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**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

Emission factor; Mediterranean; N fertilization; nitrous oxide; rainfed cropping
systems; soil management; STICS model.

23

24

Abstract

25 There is a strong need to identify agricultural management practices that maintain
26 agronomic productivity while diminishing soil N₂O emissions. The yield-scaled N₂O
27 emissions (YSNE) indicator can help to evaluate the adequacy of a given agricultural
28 practice under both aspects. Long-term (18-yr) soil water and mineral N dynamics, crop
29 biomass and yields, and 2011-2012 soil N₂O emissions and ancillary variables were
30 measured on barley (*Hordeum vulgare* L.) production in a tillage (conventional tillage,
31 CT; no-tillage, NT) and N rate (0, 60 and 120 kg N ha⁻¹) combination under rainfed
32 Mediterranean conditions (NE Spain). Once evaluated, the STICS soil-crop model was
33 used to simulate the 18-yr soil N₂O emissions of each tillage system under increasing N
34 rates (0, 30, 60, 90 and 120 kg N ha⁻¹) in order to identify optimum management to
35 reduce YSNE, being initialized with observed data. Cropping season precipitation was
36 highly variable during the experiment, being a key regulating mechanism for crop yields
37 and simulated soil N₂O emissions. Crop yield under NT with N outperformed CT in 11
38 years. STICS performed reasonably well when simulating cumulative N₂O emissions
39 and ancillary variables with model efficiencies greater than 0.5. The 18-yr average
40 simulated cumulative N₂O emissions were 0.50, 0.82 and 1.09 kg N₂O-N ha⁻¹ yr⁻¹ for
41 CT-0, CT-60 and CT-120, respectively, and they were 0.53, 0.92 and 1.19 kg N₂O-N ha⁻¹
42 yr⁻¹ for their counterparts under NT. These averages mask a large variability between
43 years, according to precipitation. The 18-yr mean yield-scaled N₂O emissions were 2.8
44 to 3.3 times lower under NT, compared to the corresponding CT treatments. Under CT,
45 N application would increase YSNE in most years while YSNE would be more resilient
46 to the application of increasing N rates under NT. Our work demonstrates that in rainfed

47 Mediterranean systems NT is a win-win strategy for the equilibrium between
48 agricultural productivity and low soil N₂O emissions.

49

50 **Abbreviations**

51 CT, conventional tillage; EF, emission factor; greenhouse gases (GHG); NT, no-tillage;

52 N₂O, nitrous oxide.

54 **1. Introduction**

55 Nitrous oxide (N₂O) is a powerful greenhouse gas (GHG) with a global warming
56 potential 265 times greater than the reference gas, i.e. carbon dioxide (CO₂) (IPCC,
57 2013). Atmospheric concentration of N₂O has increased about 20% since the beginning
58 of the industrial revolution, boosted after the invention of the Haber-Bosch process, and
59 reaching a current value of 324.2 ppb (IPCC, 2013). Most of the emissions of N₂O are
60 originated in soils treated with nitrogen (N) fertilizer as a result of the nitrification and
61 denitrification processes (Butterbach-Bahl *et al.*, 2013). These processes are the result
62 of soil microorganism activities and are modulated by the amount of substrate (organic
63 materials, mineral N) and environmental conditions (O₂, soil pH and temperature),
64 which are modified, in turn, by a range of agricultural management practices. However,
65 in agroecosystems, N is key for maintaining yield potential. Consequently, the
66 increasing demand of food, feed and energy will probably raise significantly the
67 emissions of N₂O from soils if agricultural management practices remain unchanged.

68 Rainfed Mediterranean agroecosystems are characterized by the low magnitude and
69 high variability of precipitation and the high evapotranspiration rates, severely limiting
70 crop yield potential. In these areas, winter cereals show a good adaptation given the
71 partial synchrony of their water needs with the distribution of precipitation and the key
72 contribution of the soil water recharge period (Lampurlanés *et al.*, 2016; Plaza-Bonilla
73 *et al.*, 2017). In different rainfed Mediterranean areas of Spain reduced and no-tillage
74 (NT) systems have been introduced during the last three decades aimed to reduce costs
75 and mitigate soil erosion (Moreno *et al.*, 2010). Under NT, crop residues are maintained
76 at the soil surface enhancing water storage thanks to (i) reduced soil water evaporation,
77 (ii) greater water infiltrability in soils prone to crusting, and (iii) improved soil water

78 characteristics (Lampurlanés *et al.*, 2016; Strudley *et al.*, 2008). The usually higher
79 water status in NT compared to conventional tillage (CT) soils has been claimed as a
80 risk for greater N₂O production and emission to the atmosphere, worsening the C
81 footprint of agroecosystems (e.g. Smith *et al.*, 2001). However, the long-term use of NT
82 greatly modifies soil physical properties with a greater proportion and connectivity of
83 macropores (Strudley *et al.*, 2008), due to soil fauna and roots activities, which, in turn,
84 increases aeration, reducing the susceptibility to denitrification and N₂O production
85 (van Kessel *et al.*, 2013).

86 Nowadays, agricultural activities must fulfill consumer demands while avoiding
87 environmental tradeoffs. A joint indicator of productivity and GHG emission such as
88 the yield-scaled N₂O emissions (YSNE) (van Groenigen *et al.*, 2010) provides a unique
89 opportunity to evaluate the adequacy of a given agricultural practice under the
90 productive and environmental points of view. Regarding to this, long-term field
91 experiments represent an invaluable tool to assess the impact of crop management
92 practices on agronomic and environmental variables with a high degree of confidence.
93 Unfortunately, long-term measurement of soil N₂O emissions are time- and resource-
94 consuming and, consequently, scarce in the literature. Simulation tools such as process-
95 based models represent an interesting strategy to overcome this limitation (Abalos *et al.*,
96 2016) and to help establish management decisions (Campbell *et al.*, 2014; Ludwig *et*
97 *al.*, 2011), but provided that the models are well validated and produce robust and
98 reasonably accurate results. Therefore, the objective of this work was to assess the long-
99 term impact of different tillage systems and N rates on soil N₂O emissions and crop
100 productivity in rainfed Mediterranean conditions with a combined experimental and
101 simulation approach using long-term field data and the STICS model (Brisson *et al.*,
102 1998, 2002, 2008). Our hypothesis was that long-term NT and adequate N fertilizer

103 rates would lead to the best equilibrium between the environmental and agronomic
104 components, as indicated by the yield-scaled N₂O emissions index (YSNE).

105

106 **2. Materials and methods**

107 *2.1. Site conditions, experimental design and crop management practices.*

108 A field experiment was established in 1996 in Agramunt, NE Spain (41°48' 36'' N,
109 1°07' 06'' E, 330 m asl) to compare two tillage types (CT, conventional tillage; NT, no-
110 tillage) and three mineral N rates (0, 60 and 120 kg N ha⁻¹). The area is representative of
111 rainfed semiarid Mediterranean conditions with a mean annual precipitation of 401 mm,
112 potential evapotranspiration (PET) of 855 mm, and annual temperature of 14.1 °C
113 (1984-2014). The 30-yr mean precipitation received during the soil water recharge
114 period (September to January) reaches 201 mm (Lampurlanés *et al.*, 2016).

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

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

125 The CT treatment consisted of one moldboard plough pass (25-30 cm depth) plus
126 one or two cultivator passes (15 cm depth) before sowing, during September and
127 October depending on soil moisture. In the NT treatment no soil tillage practices were
128 carried out. Three to five days before sowing, the weeds were controlled by applying
129 1.5 L ha⁻¹ of glyphosate [N-(phosphonomethyl)glycine]. In the region, NT has been

130 progressively introduced with the aim of both reducing costs and either maintaining or
131 increasing yields (Cantero-Martínez *et al.*, 2003). Barley sowing (cv. Hispanic from
132 1996 to 2010 and cv. Cierzo from 2010 to 2014) was performed in November with the
133 use of a commercial 3-m wide NT drill with disk openers at a rate of 450 seeds m⁻² in
134 rows spaced 17 cm apart. Continuous winter cereal production, mainly barley,
135 represented the most common practice in the area, due to higher risks associated to
136 alternative crops (Álvaro-Fuentes *et al.*, 2009). N fertilization was split into two
137 applications: one before sowing with a third of the rate which was surface broadcasted
138 and incorporated with tillage in CT, and one as top-dressing, also broadcasted, with the
139 other two thirds at the beginning of the tillering stage (i.e. between January and
140 February depending on the year) using ammonium nitrate (33.5% N). Soil analysis for
141 determining P and K levels was carried out each 3-4 years. Given the medium-high
142 levels of available P and K, applications were oriented to satisfy crop needs at an equal
143 rate for both tillage treatments: ca. 40-50 kg P₂O₅ ha⁻¹ yr⁻¹ and 90 kg K₂O ha⁻¹ yr⁻¹. The
144 grain was harvested using a commercial combine at the end of June or beginning of
145 July, which chopped and spread uniformly crop residues over the soil surface. In the CT
146 treatment, crop residues were incorporated into the soil with tillage operations. Under
147 NT, crop residues were maintained on the soil surface throughout the study period.

148 2.2. Soil and crop sampling and measurements.

