.90 (0.75)	1.10 (0.41)	1.28 (0.75)
2002-2003	0.18 (0.59)	0.30 (0.63)	0.42 (0.66)	0.50 (0.64)	0.57 (0.64)	0.07 (0.47)	0.13 (0.43)	0.19 (0.42)	0.26 (0.67)	0.34 (0.45)
2003-2004	0.29 (0.64)	0.42 (0.66)	0.58 (0.66)	0.69 (0.66)	0.77 (0.65)	0.21 (0.53)	0.33 (0.58)	0.64 (0.69)	0.69 (0.72)	0.70 (0.64)
2004-2005	0.16 (0.65)	0.32 (0.67)	0.44 (0.68)	0.55 (0.68)	0.62 (0.67)	0.20 (0.52)	0.44 (0.66)	0.71 (0.71)	0.83 (0.66)	0.95 (0.73)
2005-2006	0.30 (0.76)	0.39 (0.75)	0.51 (0.75)	0.57 (0.73)	0.63 (0.71)	0.21 (0.68)	0.28 (0.68)	0.33 (0.66)	0.41 (0.71)	0.48 (0.66)
2006-2007	0.29 (0.58)	0.37 (0.58)	0.47 (0.59)	0.55 (0.59)	0.64 (0.59)	0.18 (0.61)	0.44 (0.67)	0.62 (0.68)	0.83 (0.74)	1.01 (0.71)
2007-2008	0.96 (0.70)	1.03 (0.69)	1.25 (0.72)	1.54 (0.72)	1.68 (0.71)	0.74 (0.63)	1.26 (0.73)	1.66 (0.76)	1.63 (0.70)	1.50 (0.71)
2008-2009	0.98 (0.76)	1.28 (0.78)	1.52 (0.78)	1.71 (0.78)	1.84 (0.78)	0.52 (0.69)	0.74 (0.71)	0.87 (0.71)	0.95 (0.64)	1.00 (0.69)
2009-2010	0.66 (0.55)	0.88 (0.61)	0.99 (0.60)	1.37 (0.65)	1.34 (0.62)	0.66 (0.58)	0.91 (0.63)	1.15 (0.66)	1.18 (0.80)	1.19 (0.63)
2010-2011	0.47 (0.48)	0.73 (0.55)	0.97 (0.60)	1.24 (0.64)	1.53 (0.67)	1.81 (0.76)	2.25 (0.78)	2.70 (0.80)	2.81 (0.67)	2.95 (0.81)
2011-2012	0.24 (0.61)	0.43 (0.64)	0.55 (0.66)	0.71 (0.67)	0.79 (0.67)	0.30 (0.64)	0.40 (0.66)	0.50 (0.68)	0.58 (0.73)	0.59 (0.62)
2012-2013	0.79 (0.66)	1.12 (0.71)	1.33 (0.72)	1.54 (0.73)	1.74 (0.74)	1.14 (0.72)	1.29 (0.72)	1.43 (0.72)	1.59 (0.73)	1.73 (0.73)
2013-2014	0.76 (0.68)	1.02 (0.70)	1.20 (0.71)	1.37 (0.72)	1.51 (0.73)	0.41 (0.59)	0.62 (0.64)	0.96 (0.71)	1.56 (0.78)	2.09 (0.81)
Mean	0.50 (0.64)	0.67 (0.66)	0.82 (0.66)	0.98 (0.67)	1.09 (0.67)	0.53 (0.63)	0.73 (0.66)	0.92 (0.68)	1.07 (0.69)	1.19 (0.69)
Standard dev.	0.4 (0.07)	0.40 (0.06)	0.4 (0.07)	0.50 (0.07)	0.6 (0.08)	0.5 (0.08)	0.54 (0.08)	0.6 (0.08)	0.65 (0.09)	0.7 (0.08)
Coef. Var. (%)	70 (11)	60 (10)	54 (11)	51 (11)	50 (12)	87 (12)	74 (12)	67 (12)	61 (13)	59 (12)

Table 4 Simulated N_2O emission factor (EF) as affected by tillage (CT, conventional tillage; NT, no-tillage) and mineral N rates (30, 60, 90 and 120 kg N ha^{-1} yr^{-1}) in a rainfed barley cropping system during the eighteen cropping seasons of the 1996-2014 period.

