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**Precipitation gradient and crop management affect N₂O emissions:
simulation of mitigation strategies in rainfed Mediterranean conditions**

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22 **Abstract**

23 In Mediterranean areas high precipitation variability and crop dependence on soil water
24 availability make the interaction between climate and agricultural management a key issue for
25 mitigating N₂O emissions. In this study we used the STICS model to capture the effect of a
26 water deficit gradient and precipitation variability on N₂O emissions and mitigation strategies
27 (i.e. N fertilizer type, grain legumes introduction in crop rotations and crop residues
28 management) in a rainfed Mediterranean transect (HWD-Senés, MWD-Selvanera and LWD-
29 Auzeville, i.e. high, medium and low water deficit, respectively). The model was first tested
30 against a database of daily N₂O fluxes measured during twelve growing seasons of winter crops
31 at the LWD site. Several scenarios were then run on each site, always over 9 successive
32 growing seasons to take into account precipitation variability. STICS showed a good ability to
33 simulate the driving variables of N₂O fluxes at the daily time scale. The mean observed and
34 simulated cumulative emissions during the growing season were 0.71 and 0.82 kg N₂O-N ha⁻¹
35 ¹, respectively. The simulated N₂O emissions (mean of all scenarios) decreased with increasing
36 water deficit being 2.51, 0.65 and 0.26 kg N₂O-N ha⁻¹ yr⁻¹ for LWD-Auzeville, MWD-
37 Selvanera and HWD-Senés, respectively, which is consistent with published results. The lower
38 N₂O emissions in the driest sites were not only related to lower fertilization rates but also to
39 other factors associated with the Mediterranean characteristics, particularly, the drier water
40 regime. Simulated N₂O emissions were highly sensitive to the interannual variability of the
41 climatic conditions. According to the simulations, urea fertilizer would lead to slightly higher
42 N₂O emissions (+6 and +8%) than ammonium- and calcium nitrate, respectively. The
43 incorporation of winter pea in the traditional cereal-based Mediterranean rotations would
44 reduce by ca. 22% the N₂O emissions in HWD-Senés without changing wheat yields.
45 Differently, in MWD-Selvanera and LWD-Auzeville, N₂O emissions would remain unchanged
46 since the emissions associated to the decomposition of low C:N ratio pea residues would

47 counteract the lower application of N fertilizer. The systematic removal of crop residues at
48 LWD-Auzeville would decrease the N₂O emissions by 20%. However, this practice seems not
49 recommendable if tillage is practiced due to the concomitant decrease of soil organic matter,
50 fact that would worsen the C footprint of the system and increase the susceptibility to soil
51 erosion. Our work highlights the interest of combining experimental and modelling approaches
52 to account for climatic variability and evaluate long-term effects of N₂O mitigation practices
53 under Mediterranean conditions.

54

55 **Keywords**

56 Cereal; Grain legumes; Mitigation strategies; N fertilizer type; Crop residue management;
57 STICS model.

58 **1. Introduction**

59

60 The Mediterranean climate is defined by warm to hot, dry summers and mild to cool,
61 wet winters. It is located between 30 and 45° north and south latitudes. Although it presents a
62 large variability between regions, its common feature is the presence of a severe water deficit
63 during the summer months, while in winter months rainfall usually exceeds evapotranspiration,
64 leading to a soil water recharge (López-Bellido, 1992). Rainfall presents a high intra- and inter-
65 annual variability, with an increasing trend of extreme events in spring and summer months
66 (Ramos and Martínez-Casasnovas, 2006). Crops in the non-irrigated Mediterranean areas
67 strongly depend on the amount of water stored in soil during the recharge period (i.e. September
68 to January) (Cantero-Martínez, et al., 2007), and cropping systems are mainly based on winter
69 cereals, given their cycle synchrony with water availability (López-Bellido, 1992; Álvaro-
70 Fuentes et al., 2009). Crop dependence on soil water availability makes the interaction between
71 climate and agricultural management a key issue both for crop production and N₂O emissions
72 mitigation.