149 Two datasets were used to calibrate and evaluate the model: one related to N₂O
150 emissions and ancillary variables (soil moisture, temperature, and ammonium and
151 nitrate nitrogen) and the other related to yearly soil profile water and mineral N contents
152 and biomass production. For the first, observed data reported in Plaza-Bonilla *et al.*
153 (2014) were used to evaluate the ability of the STICS model in simulating soil N₂O
154 emissions. Briefly, soil N₂O emissions were quantified during the 2011-2012 cropping

155 season with the use of two static chambers per plot. Gas measurements were performed
156 every two to three weeks, being more frequent during fertilizer applications. Cumulative
157 N₂O-N losses were calculated with the trapezoid rule, taking into account the number of
158 days between consecutive measurements. On every sampling date, the soil temperature
159 (5 cm depth) was measured with a hand-held probe and a soil sample (0-5 cm depth)
160 was taken for soil water and mineral N (ammonium, NH₄⁺, and nitrate, NO₃⁻) content
161 determination. Soil water content (SWC) was quantified with the gravimetric method.
162 Soil bulk density (0-5 cm depth) was also measured with the cylinder method
163 (Grossman and Reinsch, 2002). Further information regarding soil N₂O emissions
164 measurement and ancillary variables can be found in Plaza-Bonilla *et al.* (2014).

165 The second dataset comprised soil profile water and mineral N content and crop
166 biomass and yield during the eighteen years covered by the experiment. Methods used
167 are described by Angás *et al.* (2006) and Morell *et al.* (2011). Briefly, soil samples were
168 taken prior to sowing, at flowering and after harvest in each cropping season studied. In
169 each plot, two representative areas of 2 by 2 m were identified and three soil samples
170 per area were taken using a mechanized soil corer, in 30-cm increments, up to a soil
171 depth of 90 cm. The sub-samples were bulked for each depth and gravimetric moisture
172 and ammonium and nitrate were quantified. Crop aboveground biomass was measured
173 at physiological maturity by cutting the plants at soil level along a 0.5 m length of the
174 seeding line in three locations per plot. Once in the laboratory, ears were separated and
175 the stems and leaves were oven-dried at 65°C during 48 h to estimate crop residues.
176 Carbon and N concentration of the biomass was analyzed by dry combustion (LECO-
177 2000 analyzer, LECO, St Joseph, MI, US). Crop yield was measured with a commercial
178 combine, taking a sub-sample for grain moisture determination.

179 *2.3. Overview of the STICS soil-crop model and its evaluation for N₂O emissions.*

180 The soil and crop model STICS (Brisson *et al.*, 1998, 2002, 2008) is a one-
181 dimension daily-step model created to simulate a range of processes related to plant
182 growth as well as water and N cycles over one or several growing seasons. The model
183 requires soil and climate characteristics as well as management practices as input
184 variables for the initialization of the simulation. In STICS, soil N₂O emission is
185 simulated relying on the concepts described in Bessou *et al.* (2010). Nitrification and
186 denitrification are simulated separately in the model, but coupled by nitrate production
187 by nitrification, since it serves as substrate for denitrification. Nitrification is
188 proportional to ammonium content and regulated by temperature and water-filled pore
189 space (WFPS). Field experiment soil pH does not constrain nitrification rate as pH
190 levels are in the high range. Soil N₂O emission as a result of nitrification represents a
191 variable fraction of the nitrification rate depending on WFPS (Khalil *et al.*, 2004). In
192 turn, denitrification is the product of a soil dependent potential rate and nitrate
193 concentration, soil temperature and SWC. The emission of N₂O associated to
194 denitrification is then calculated as a variable fraction of the denitrification rate
195 depending on pH and WFPS. A more detailed description of N₂O emission simulation
196 by STICS can be found in Plaza-Bonilla *et al.* (2017).

197 Independent data from the two datasets obtained were used to calibrate the model.
198 First, model calibration for N₂O emissions simulation was performed using the data
199 obtained in the CT-60 and NT-60 treatments. Second, soil profile (i.e. 0-90 cm depth at
200 30-cm increments) water and mineral N contents and crop biomass production was
201 calibrated with data obtained in the first three seasons (i.e. from 1996-1997 to 1998-
202 1999), when more intensive crop biomass samplings were performed. The soil was
203 divided in different layers according to the soil sampling depths established in the field
204 experiment (i.e. 0-5, 5-30, 30-60 and 60-90 cm depth). Soil input variables were

205 obtained from analysis, with the exception of gravimetric soil moisture at field capacity
206 and permanent wilting point, which were initially estimated using a pedotransfer
207 function (Saxton and Rawls, 2006). For each treatment, soil surface crop residues
208 characteristics (i.e. amount, N concentration and C:N ratio) were introduced as crop
209 management inputs. During the calibration process a poorer simulation of soil surface
210 (0-5 cm depth) water dynamics on the high range of the values was detected under CT
211 compared to NT. Therefore, field capacity was tuned as suggested by soil moisture
212 measurements (0.179 and 0.206 g g⁻¹ for CT and NT, respectively). Soil depth at which
213 denitrification can take place was set at 0-20 cm depth. Potential denitrification rate was
214 set at 3 kg N ha⁻¹ d⁻¹, based on maximum N₂O peaks in the same field under irrigated
215 conditions and the maximum N₂:N₂O ratio measured in the laboratory under controlled
216 conditions (Klemedtsson *et al.* 1988).

217 The performance of the model to simulate soil N₂O emissions and its ancillary
218 variables was evaluated by comparing the measured data obtained in the 2011-2012
219 season for the CT-0, CT-120, NT-0 and NT-120 treatments with the simulated values.
220 In turn, the model performances to simulate soil profile (0-90 cm depth) water and
221 mineral N contents and crop biomass dynamics was evaluated with data of the last 15
222 years of the experiments. The linear relationship between observed and simulated values
223 (intercept, slope and coefficient of determination) and other statistical criteria were
224 calculated: relative root mean square error (rRMSE), mean deviation or bias (MD) and
225 model efficiency (ME):

226

227

228

229 Where:

230 n is the number of observations, S_i and O_i are the simulated and the observed values,
231 respectively and
232 \bar{O}
233 is the mean of the observed values.

234 *Long-term simulation of N₂O emissions.*

235 After evaluation, and judging a satisfactory performance, the model was used to
236 simulate the emissions of N₂O of the eighteen years of differentiated tillage (CT and
237 NT) and increasing N fertilization treatments (0, 30, 60, 90, and 120 kg N ha⁻¹), covered
238 by the range compared experimentally (0 to 120 kg N ha⁻¹), to identify the impact of N
239 rates on N₂O emissions, EF and YSNE for a given tillage treatment. Independent runs
240 were initialized using the observed soil moisture and mineral N contents (at 0-30, 30-60
241 and 60-90 cm) for the 0, 60 and 120 kg N ha⁻¹ treatments and interpolating the values
242 for the 30 and 90 kg N ha⁻¹ scenarios, and the actual management practices (Table S1)
243 and climate inputs. This approach combining modelling and experimental results
244 carrying out yearly independent simulations aimed at reducing the uncertainty of the
245 N₂O simulated values.

246 For each tillage system the emission factor (EF) was calculated as the difference
247 between simulated cumulative N₂O emission from a fertilized treatment (30, 60, 90 and
248 120 kg N ha⁻¹) and the non-fertilized control, divided by the amount of N fertilizer
249 applied on each treatment. For each year, tillage and nitrogen rate combination, YSNE
250 was calculated as the quotient between the cumulative annual N₂O emissions and grain
251 yield (as dry matter). Since grain yield was only measured in 0, 60 and 120 kg N ha⁻¹
252 treatments, a segmented regression (assuming a linear-plateau model) for each tillage x
253 year combination was carried out to analyze grain yield response to N application and

254 estimate grain yields under the 30 and 90 kg N ha⁻¹ scenarios, using the non-linear
255 platform of the JMP 12 statistical package (SAS Institute Inc, 2015).

256 An analysis of variance was performed for measured grain yield with tillage, N
257 fertilization, year and their interaction as sources of variation. When significant,
258 differences among treatments were identified at 0.05 probability level of significance by
259 a LSD test. Grain yield data of the 2004-2005 season was excluded from the analysis
260 due to lack of replicates (i.e. only one replicate was harvested due to extreme dry
261 conditions during the season). A multiple linear regression was calculated to predict
262 simulated cumulative N₂O emission based on observed key variables (i.e. cropping
263 season precipitation, water deficit, amount of nitrate-N at the beginning of the season
264 and crop residues returned to the soil). The simple and combined effects of the last
265 variables on the fraction of N₂O emissions produced by denitrification were also
266 analyzed. Data analysis was performed with the JMP 12 statistical package (SAS
267 Institute Inc, 2015).

268

269 **3. Results**

270 *3.1. Weather characteristics during the experimental period*

271 The precipitation from July (year y) to June (year y+1) was highly variable during
272 the study period, ranging between 244 mm in the 2004-2005 cropping season to 702
273 mm in the 2009-2010 cropping season (Figure 1). Of the eighteen years that covered the
274 experiment, 9 received an amount of precipitation below the 30-year average, i.e. 401
275 mm. Annual temperature ranged between 12.8 °C in the 2007-2008 season and 14.7°C
276 in the 2000-2001 and 2011-2012 seasons (Figure 1). The yearly dynamics of air
277 temperature followed the typical Mediterranean pattern (with a continental trend) being
278 the winters mild to cold and the summers very hot with hourly temperatures well-above
279 35 °C. Of the 18 years a total of 168 days presented a mean daily temperature below 0
280 °C, being a 6%, 44%, 32%, 15% and 3% in November, December, January, February
281 and March, respectively.