Cropping season	Emission factor (%)							
	CT-30	CT-60	CT-90	CT-120	NT-30	NT-60	NT-90	NT-120
1996-1997	0.12	0.21	0.27	0.31	0.10	0.18	0.28	0.32
1997-1998	0.19	0.18	0.17	0.17	0.09	0.15	0.21	0.28
1998-1999	0.14	0.18	0.19	0.19	0.07	0.07	0.16	0.21
1999-2000	0.91	0.82	0.79	0.75	0.72	0.70	0.91	0.93
2000-2001	0.42	0.56	0.76	0.72	0.80	0.68	0.62	0.55
2001-2002	0.82	0.69	0.53	0.44	1.21	1.08	0.94	0.86
2002-2003	0.43	0.40	0.36	0.33	0.20	0.20	0.21	0.23
2003-2004	0.43	0.48	0.44	0.40	0.39	0.71	0.52	0.40
2004-2005	0.52	0.46	0.43	0.39	0.79	0.84	0.70	0.62
2005-2006	0.31	0.35	0.30	0.28	0.22	0.21	0.23	0.22
2006-2007	0.28	0.30	0.30	0.29	0.85	0.72	0.72	0.69
2007-2008	0.24	0.49	0.64	0.60	1.76	1.54	0.99	0.64
2008-2009	1.01	0.90	0.82	0.72	0.73	0.59	0.47	0.40
2009-2010	0.76	0.56	0.80	0.57	0.83	0.81	0.57	0.44
2010-2011	0.84	0.83	0.85	0.88	1.46	1.47	1.11	0.95
2011-2012	0.63	0.52	0.52	0.46	0.36	0.34	0.31	0.24
2012-2013	1.11	0.91	0.84	0.79	0.49	0.47	0.50	0.49
2013-2014	0.86	0.74	0.68	0.63	0.69	0.92	1.28	1.40
Mean	0.56	0.53	0.54	0.50	0.65	0.65	0.60	0.55
Standard dev.	0.32	0.24	0.24	0.22	0.48	0.43	0.34	0.32
Coef. Var. (%)	57	45	44	44	73	66	57	59