73 Nitrous oxide is a powerful greenhouse gas with a global warming potential (GWP) 265
74 times greater than carbon dioxide (IPCC, 2013). Besides its strong implication in radiative
75 forcing, N₂O also influences the depletion of the ozone layer in the stratosphere (Crutzen,
76 1974). Soil N₂O emissions are the result of the nitrification-denitrification processes (Bremner,
77 1997). They are known to be highly dependent on mineral nitrogen availability and soil
78 moisture. The continuous increase in fertilizer use since the invention of the Haber-Bosch
79 process of industrial N₂ fixation has exacerbated N₂O emissions from soils (Gruver and
80 Galloway, 2008). Nitrogen management has been traditionally oriented towards optimizing the
81 use of N by the crop. In some areas, a significant fraction of N fertilizer is still applied before
82 sowing, which, especially for winter crops, can enhance leaching losses in the rainiest locations

83 and/or lead to an overuse of soil water due to the increase in plant transpiration during the
84 vegetative stages. Because it remains difficult to optimize N fertilization strategies to crop
85 needs under variable water stress conditions, the resulting periods of high mineral N
86 availability can also induce N losses as N₂O. Different fertilization strategies have been tested
87 as a means of mitigating N₂O emissions in the Mediterranean agroecosystems. Among them,
88 (i) the adaptation of N fertilizer application to crop needs, (ii) the split of N fertilizer at key
89 crop development stages, (iii) the use of organic and synthetic fertilizers, and (iv) the use of
90 nitrification inhibitors (e.g. Aguilera et al., 2013; Meijide et al., 2007, 2009; Plaza-Bonilla et
91 al., 2014a; Sanz-Cobeña et al., 2012; Vallejo et al., 2001). Although there is a growing set of
92 knowledge about the impact of fertilization management on N₂O emissions in the
93 Mediterranean areas, the site and temporal specificity of the studies carried out limit our ability
94 to establish general rules for optimized management practices at the regional level, according
95 to climate idiosyncrasies. In particular it would be useful to better know, among fertilization
96 management strategies, which ones are more strongly affected by a more or less pronounced
97 aridity or precipitation variability. Process based models are complementary to site specific
98 studies in that they have the potential to integrate a range of processes and to study the
99 interactions between pedoclimatic conditions and agricultural management practices (De
100 Antoni-Migliorati et al., 2015; Doltra et al., 2015).

101 The objectives of this study were to i) compile a dataset of N₂O emission obtained in
102 Mediterranean conditions and evaluate the ability of a simulation soil-crop model (STICS) to
103 predict the observed fluxes, ii) evaluate its ability to capture the effect of a gradient in mean
104 precipitation and year to year irregularity on N₂O emissions in a Mediterranean transect and
105 iii) to test the efficiency of several agricultural management strategies for mitigating N₂O
106 emissions along such a climatic gradient.

107 2. Materials and methods

108 2.1. Selection of a representative precipitation transect under Mediterranean 109 conditions

110 Three locations representative of the Mediterranean climate were chosen according to
111 a rainfall gradient: Senés, Selvanera and Auzeville (Table 1). This choice was based on (i) the
112 availability of soil N₂O emission data in (or close to) each location to validate the STICS model
113 or check the range of simulated values (Plaza-Bonilla et al., 2014a; Peyrard et al., 2016) and
114 (ii) the presence of cropping systems representative of dryland Mediterranean agriculture.
115 Senés (NE Spain), representative of the Monegros county, was chosen as the lower yield
116 potential threshold given its low annual precipitation (336 mm), large potential
117 evapotranspiration (1250 mm) and long water deficit period (Fig. 1). The upper threshold of
118 the transect was located in Auzeville (SW France) which represents one of the most northern
119 latitude under Mediterranean climate influence and the smallest water deficit (with annual
120 precipitation and potential evapotranspiration values of 685 and 905 mm, respectively) (Fig.
121 1). Finally, Selvanera (NE Spain) was chosen given its intermediate water deficit, annual
122 precipitation (450 mm) and potential evapotranspiration (800 mm) (Fig. 1). Site and soil
123 characteristics of each location of the transect are shown in Table 1. The average productivity
124 of winter cereal (i.e. wheat or barley) is around 1000, 3200 and 5500 kg ha⁻¹ for Senés,
125 Selvanera and Auzeville, respectively (Plaza-Bonilla et al., 2014b, 2016).