282 *3.2. Tillage and nitrogen effects on barley grain yield.*

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

291 Barley grain yield was significantly affected by the tillage x nitrogen x year
292 interaction ($p = 0.004$). Significant differences between treatments were observed in 17
293 out of the 18 years that covered the experiment, since the 2004-2005 season was not
294 included in the analysis. In the first two years of experiment CT led to greater grain
295 yields than NT (Figure 2). Differently, from the third year of experiment onwards,
296 greater yields were observed under NT compared to CT in the treatments with 60 and
297 120 kg N ha⁻¹ in 13 cropping seasons. The exceptions were observed in the rainy 2003-
298 2004 and 2009-2010 seasons, when no differences between tillage systems were found
299 at a given N rate different from the control. Crop yield response to N application was
300 severely affected by the type of tillage performed. In this line, no grain yield response to
301 the application of 60 kg N ha⁻¹ was observed under CT, while greater grain yields than
302 the control treatment were observed in 11 occasions under NT. The application of
303 further 60 kg N ha⁻¹ under NT (i.e. a rate of 120 kg N ha⁻¹) only increased grain yield in
304 three cropping seasons (1997-1998, 1999-2000, and 2000-2001) while reduced grain
305 yield in the 2009-2010 cropping season.

306 *3.3. Model evaluation.*

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

316 Observed and simulated soil N₂O emissions were similar, with observed and simulated
317 values ranging from -2.7 to 9.7 g N₂O-N ha⁻¹ d⁻¹ and from 0 to 15.3 g N₂O-N ha⁻¹ d⁻¹,
318 respectively. Measured cumulative N₂O emission during the 2011-2012 barley growing
319 season was calculated at 0.09, 0.40, 0.09 and 0.22 kg N₂O-N ha⁻¹ for the CT-0, CT-120,
320 NT-0 and NT-120 treatments, respectively, while the corresponding simulated values
321 were in the same range with 0.08, 0.34, 0.10 and 0.30 kg N₂O-N ha⁻¹. The agreement
322 between observed and simulated cumulative N₂O values was very good, with a ME of
323 0.83 and rather low MD and rRMSE, although simulated values presented a slight
324 underestimation (i.e. slope of 0.84).

325 In the 2000-2014 period, measured soil moisture of the rooting depth (0-90 cm)
326 ranged from 78 to 235 mm and 76-218 mm for CT and NT, respectively.
327 Comparatively, the corresponding simulated values ranged from 82 to 240 and 69-234
328 mm, respectively. The model showed a good performance with a low rRMSE (17.6%)
329 and a ME and slope of the regression of 0.62 and 1.09, respectively (Table 2). The
330 model simulated better the amount of soil nitrate in the first 30 cm soil depth and in the
331 whole rooting depth (0-90 cm) than in the soil surface (0-5 cm) in the 2011-2012 barley
332 cropping season (Table 2). For the 0-90 cm soil depth, the agreement between observed
333 and simulated values led to a ME of 0.74 and a slope close to 1 (i.e. 0.92). However, the
334 rRMSE reached a 44.8%. Barley above-ground biomass and grain yield were highly
335 variable during the experimental period (Figure 4). In the CT-0, CT-60 and CT-120
336 treatments observed biomass ranged from 0.5 to 10.6 Mg ha⁻¹, 0.7-11.7 Mg ha⁻¹ and 0.3-
337 11.3 Mg ha⁻¹, respectively. In NT-0, NT-60 and NT-120 observed biomass ranged from
338 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
339 the same cropping seasons (Figure 4). The model was relatively able to simulate the

340 great temporal variability on crop growth and grain yield, although the ME was lower
341 than 0.25 for both variables (Figure 4; Table 2).

342

344 *3.4. Predicting long-term tillage and increasing N rates impact on N₂O emissions,*
345 *yield-scaled N₂O emissions, and emission factor.*

346 Simulated annual cumulative N₂O emissions were 0.50, 0.67, 0.82, 0.98 and 1.09 kg
347 N₂O-N ha⁻¹ yr⁻¹ for the CT-0, CT-30, CT-60, CT-90, and CT-120 treatments,
348 respectively, as an average of the 1996 to 2014 period. Slightly greater average annual
349 values were simulated for the same N rates under NT, with 0.53, 0.73, 0.92, 1.07, and
350 1.19 kg N₂O-N ha⁻¹ yr⁻¹, respectively (Table 3). A great variability between years on
351 cumulative N₂O emissions was also simulated by the model, with coefficients of
352 variation greater than 50% for the different treatments. The lowest value (0.07 kg N₂O-
353 N ha⁻¹ yr⁻¹) was obtained under NT-0 in the 2002-2003 season, while the highest (2.95
354 kg N₂O-N ha⁻¹ yr⁻¹) was simulated under NT-120 in 2010-2011. The fraction of N₂O
355 derived from denitrification ranged between 0.42 and 0.81, with an average of 0.66 and
356 being very similar between tillage treatments. For a given tillage treatment, slight
357 greater values were simulated at greater N rate, as an average of the 18 years of the
358 experiment (Table 3).

359 The simulated N₂O EF was about 0.57% in average of the 18 years, with values of
360 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,
361 CT-120, NT-30, NT-60, NT-90, and NT-120 treatments, respectively, with coefficients
362 of variation between 44% and 73% (Table 4). This emission factor of N₂O only
363 exceeded 1% in 2 situations under CT and in 9 situations under NT out of the 18 years
364 crossed with 8 tillage x N rate combinations (144 situations) (Table 4).

365 In general, for a given tillage treatment, YSNE increased when increasing the N
366 rate, being the lowest values found in the control treatment (0 kg N ha⁻¹) in most of the
367 year x tillage combinations (Figure 5). However, that increase was of a greater

368 magnitude under CT compared to NT, being YSNE of NT less responsive to the
369 application of increasing N rates. Regarding to this, as an average of the eighteen
370 cropping seasons studied, the yield-scaled N₂O emissions (YSNE) were 1.25, 1.40,
371 1.58, 1.88, and 2.11 g N₂O-N kg⁻¹ grain under CT-0, CT-30, CT-60, CT-90 and CT-120,
372 respectively. In turn, under NT the values were 0.45, 0.52, 0.56, 0.59, and 0.63 g N₂O-N
373 kg⁻¹ grain, for the NT-0, NT-30, NT-60, NT-90, and NT-120 treatments, respectively
374 (Figure 5). In most of the cases, greater YSNE were observed under CT compared to
375 NT for a given N rate (Figure 5). Exceptions were observed in the first two cropping
376 seasons (1996-1997 and 1997-1998) when lower yields occurred under NT, and in
377 2010-2011. Yield-scaled N₂O emissions were highly variable among years, with
378 coefficients of variation above 100% in all the treatments, except NT-90 and NT-120.
379 Independently of the treatment, the lowest YSNE values were found in the one of the
380 highest yielding cropping seasons, i.e. 1997-1998. Differently, the highest YSNE was
381 observed in CT-120 in the 2007-2008 season, with 15.2 g N₂O-N kg⁻¹ grain. Under NT
382 the greatest value was 2.69 g N₂O-N kg⁻¹ grain, for NT-60 in 2007-2008 (Figure 5). A
383 linear relationship was found between precipitation and the quotient between NT YSNE
384 and CT YSNE for all N rates (excluding three cropping seasons) (Fig. S1,
385 supplementary material). According to this relationship, YSNE values would be higher
386 in NT than CT in years with precipitation above 608 mm.

387 A multiple linear regression was calculated to predict cumulative N₂O emissions
388 based on different dependent variables. Cumulative N₂O emissions (kg N₂O-N ha⁻¹)
389 were significantly explained ($P < 0.001$; $R^2 = 0.31$) by the combination of seasonal
390 precipitation (PPT, mm), water deficit (as seasonal precipitation minus potential
391 evapotranspiration, mm), crop residues of the previous season (Mg DM ha⁻¹) and the
392 amount of soil nitrate at 0-30 cm soil depth at the beginning of the season (kg NO₃⁻-N),

393 being the four variables significant predictors of cumulative N₂O emissions. The
394 resulting linear multiple variables model was as follows:

395 Cumulative N₂O emissions = 0.0061 (PPT) – 0.0046 (Water deficit) + 0.1650 (Crop
396 residues) + 0.0012 (Soil Nitrate-N) – 5.45.

397 In the CT treatment, the amount of crop residues incorporated to the soil in the
398 previous season was negatively related to the fraction of N₂O emitted due to
399 denitrification (N₂O_{den}), following the relationship: $N_2O_{den} = 0.71 - 0.024$ (Crop
400 residues). No significant relationship was found between N₂O_{den} and precipitation,
401 water deficit, and soil nitrate (0-30 cm).