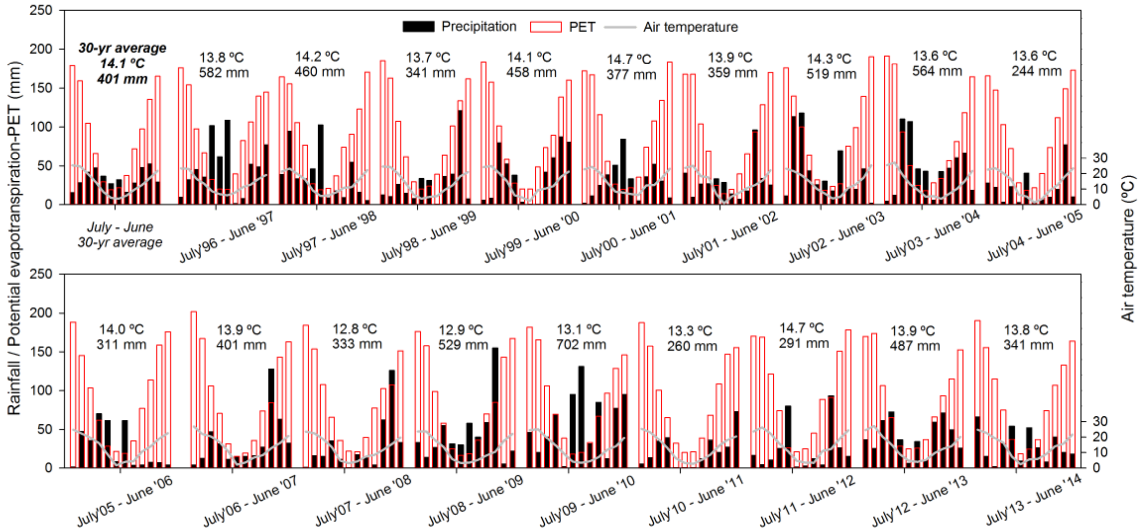
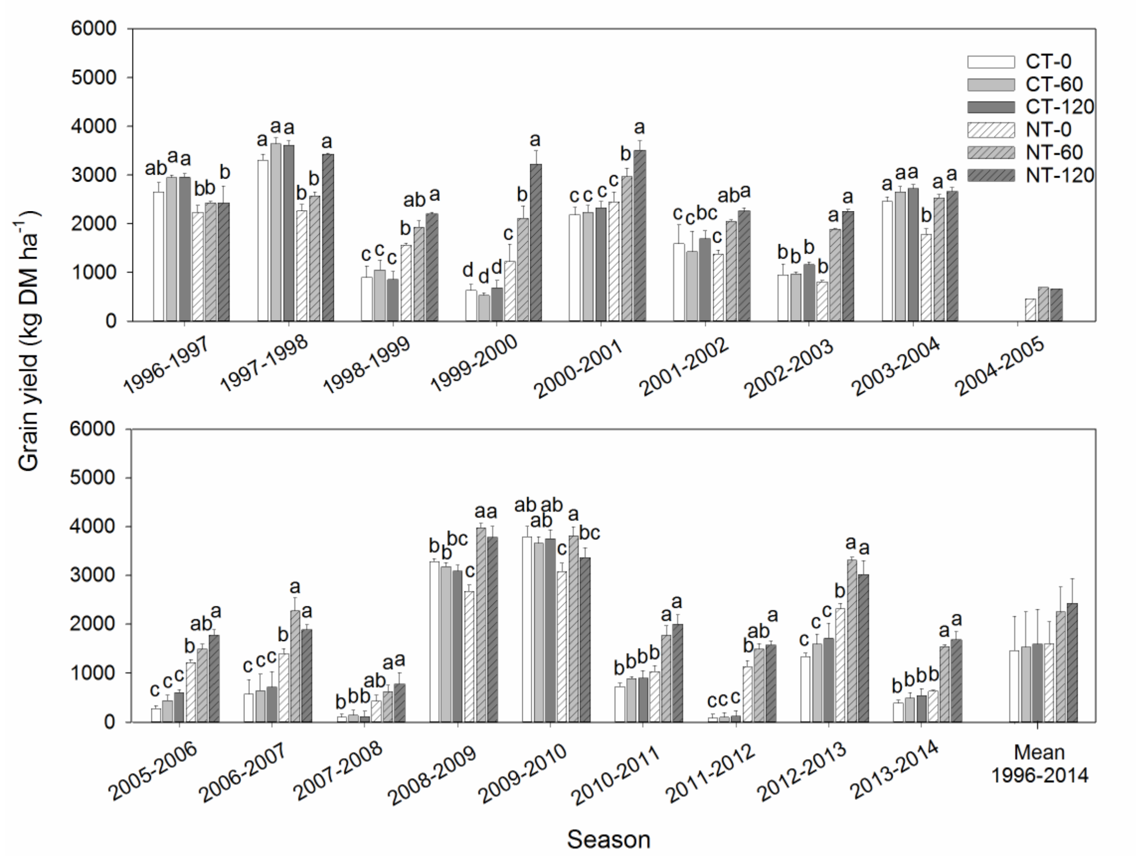

Precipitation
PET
Air temperature
Rainfall / Potential evapotranspiration-PET (mm)
Air temperature (ºC)
30-yr average
14.1 ºC
401 mm
July - June
30-yr average
13.8 ºC
582 mm
July96 - June '97
14.2 ºC
460 mm
July97 - June '98
13.7 ºC
341 mm
July98 - June '99
14.1 ºC
458 mm
July99 - June '00
14.7 ºC
377 mm
July00 - June '01
13.9 ºC
359 mm
July01 - June '02
14.3 ºC
519 mm
July02 - June '03
13.6 ºC
564 mm
July03 - June '04
13.6 ºC
244 mm
July04 - June '05
14.0 ºC
311 mm
July05 - June '06
13.9 ºC
401 mm
July06 - June '07
12.8 ºC
333 mm
July07 - June '08
12.9 ºC
529 mm
July08 - June '09
13.1 ºC
702 mm
July09 - June '10
13.3 ºC
260 mm
July10 - June '11
14.7 ºC
291 mm
July11 - June '12
13.9 ºC
487 mm
July12 - June '13
13.8 ºC
341 mm
July13 - June '14

Fig. 1



Grain yield (kg DM ha-1)
CT-0
CT-60
CT-120
NT-0
NT-60
NT-120
1996-1997
1997-1998
1998-1999
1999-2000
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
2007-2008
2008-2009
2009-2010
2010-2011
2011-2012
2012-2013
2013-2014
Mean 1996-2014
Season

Fig. 2

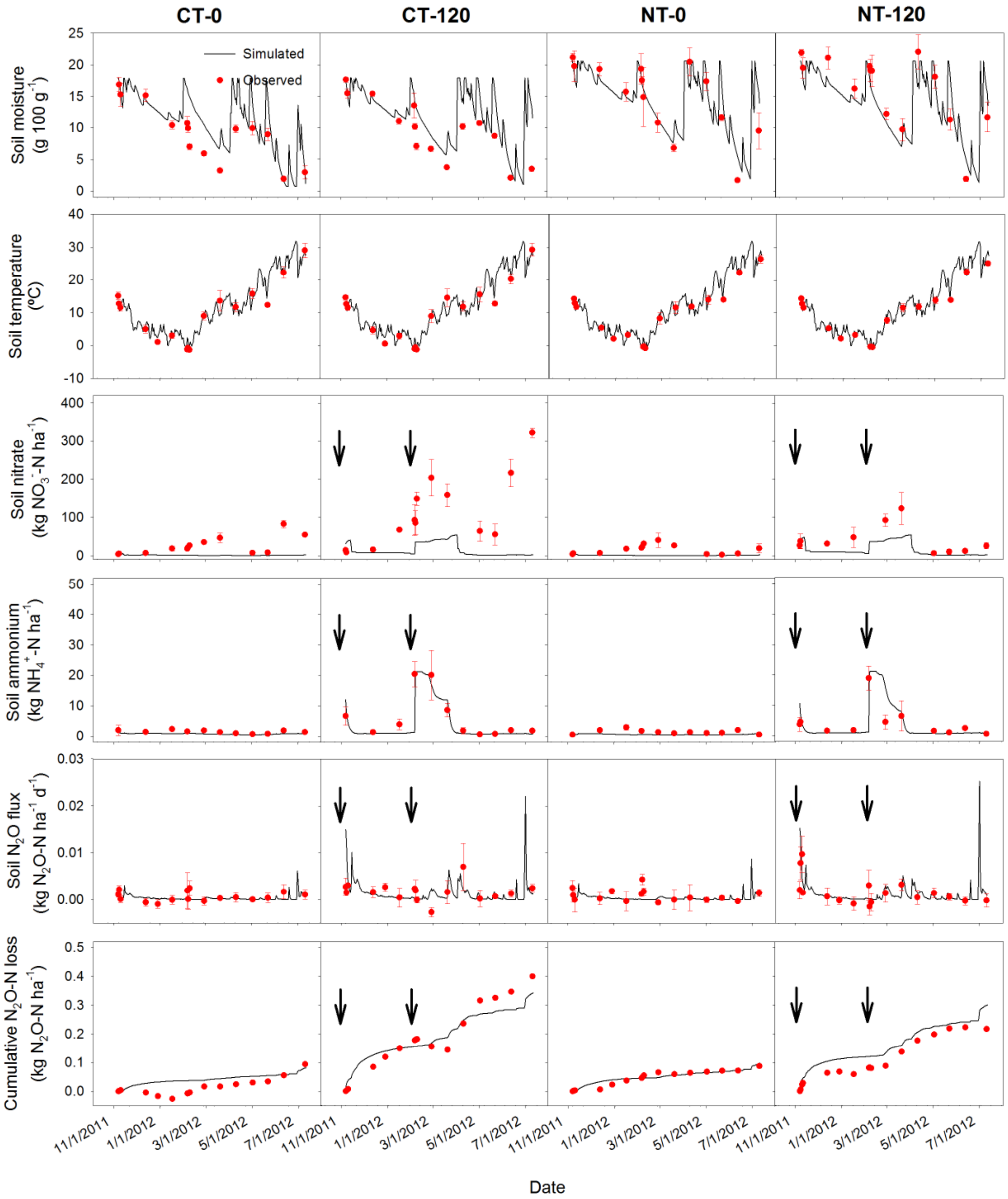

CT-0
CT-120
NT-0
NT-120
Simulated
Observed
Soil moisture (g 100 g^{-1})
Soil temperature (ºC)
Soil nitrate (kg NO$_3^-$-N ha^{-1})
Soil ammonium (kg NH$_4^+$-N ha^{-1})
Soil N$_2$O flux (kg N$_2$O-N ha^{-1} d^{-1})
Cumulative N$_2$O-N loss (kg N$_2$O-N ha^{-1})
11/1/2011
1/1/2012
3/1/2012
5/1/2012
7/1/2012
Date