402

403

404

405 **4. Discussion**

406 *4.1. Long-term tillage and N fertilization effects on barley yields*

407 As an average of the 18 years of experiment, NT increased grain yield by a 10, 47
408 and 53% compared to CT when applying 0, 60 and 120 kg N ha⁻¹, respectively. Under
409 semiarid rainfed Mediterranean conditions NT increases the amount of water stored in
410 the soil proportionally to the aridity of the site, increasing crop yields (Lampurlanés *et*
411 *al.* 2016), with differences between tillage systems being larger in drier years. The
412 impact of soil water availability on NT performance would be confirmed by the lack of
413 differences between tillage systems when applying 60 or 120 kg N ha⁻¹ in the 2003-
414 2004 and 2009-2010 seasons, when rainfall was above than the average. The long-term
415 data also showed differences between tillage systems on grain yield response to N
416 fertilization. The application of 60 kg N ha⁻¹ led to greater yields than the control
417 without N in 11 occasions (i.e. years) under NT. The grain yield response to the highest
418 N rate (120 kg N ha⁻¹) was uncommon, being only observed in 3 occasions out of 18
419 under NT. Differently, no response to N fertilizer was observed under CT. Grain yield
420 response to N fertilization under NT would be the consequence of greater amount of
421 water available for the crop, being modulated by soil mineral N availability and the
422 aridity of the site (Cantero-Martínez *et al.*, 2016). The aridity of the site would play a
423 major role, since the differential response of yields to N fertilization depending on the
424 tillage system has not been observed in wetter rainfed Mediterranean environments such
425 as Central Italy (Seddaiu *et al.*, 2016).

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

429 1 or 2 years after NT implementation, but never greater under NT. Moreover, as an
430 average of all studies covered by the meta-analysis, they reported a 12% decline in
431 yields when using NT without N fertilizer applications. Both aspects differ from our
432 results, pointing out the need to take into account the local component (i.e. specific
433 pedoclimatic conditions and agricultural management practices) to evaluate the
434 performance of NT on crop yields in a given location. The lag period of 2 years until
435 NT reached greater yields than CT would be the consequence of the time required for
436 the improvement on soil hydraulic properties, related to the amount of soil organic
437 matter and soil aggregate stability, which are greatly influenced by NT duration
438 (Álvaro-Fuentes *et al.*, 2014; Pittelkow *et al.*, 2015; Plaza-Bonilla *et al.*, 2013).

439 *4.2. Model evaluation, and magnitude and temporal variation of simulated N₂O*
440 *emissions.*

441 We used an approach that links long-term observed field data with model
442 retrospective simulation to assess the long-term impact of different tillage systems and
443 increasing N rates on soil N₂O emissions and crop productivity in rainfed Mediterranean
444 conditions. The main aim of the approach followed was to reduce the uncertainty
445 associated to the predictions, similarly than Ludwig *et al.* (2011).

446 According to the results obtained from the different statistical tests used, the STICS
447 model performed relatively well when simulating the different soil N₂O emission
448 ancillary variables, i.e. soil moisture, temperature, and ammonium and nitrate nitrogen.
449 Coucheney *et al.* (2015) reported a good overall accuracy when using STICS to
450 simulate soil water and N and plant biomass in a wide range of pedoclimatic conditions
451 in France under 15 different crops, highlighting the versatility of the model to accurately
452 simulate under different conditions.

453 The agreement between observed and simulated soil nitrate at 0-30 and 0-90 cm
454 depth, indicated by the rRMSE, was similar than the one reported by Coucheney *et al.*
455 (2015). In our study, the prediction of the magnitude and dynamics of cumulative N₂O
456 emissions was accurate, in line with those reported by Plaza-Bonilla *et al.* (2017) when
457 using STICS to simulate the cumulative emission of N₂O under durum wheat and faba
458 bean in low-input cropping systems of SW France. However, it must be taken into
459 account that the non-continuous measurements of N₂O emissions under field conditions
460 may underestimate the actual N₂O-N losses (Campbell *et al.*, 2014). The model was also
461 able to accurately simulate the dynamics of SWC and nitrate N and crop above-ground
462 biomass and grain yield during the duration of the field experiment under different
463 tillage systems and N rates. Soil water and crop growth have a great influence on the
464 amount of N susceptible to be nitrified and/or denitrified. These aspects justify the
465 implementation of STICS as a tool to estimate soil N₂O emissions, given the high year-
466 to-year variability of water availability and crop performance under Mediterranean
467 conditions (Flower *et al.*, 2017; Lampurlanés *et al.*, 2016; Seddaiu *et al.*, 2016).

468 Interestingly, throughout the simulation period (1996-2014), the model predicted a
469 high year-to-year variability of soil N₂O emissions under rainfed Mediterranean
470 conditions independently of the mineral N rate applied, according to the irregularity of
471 precipitations as shown by Plaza-Bonilla *et al.* (2017). According to the model,
472 denitrification would play a slightly greater role than nitrification on soil N₂O
473 emissions. Similarly, Meijide *et al.* (2007) reported greater relative importance of
474 denitrification over nitrification on soil N₂O emissions under Mediterranean conditions.
475 The magnitudes of the annual emissions simulated were in agreement with the ones
476 reported in the literature for similar Mediterranean environments and cropping systems.
477 Values as low as 72 g N₂O-N ha⁻¹ yr⁻¹ were reported by Tellez-Rio *et al.* (2017) from a

478 NT wheat in Central Spain. Garcia-Marco *et al.* (2016) reported cumulative emissions
479 between 183 and 1110 g N₂O-N ha⁻¹ in a triticale cropping season (i.e. from September
480 to June) in SW Spain. Menéndez *et al.* (2008) measured N₂O emissions during wheat
481 fertilization events in a rainfed area of southern Spain, quantifying values as high as and
482 2378 g N₂O-N ha⁻¹. Similarly, in Central Italy, Bosco *et al.* (2015) observed N₂O
483 cumulative emissions ranging between 827 and 2340 g N₂O-N ha⁻¹ in a durum wheat
484 season when applying 0 and 170 kg N ha⁻¹, respectively.

485 Cumulative N₂O emissions were partly explained by the combination of seasonal
486 precipitation, water deficit, crop residues of the previous season and the amount of soil
487 nitrate at 0-30 cm soil depth at the beginning of the season. Soil water availability plays
488 a major role regulating the nitrification and denitrification rates, being a key soil N₂O
489 controlling mechanism under Mediterranean conditions (Plaza-Bonilla *et al.*, 2017). In
490 turn, release of C after crop residues incorporation provides the energy for microbial
491 denitrification (Ábalos *et al.*, 2013), while nitrate acts as electron acceptor during
492 denitrification. The high year-to-year variability of N₂O emissions under Mediterranean
493 conditions would consequently be explained by the variability in the last variables.

494 4.3. Long-term tillage and N fertilization effects on N₂O emissions, and yield-scaled 495 N₂O ratio.

496 The STICS model predicted that in rainfed Mediterranean systems cumulative N₂O
497 emissions would be greatly affected by N rate, with a minor impact of tillage systems,
498 coinciding with the findings of Plaza-Bonilla *et al.*, (2014) and Bosco *et al.*, (2015) in
499 tillage and N fertilization combination experiments.

500 In general, the use of NT led to greater crop yields and similar cumulative N₂O
501 emissions than CT, resulting on lower (-66%) YSNE in most cropping seasons.

502 According to the data of 15 out of 18 cropping seasons studied, YSNE would only be
503 greater under NT compared to CT in years with precipitation above 600 mm. In most of
504 the cropping seasons YSNE would increase when increasing the N rate under CT.
505 Differently to CT, under NT, YSNE would be more resilient to the application of
506 increasing N fertilizer rates, providing the farmers and stakeholders more versatility
507 when using or establishing a recommended N rate in the rainfed Mediterranean area.
508 Regarding to this, in the case-study covered here, the recommended rate would range
509 between 30 and 60 kg N ha⁻¹. This range would optimize barley grain yield while
510 maintaining YSNE at low values, close to the obtained when applying no N fertilizer.
511 Kim and Giltrap (2017) stressed the need to increase our knowledge in the response of
512 YSNE to N input in different cropping systems and pedoclimatic conditions, given the
513 current lack of data. The YSNE permits to identify the best strategy in terms of
514 emissions of N₂O per production unit for a given pedoclimatic and cropping system
515 content. For instance, in less water-limited environment of Upper Midwest USA,
516 Venterea *et al.* (2011) observed lower corn (*Zea mays* L.) grain yields under NT, which
517 resulted in yield-scaled N₂O emissions with NT being more than 50% greater than CT.
518 In the climatic conditions of last authors study lower soil temperature in spring under
519 NT delay crop growth, affecting yields negatively. Contrarily, in rainfed Mediterranean
520 agroecosystems the lower YSNE and greater grain yields under NT should be seen as a
521 win-win strategy for the relationship between agricultural productivity and
522 environmental sustainability. Moreover, in these areas it could be expected that a wider
523 assessment of the GHG footprint of the cropping system would equally be favorable to
524 NT, given the potential of this system to sequester soil organic carbon, at least, during
525 the first decade after its implementation (Álvaro-Fuentes *et al.*, 2014).

526 The slightly greater soil N₂O emissions found under NT when compared to CT at a
527 given N rate could be explained by the greater amount of water stored in the soil under
528 NT (Lampurlanés *et al.*, 2016), which would increase the nitrification rate and/or reduce
529 the air-filled porosity boosting denitrification during rainy periods. However, the long-
530 term maintenance of NT is also related to a soil structure improvement, mainly as a
531 result of greater water-stability of soil macroaggregates (Plaza-Bonilla *et al.*, 2013),
532 which may offset the impact of soil moisture on N₂O emissions under non-tilled soils
533 (van Kessel *et al.*, 2013). Unfortunately, most models ignore the dynamic nature of soil
534 structure and the impact of soil management on its temporal evolution (Vereecken *et al.*,
535 2016). Different works have been performed to study the impact of tillage practices on
536 soil N₂O emissions under field crops cultivation in rainfed Mediterranean conditions.
537 Lower cumulative N₂O emissions in NT compared to CT have been found in Spain
538 under wheat (Tellez-Rio *et al.*, 2017), and triticale (Garcia-Marco *et al.*, 2016)
539 cultivation, and in south-eastern Australia (Li *et al.*, 2016) in a canola crop. Other
540 authors have reported no differences between CT and NT (Bosco *et al.*, 2015;
541 Menéndez *et al.*, 2008; Tellez-Rio *et al.*, 2015a, 2015b). Contrasting results depending
542 on the amount of years since NT implementation on barley cultivation were observed by
543 Plaza-Bonilla *et al.* (2014) with greater soil N₂O emissions under NT compared to CT
544 in the short-term (3-yr) and the contrary results in the long-term experiment covered by
545 the present work.

546 Average EF for the CT-60, CT-120, NT-60 and NT-120 treatments ranged between
547 0.50 and 0.65. These values were in the high range of the EF reported by a recent meta-
548 analysis of N₂O emissions from Mediterranean rainfed cropping systems (Cayuela *et*
549 *al.*, 2017). The pioneering work of Bouwman (1996) led to the establishment of the
550 IPCC Tier 1 value that was subsequently updated to 1% (IPCC, 2006).

551

552 **5. Conclusions**

553 Overall, STICS showed a satisfactory performance when simulating soil N₂O
554 emission and ancillary variables such as biomass and nitrogen and water dynamics
555 budgets in the water-limited rainfed Mediterranean agroecosystem studied. According
556 to our approach including retrospective model simulations and long-term field
557 measurements the use of long-term NT and medium N fertilizer rates (30-60 kg N ha⁻¹)
558 supposes a win-win strategy to maximize barley grain yield while maintaining low
559 yield-scaled N₂O emissions in rainfed Mediterranean agroecosystems. Similar than
560 grain yields, soil N₂O emissions would present a very high year-to-year variability,
561 according to the simulations, being modulated by precipitation and water deficit, soil
562 nitrate and the amount of crop residues. Increasing N fertilization under CT would led
563 to an increase in the magnitude of N₂O emissions and YSNE, given the lack of enough
564 water in the soil restricting crop response to mineral N application. Finally, our work
565 gives some evidence that the EF is almost half of the proposed by IPCC in such semi-
566 arid Mediterranean conditions, which needs to be taken into account when evaluating
567 the contribution of agriculture to GHG emissions.

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578 **References**

- 579 Abalos, D.; Cardenas, L.M.; Wu, L. 2016. Climate change and N₂O emissions from
580 South West England grasslands: A modelling approach. *Atmospheric Environment*
581 132, 249-257.
- 582 Ábalos, D.; Sanz-Cobena, A.; Garcia-Torres, L.; van Groenigen, J.W.; Vallejo, A. 2013.
583 Role of maize stover incorporation on nitrogen oxide emissions in a non-irrigated
584 Mediterranean barley field. *Plant and Soil* 364, 357-371.
- 585 Álvaro-Fuentes, J.; Lampurlanés, J.; Cantero-Martínez, C. 2009. Alternative crop
586 rotations under Mediterranean no-tillage conditions: biomass, grain yield, and
587 water-use efficiency. *Agronomy Journal* 101, 1227-1233.
- 588 Álvaro-Fuentes, J.; Plaza-Bonilla, D.; Arrúe, J.L.; Lampurlanés, J.; Cantero-Martínez,
589 C. 2014. Soil organic carbon storage in a no-tillage chronosequence under
590 Mediterranean conditions. *Plant and Soil* 376, 31-41.
- 591 Angás, P.; Lampurlanés, J.; Cantero-Martínez, C. 2006. Tillage and N fertilization
592 effects on N dynamics and barley yield under semiarid Mediterranean conditions.
593 *Soil and Tillage Research* 87, 59-71.
- 594 Bessou, C.; Mary, B.; Leonard, J.; Roussel, M.; Grehan, E.; Gabrielle, B. 2010.
595 Modelling soil compaction impacts on nitrous oxide emissions in arable fields.
596 *European Journal of Soil Science* 61, 348-363.
- 597 Bosco, S.; Volpi, I.; o di Nasso, N.N.; Triana, F.; Roncucci, N.; Tozzini, C.; Villani, R.;
598 Laville, P.; Neri, S.; Mattei, F.; Virgili, G.; Nuvoli, S.; Fabbrini, L.; Bonari, E. 2015.
599 LIFE+IPNOA mobile prototype for the monitoring of soil N₂O emissions from
600 arable crops: first-year results on durum wheat. *Italian Journal of Agronomy* 10,124-
601 131.
- 602 Bouwman, A.F. 1996. Direct emission of nitrous oxide from agricultural soils. *Nutrient*
603 *Cycling in Agroecosystems* 46, 53-70.

604 Brisson, N.; Mary, B.; Ripoche, D.; Jeuffroy, M.H.; Ruget, F.; Nicoullaud, B.; Gate, P.;
605 Devienne-Barret, F.; Antonioletti, R.; Durr, C.; Richard, G.; Beaudoin, N.; Recous,
606 S.; Tayot, X.; Plenet, D.; Cellier, P.; Machet, J.M.; Meynard, J.M.; Delecolle, R.
607 1998. STICS: a generic model for the simulation of crops and their water and
608 nitrogen balances. I. Theory and parameterization applied to wheat and corn.
609 *Agronomie* 18, 311–346.

610 Brisson, N.; Ruget, F.; Gate, P.; Lorgeau, J.; Nicoullaud, B.; Tayot, X.; Plenet, D.;
611 Jeuffroy, M.H.; Bouthier, A.; Ripoche, D.; Mary, B.; Justes, E. 2002. STICS: a
612 generic model for simulating crops and their water and nitrogen balances. II. Model
613 validation for wheat and maize. *Agronomie* 22, 69–92.

614 Brisson, N.; Launay, M.; Mary, B.; Beaudoin, N. 2008. Conceptual basis, formalisations
615 and parameterization of the STICS crop model. Editions QUAE, INRA, 78026
616 Versailles Cedex.

617 Butterbach-Bahl, K.; Baggs, E.M.; Dannenmann, M.; Kiese, R.; Zechmeister-
618 Boltenstem, S. 2013. Nitrous oxide emissions from soils: how well do we
619 understand the processes and their controls? *Philosophical Transactions of the Royal*
620 *Society B Biological Sciences* 368, 20130122.

621 Campbell, E.E.; Johnson, J.M.F.; Jin, V.L.; Lehman, R.M.; Osborne, S.L.; Varvel, G.E.;
622 Paustian, K. 2014. Assessing the soil carbon, biomass production, and nitrous oxide
623 emission impact of corn stover management for bioenergy production using
624 DayCent. *Bioenergy Research* 7, 491-502.

625 Cantero-Martínez, C.; Angas, P.; Lampurlanés, J. 2003. Growth, yield and water
626 productivity of barley (*Hordeum vulgare* L.) affected by tillage and N fertilization in
627 Mediterranean semiarid, rainfed conditions of Spain. *Field Crops Research* 84, 341-
628 357.

629 Cantero-Martínez, C.; Plaza-Bonilla, D.; Angás, P.; Álvaro-Fuentes, J. 2016. Best
630 management practices of tillage and nitrogen fertilization in Mediterranean rainfed
631 conditions: Combining field and modelling approaches. *European Journal of*
632 *Agronomy* 79, 119-130.

633 Cayuela, M.L.; Aguilera, E.; Sanz-Cobena, A.; Adams, D.C.; Abalos, D.; Barton, L.;
634 Ryals, R.; Silver, W.L.; Alfaro, M.A.; Pappa, V.A.; Smith, P.; Garnier, J.; Billen, J.;
635 Bouwman, L.; Bondeau, A.; Lassaletta, L. 2017. Direct nitrous oxide emissions in
636 Mediterranean cropping systems: Emission factors based on a meta-analysis of
637 available measurement data. *Agriculture, Ecosystems and Environment* 238, 25-35.

638 Coucheney, E.; Buis, S.; Launay, M.; Constantin, J.; Mary, B.; García de Cortázar-
639 Aauri, I.; Ripoche, D.; Beaudoin, N.; Ruget, F.; Andrianarisoa, K.S.; Le Bas, C.;
640 Justes, E.; Léonard, J. 2015. Accuracy, robustness and behavior of the STICS soil-
641 crop model for plant, water and nitrogen outputs: Evaluation over a wide range
642 agro-environmental conditions in France. *Environmental Modelling and Software*
643 64, 177-190.

644 Flower, K.C.; Ward, P.R.; Cordingley, N.; Micin, S.F.; Craig, N. 2017. Rainfall,
645 rotations and residue level affect no-tillage wheat yield and gross margin in a
646 Mediterranean-type environment. *Field Crops Research* 208, 1-10.

647 Garcia-Marco, S.; Abalos, D.; Espejo, R.; Vallejo, A.; Mariscal-Sancho, I. 2016. No
648 tillage and liming reduce greenhouse gas emissions from poorly drained soils in
649 Mediterranean areas. *Science of the Total Environment* 506-507, 512-520.