Fig. 3

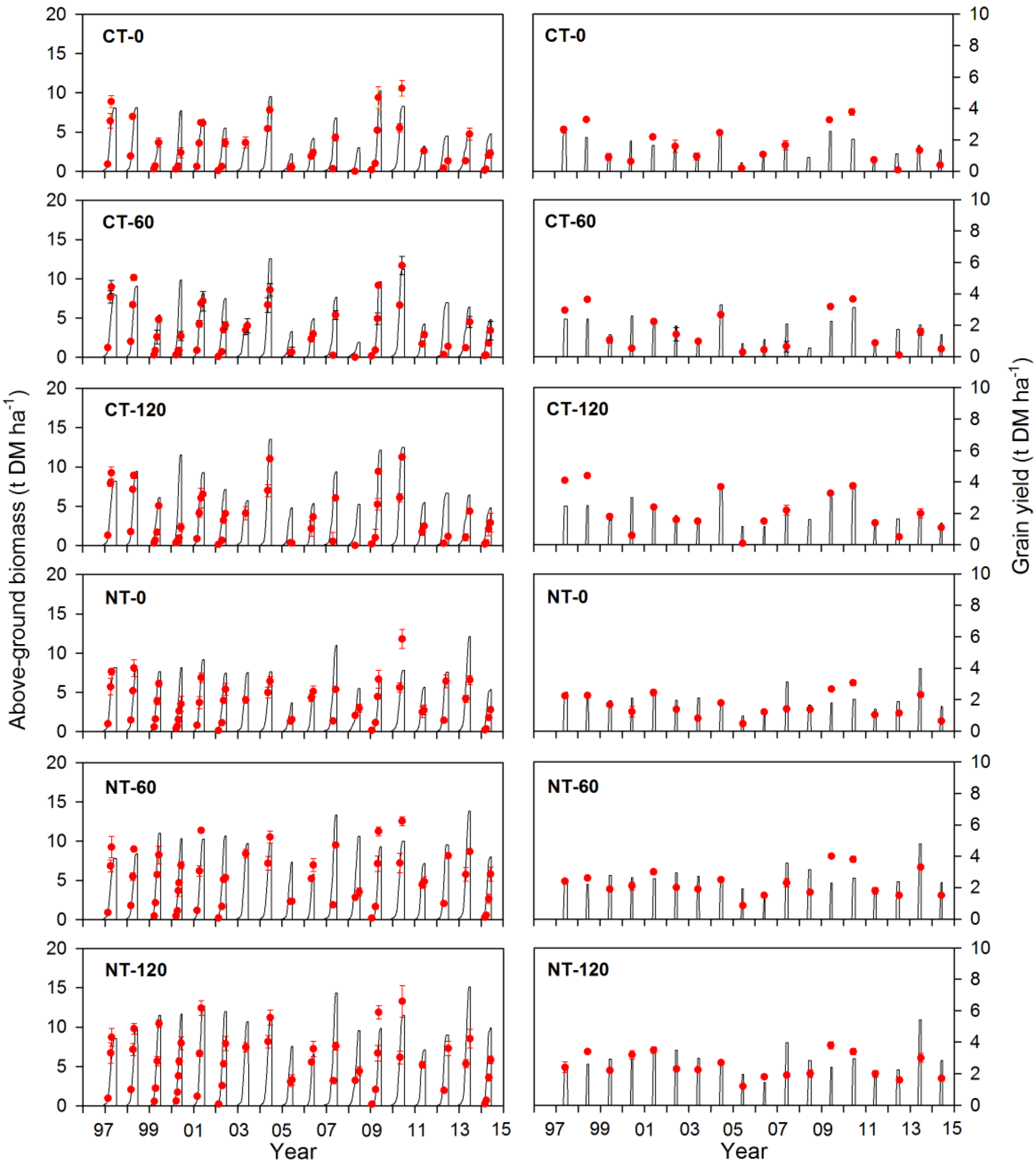

CT-0
CT-60
CT-120
NT-0
NT-60
NT-120
Above-ground biomass (t DM ha^{-1})
Grain yield (t DM ha^{-1})
Year
Year
97
99
01
03
05
07
09
11
13
15