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

653 IPCC, 2006. Agriculture, forestry and other land use. In: Eggleston, H.S.; Buendia, L.;
654 Miwa, K.; Ngara, T.; Tanabe, K. (Eds.), 2006 IPCC Guidelines for National
655 Greenhouse Gas Inventories. Institute for Global Environmental Strategies,
656 Hayama, Japan.

657 IPCC, 2013. Contribution of Working Group I to the Fifth Assessment Report of the
658 Intergovernmental Panel on Climate Change. *Climate Change 2013: The Physical*
659 *Science Basis*. Cambridge University Press, Cambridge, United Kingdom and New
660 York NY, USA.

- 661 Khalil K., Mary B. and Renault P., Nitrous oxide production by nitrification and
662 denitrification in soil aggregates as affected by O₂ concentration, *Soil Biology and*
663 *Biochemistry* 36, 2004, 687-699.
- 664 Kim, D-G.; Giltrap, D. 2017. Determining optimum nitrogen input rate and optimum
665 yield-scaled nitrous oxide emissions: Theory, field observations, usage, and
666 limitations. *Agriculture, Ecosystems and Environment* 247, 371-378.
- 667 Klemetsson, L.; Svensson, B.H.; Rosswall, T. 1988. A method of selective inhibition
668 to distinguish between nitrification and denitrification as sources of nitrous oxide in
669 soil. *Biology and Fertility of Soils* 6, 112-119.
- 670 Lampurlanés, J.; Plaza-Bonilla, D.; Álvaro-Fuentes, J.; Cantero-Martínez, C. 2016.
671 Long-term analysis of soil water conservation and crop yield under different tillage
672 systems in Mediterranean rainfed conditions. *Field Crops Research* 189, 59-67.
- 673 Li, G.D.D.; Conyers, M.K.; Schwenke, G.D.; Hayes, R.C.; Liu, D.L.; Lowrie, A.J.;
674 Poile, G.J.; Oates, A.A.; Lowrie, R.J. 2016. Tillage does not increase nitrous oxide
675 emissions under dryland canola (*Brassica napus* L.) in a semiarid environment of
676 south-eastern Australia. *Soil Research* 54, 512-522.
- 677 Ludwig, B.; Bergstermann, A.; Priesack, E.; Flessa, H. 2011. Modelling of crop yields
678 and N₂O emissions from silty arable soils with differing tillage in two long-term
679 experiments. *Soil and Tillage Research* 112, 114-121.
- 680 Meijide, A.; Díez, J.A.; Sánchez-Martín, L.; López-Fernández, S.; Vallejo, A. 2007.
681 Nitrogen oxide emissions from an irrigated maize crop amended with treated pig
682 slurries and composts in a Mediterranean climate. *Agriculture, Ecosystems and*
683 *Environment* 121, 383-394.
- 684 Menéndez, S.; López-Bellido, R.J.; Benítez-Vega, J.; González-Murua, C.; López-
685 Bellido, L.; Estavillo, J.M. 2008. Long-term effect of tillage, crop rotation and N
686 fertilization to wheat on gaseous emissions under rainfed Mediterranean conditions.
687 *European Journal of Agronomy* 28, 559-569.
- 688 Morell, F.J.; Lampurlanés, J.; Álvaro-Fuentes, J.; Cantero-Martínez, C. 2011. Yield and
689 water use efficiency of barley in a semiarid Mediterranean agroecosystem: long-
690 term effects of tillage and N fertilization. *Soil and Tillage Research* 117, 76-84.

691 Moreno, F.; Arrúe, J.L.; Cantero-Martínez, C.; López, M.V.; Murillo, J.M.; Sombrero,
692 A.; López-Garrido, R.; Madejón, E.; Moret, D.; Álvaro-Fuentes, J. 2010.
693 Conservation agricultura under mediterranean conditions in Spain. In: Lichtfouse, E.
694 (Ed.). Biodiversity, Biofuels, Agroforestry and Conservation Agriculture.
695 Sustainable Agriculture Reviews. Springer, London, pp. 175-193. ISBN 978-90-
696 481-9512-1.

697 Pittelkow, C.M.; Linquist, B.A.; Lundy, M.E.; Liang, X.; van Groenigen, K.J.; Lee, J.;
698 van Gestel, N.; Six, J.; Venterea, R.T.; van Kessel, C. 2015. When does no-till yield
699 more? A global meta-analysis. *Field Crops Research* 183, 156-168.

700 Plaza-Bonilla, D.; Cantero-Martínez, C.; Viñas, P.; Álvaro-Fuentes, J. 2013. Soil
701 aggregation and organic carbon protection in a no-tillage chronosequence under
702 Mediterranean conditions. *Geoderma* 193-194, 76-82.

703 Plaza-Bonilla, D.; Álvaro-Fuentes, J.; Arrúe, J.L.; Cantero-Martínez, C. 2014. Tillage
704 and nitrogen fertilization effects on nitrous oxide emissions in a rainfed
705 Mediterranean area. *Agriculture, Ecosystems and Environment* 189, 43-52.

706 Plaza-Bonilla, D.; Léonard, J.; Peyrard, C.; Mary, B.; Justes, E. 2017. Precipitation
707 gradient and crop management affect N₂O emissions: Simulation of mitigation
708 strategies in rainfed Mediterranean conditions. *Agriculture, Ecosystems and*
709 *Environment* 238, 89-103.

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

711 Saxton, K.E.; Rawls, W.J. 2006. Soil water characteristics estimates by texture and
712 organic matter for hydrologic solutions. *Soil Science Society of America Journal* 70,
713 1569-1578.

714 Seddaiu, G.; Iocola, I.; Farina, R.; Orsini, R.; Iezzi, G.; Roggero, P.P. 2016. Long term
715 effects of tillage practices and N fertilization in rainfed Mediterranean cropping
716 systems: durum wheat, sunflower and maize grain yield. *European Journal of*
717 *Agronomy* 77, 166-178.

718 Smith, P.; Goulding, K.W.; Smith, K.A.; Powlson, D.S.; Smith, J.U.; Falloon, P.;
719 Coleman, K. 2001. Enhancing the carbon sink in European agricultural soils:

720 including trace gas fluxes in estimates of carbon mitigation potential. *Nutrient*
721 *Cycling in Agroecosystems* 60, 237–252.

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

724 Strudley, M.W.; Green, T.R.; Ascough II, J.C. 2008. Tillage effects on soil hydraulic
725 properties in space and time: State of the science. *Soil and Tillage Research* 99, 4-
726 48.

727 Tellez-Rio, A.; Garcia-Marco, S.; Navas, M.; Lopez-Solanilla, E.; Rees, R.M.; Tenorio,
728 J.L.; Vallejo, A. 2015a. Nitrous oxide and methane emissions from a vetch cropping
729 season are changed by long-term tillage practices in a Mediterranean
730 agroecosystem. *Biology and Fertility of Soils* 51, 77-88.

731 Tellez-Rio, A.; Garcia-Marco, S.; Navas, M.; Lopez-Solanilla, E.; Tenorio, J.L.;
732 Vallejo, A. 2015b. N₂O and CH₄ emissions from a fallow-wheat rotation with low N
733 input in conservation and conventional tillage under a Mediterranean
734 agroecosystem. *Science of the Total Environment* 508, 85-94.

735 Tellez-Rio, A.; Vallejo, A.; Garcia-Marco, S.; Martin-Lammerding, D.; Tenorio, J.L.;
736 Rees, R.M.; Guardia, G. 2017. Conservation agriculture practices reduce the global
737 warming potential of rainfed low N input semi-arid agriculture. *European Journal of*
738 *Agronomy* 84, 95-104.

739 Van Groenigen, J.W.; Velthof, G.L.; Oenema, O.; van Groenigen, K.J. 2010. Towards
740 an agronomic assessment of N₂O emissions: a case study for arable crops. *European*
741 *Journal of Soil Science* 61, 903-913.

742 van Kessel, C.; Venterea, R.; Six, J.; Adviento-Borbe, M.A.; Linquist, B.; van
743 Groenigen, K.J. 2013. Climate, duration, and N placement determine N₂O emissions
744 in reduced tillage systems: a meta-analysis. *Global Change Biology* 19, 33-44.

745 Venterea, R.; Maharjan, B.; Dolan, M.S. 2011. Fertilizer source and tillage effects on
746 yield-scaled nitrous oxide emissions in a corn cropping system. *Journal of*
747 *Environmental Quality* 40, 1521-1531.

748 Vereecken, H.; et al. 2016. Modeling soil processes: review, key challenges, and new
749 perspectives. *Vadose Zone Journal* 15. DOI: 10.2136/vzj2015.09.0131.

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752 **Figure captions**

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

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

764 **Fig. 3** Dynamics of soil moisture (0-5 cm), soil temperature (5 cm), soil nitrate and soil
765 ammonium (0-5 cm), soil N₂O flux and cumulative N₂O-N loss in the 2011-2012 barley
766 season under different types of tillage (CT, conventional tillage; NT, no-tillage) and
767 mineral N rates (0, control; 120, 120 kg N ha⁻¹) used for STICS evaluation. Simulated
768 and observed values are shown by continuous lines and circles, respectively. Vertical
769 bars correspond to the standard error. Arrows indicate N fertilizer applications.

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

774 **Fig. 5** Yield-scaled N₂O emissions calculated as the quotient between simulated
775 cumulative soil N₂O emissions and grain yield (dry matter) as affected by tillage (CT,
776 conventional tillage; NT, no-tillage) and mineral N rates (0, 30, 60, 90, and 120 kg N
777 ha⁻¹ yr⁻¹) in a rainfed barley cropping system during the eighteen cropping seasons of
778 the 1996-2014 period. n.d., not-determined. For each sub-figures row, the Y-axis scale
779 corresponds to the sub-figure in the left.

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

Soil characteristic	
Soil classification ^a	Typic Xerofluvent
pH (H ₂ O, 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

784 ^a According to the USDA classification (Soil Survey Staff, 2014).

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788 **Table 2.** Statistical criteria showing the performance of the STICS model when simulating different variables related to (i) soil N₂O emissions
789 and (ii) other agronomic soil and crop variables. For soil N₂O emissions data corresponds to the conventional- and no-tillage treatments without
790 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
791 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 ₂ O 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 °C	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 ₂ O-N	-	4	0.83	0.006 kg N ₂ O-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
	Soil nitrate	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

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

793 **Table 3** Simulated cumulative soil N₂O emissions and fraction of total N₂O emission corresponding to denitrification (between brackets) as
 794 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
 795 cropping system during the eighteen cropping seasons of the 1996-2014 period.

Cropping season	Cumulative N ₂ O-N emission (kg N ₂ O-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)

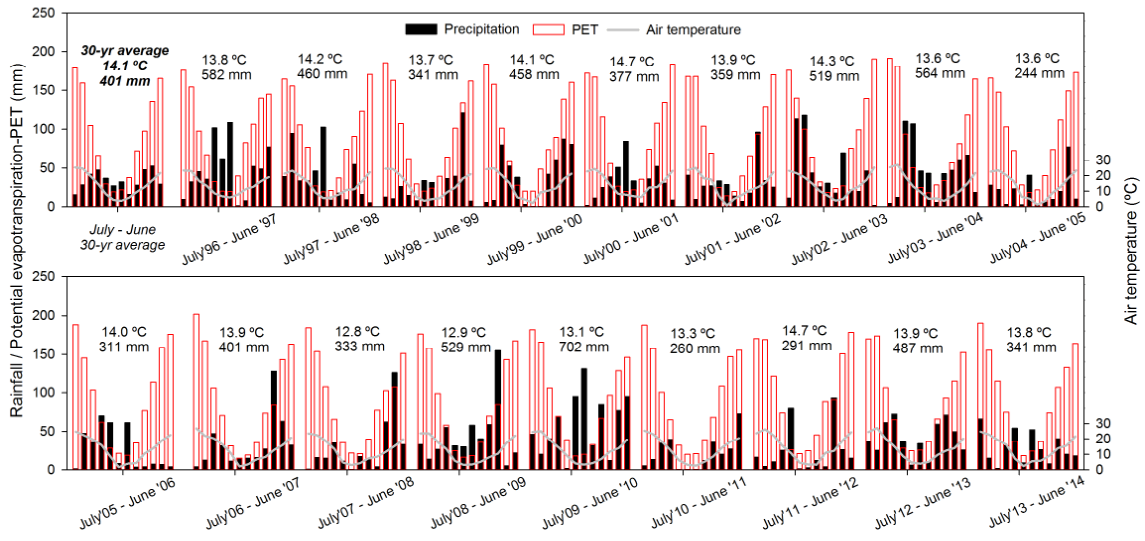
797 **Table 4** Simulated N₂O emission factor (EF) as affected by tillage (CT, conventional
798 tillage; NT, no-tillage) and mineral N rates (30, 60, 90 and 120 kg N ha⁻¹ yr⁻¹) in a rainfed
799 barley cropping system during the eighteen cropping seasons of the 1996-2014 period.

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

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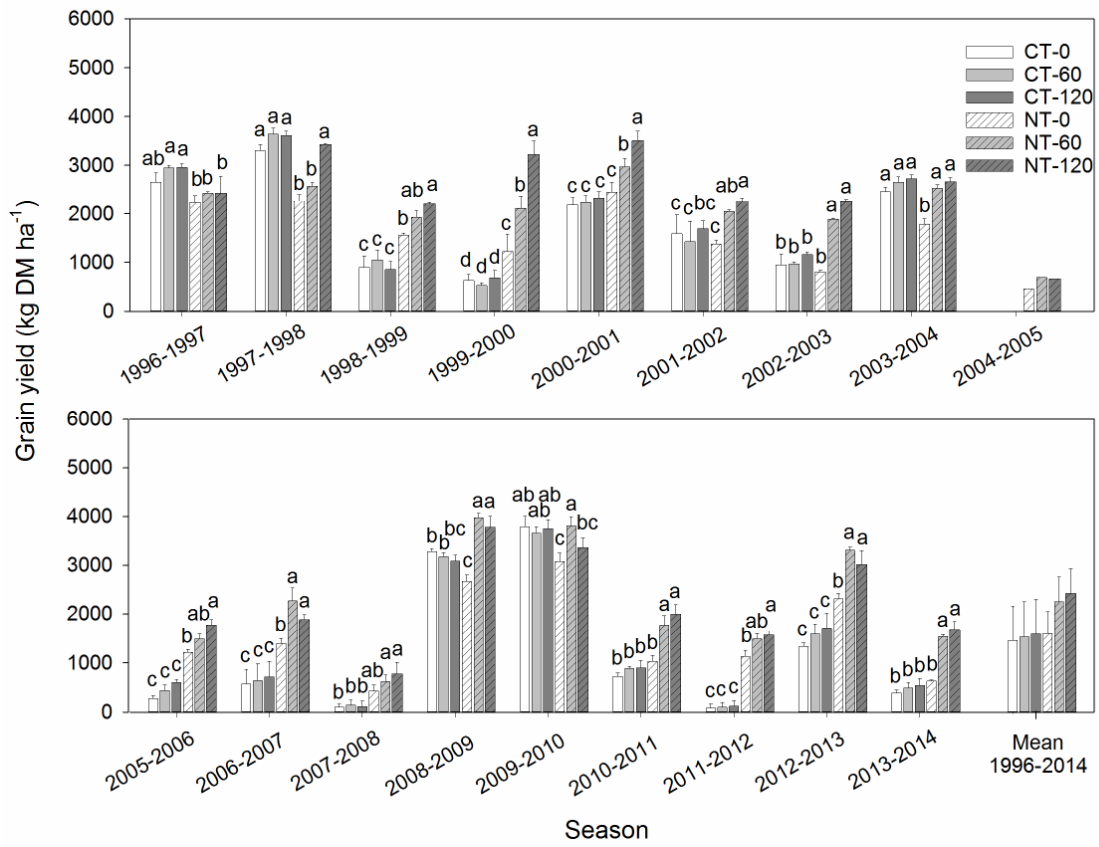


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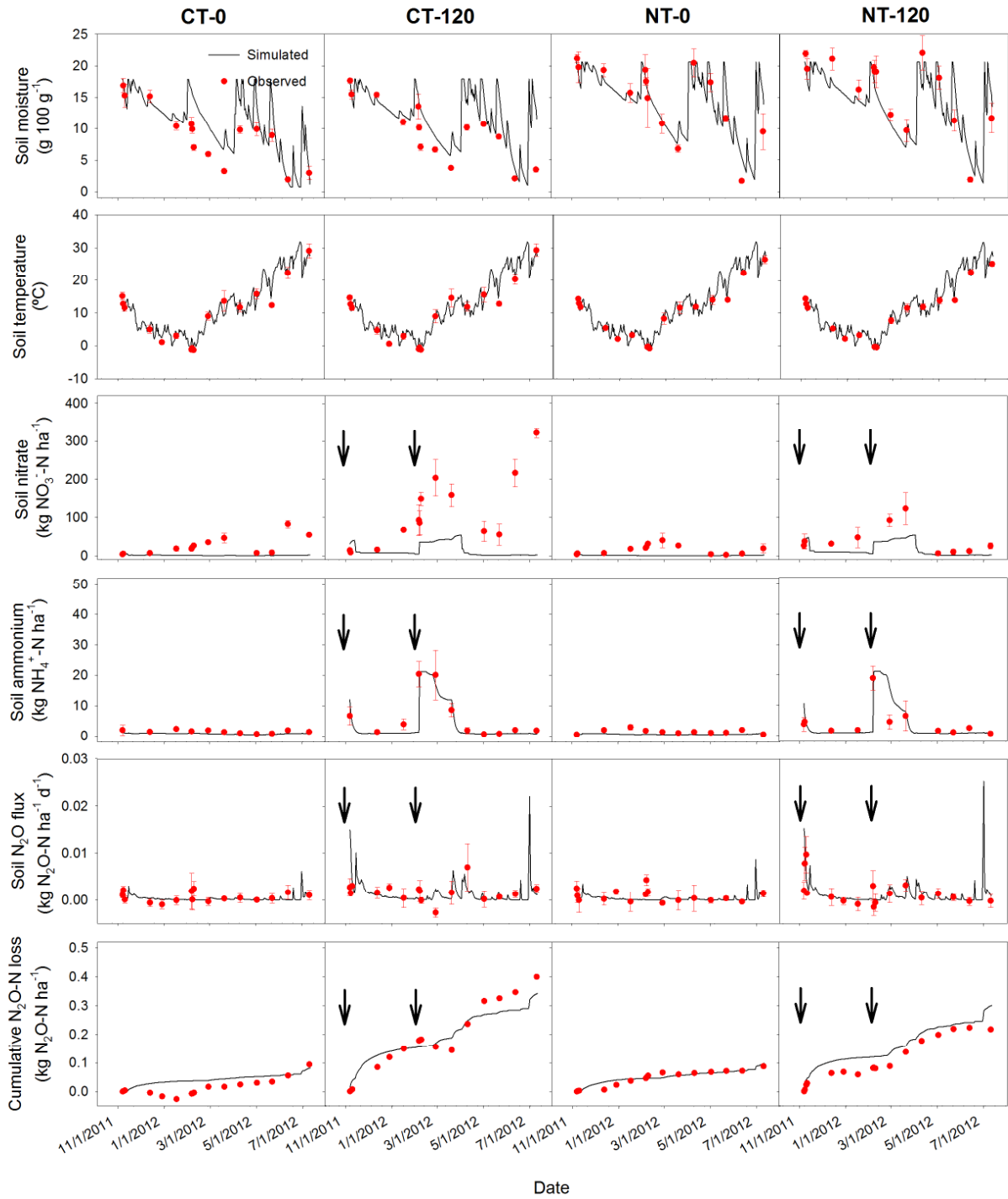
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805 **Fig. 1**