Fig. 4

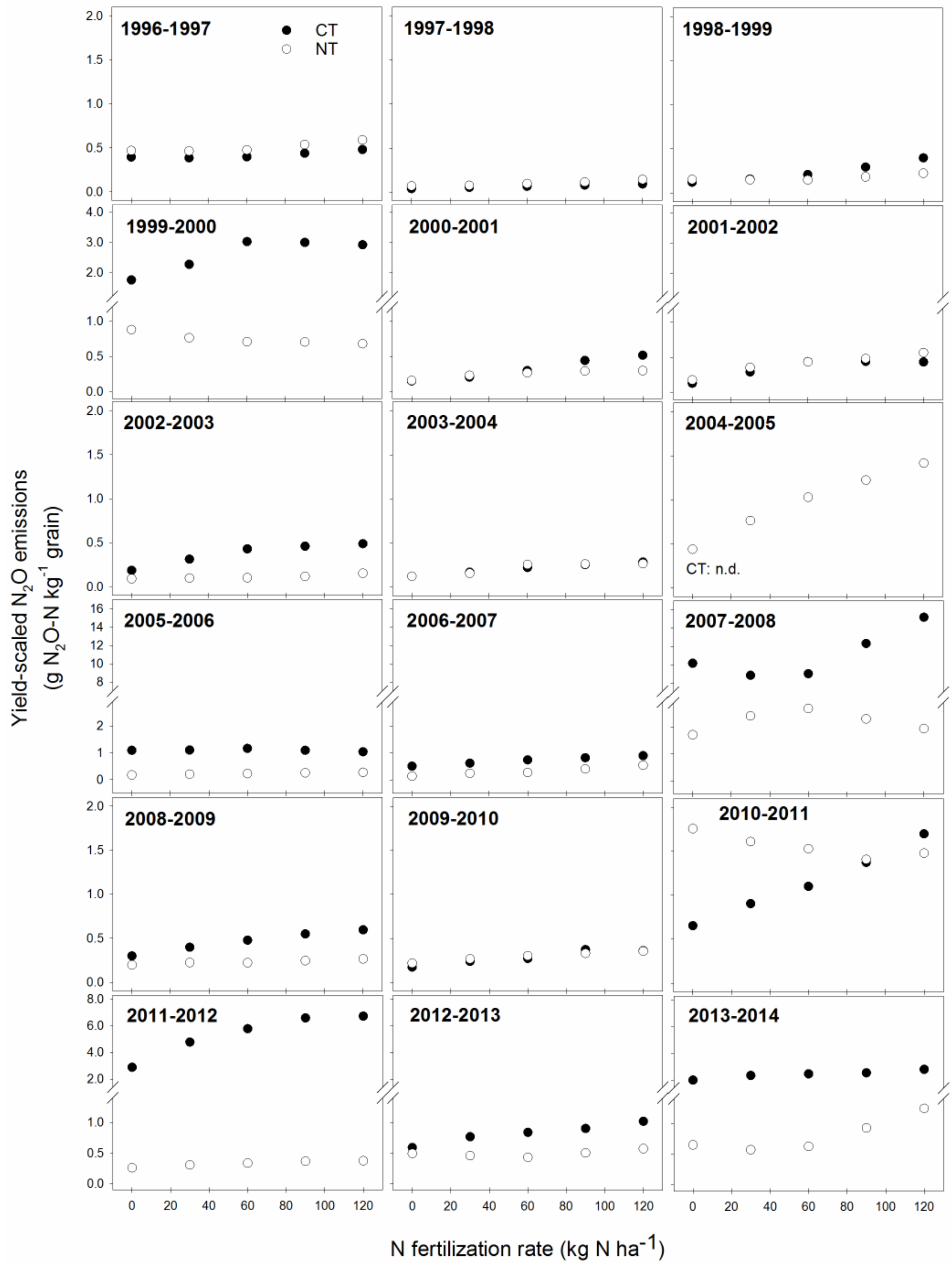

1996-1997
CT
NT
1997-1998
1998-1999
1999-2000
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
CT: n.d.
2005-2006
2006-2007
2007-2008
2008-2009
2009-2010
2010-2011
2011-2012
2012-2013
2013-2014
Yield-scaled N_2O emissions
($g\ N_2O\text{-}N\ kg^{-1}$ grain)
N fertilization rate ($kg\ N\ ha^{-1}$)

Fig. 5