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809 **Fig. 2**

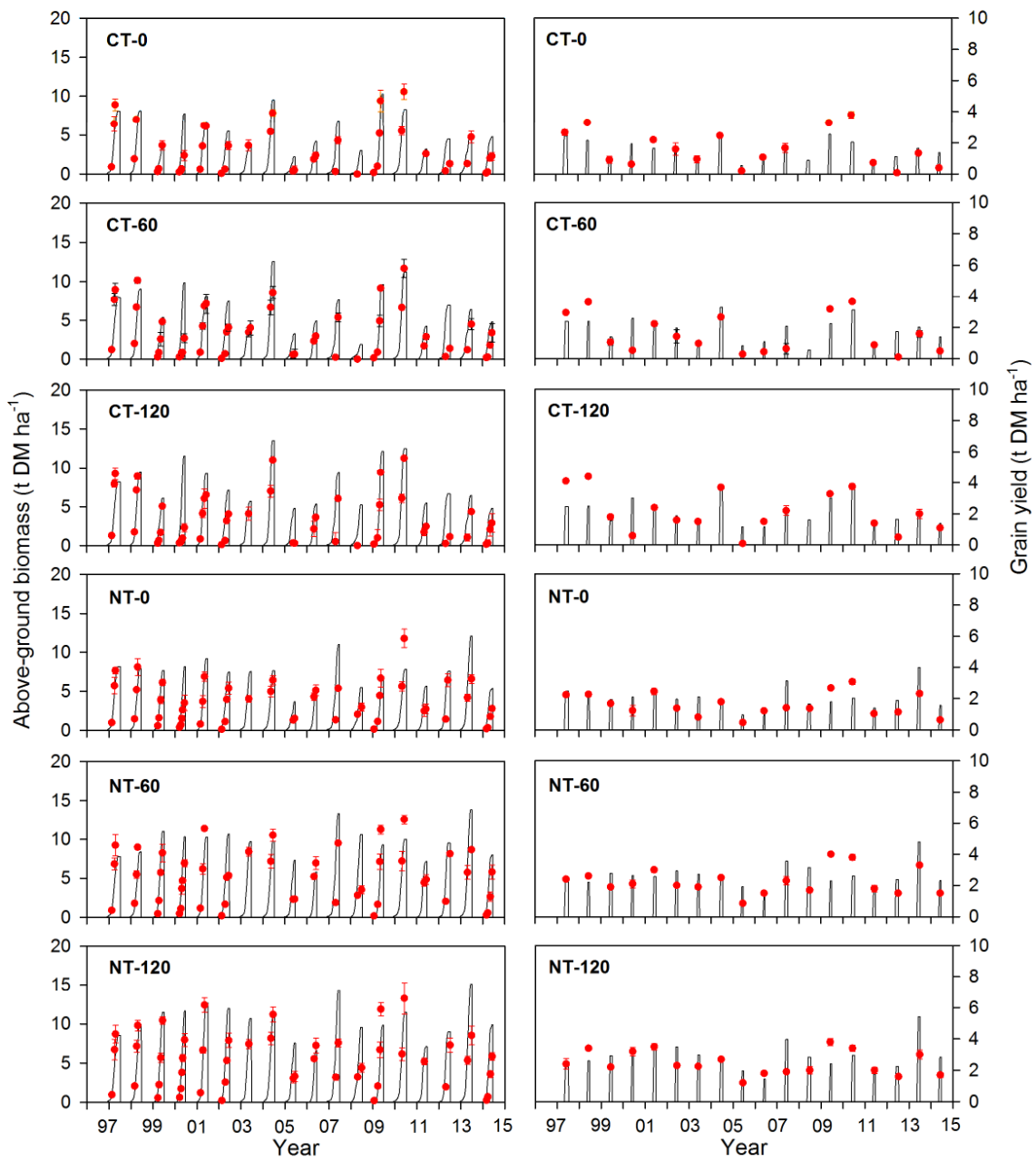


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Fig. 3

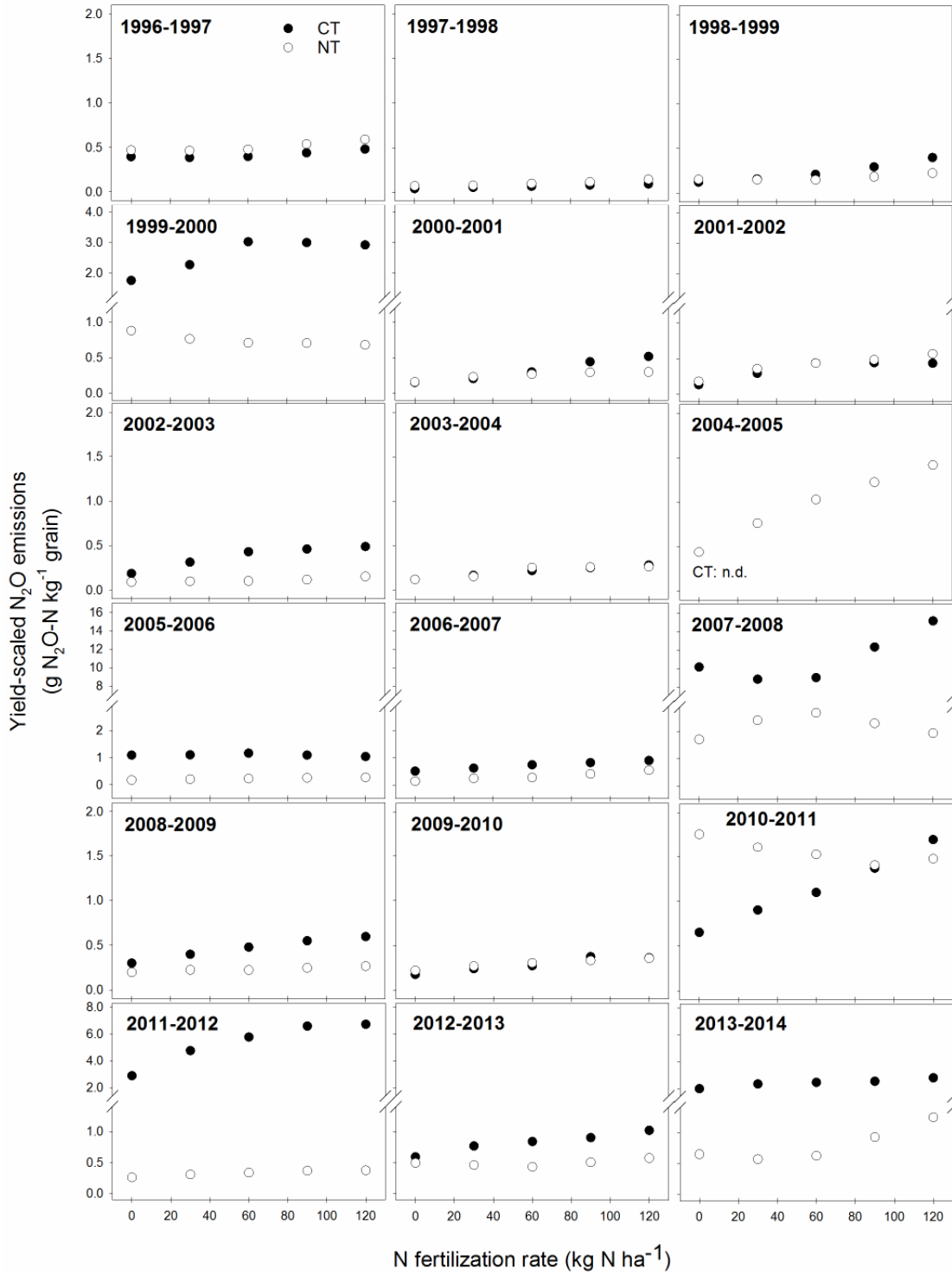
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816 **Fig. 4**

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820 **Fig. 5**

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