126 Traditional cropping systems consist of barley (*Hordeum vulgare* L.) monocropping or a
127 barley-wheat (*Triticum aestivum* L.) rotation in Senés, winter cereal rotations including winter
128 pea (*Pisum sativum* L.) and/or rapeseed (*Brassica napus* L.) in Selvanera and wheat –
129 sunflower (*Helianthus annuus* L.) rotation in Auzeville. Only a small proportion of the farmers
130 includes grain legumes such as vetch (*Vicia sativa* L.) and winter pea (*Pisum sativum* L.) in the
131 rotations in Senés and Selvanera given the high probability of harvest loss due to water stress

132 and doubtful economic benefit (Álvaro-Fuentes et al., 2009). Soil management in the area of
133 Senés and Selvanera is based on reduced tillage (i.e. vertical tillage with chisel ploughs and/or
134 cultivators) and no-tillage (Álvaro-Fuentes et al., 2009; Angás et al., 2006). In turn, in the area
135 surrounding Auzeville, traditional soil management is based on conventional, inversion tillage
136 with moldboard plough (Plaza-Bonilla et al., 2016).

137

138 2.2. *Overview and evaluation of the soil-crop model STICS for N₂O emissions.*

139 The soil and crop model STICS (Brisson et al., 1998, 2002, 2008) is a one-dimensional
140 daily time-step model which simulates plant growth as well as water, C and N cycles over one
141 or several growing seasons. It considers several soil layers with specific properties and uses
142 pedoclimatic characteristics and management practices as inputs for the simulation. The
143 description of the physical and biological processes occurring in the soil-crop system mostly
144 relies on a set of generic parameters which are considered not specific of a context of study and
145 thus are not subject to any calibration. This reduces the risk of introducing bias through specific
146 calibration which often relies on limited or uncertain data when comparing scenarios over a
147 range of contexts. Recently, Coucheney et al. (2015) evaluated the ability of the STICS model
148 to simulate different plant, water and nitrogen outputs over a wide range of pedoclimatic
149 conditions and N fertilization rates in France. Despite the large diversity of conditions
150 considered and the use of the standard set of model parameters, simulated results were shown
151 to be good enough to allow useful predictions of crop and soil variables when the objective is
152 to compare a variety of pedoclimatic and agronomic situations.

153 The simulation of N₂O emissions in STICS relies on the concepts described in Bessou
154 et al. (2010). Nitrification and denitrification processes, and the N₂O emissions associated to
155 each process, are simulated separately. Coupling of nitrification and denitrification exists
156 through the production of nitrate by nitrification, which then serves as substrate for

157 denitrification and N₂O emissions associated to this pathway. Processes are described using a
158 functional approach which is similar to that used in other models like DayCent or Ecosse.

159 Nitrification rate is considered to be proportional to NH₄⁺ content, which proved to be
160 a good approximation over the typical range of ammonium content in soil. It is affected by
161 temperature, increasing until an optimum rate at 32.5°C and then decreasing again (Benoit et
162 al., 2015). Water filled pore space (WFPS) strongly influences the rate of nitrification:
163 nitrification increases until field capacity is reached, then decreases because of the decline of
164 soil aeration (Khalil et al., 2004). In the context of the study, pH does not constrain nitrification
165 rate as pH levels are in the high range. N₂O emission associated to the nitrification pathway is
166 calculated as a variable fraction of the nitrification rate. That fraction remains low for WFPS
167 values below 60% (0.16-0.29%) but strongly increase with WFPS afterwards to reach a
168 maximum of 2.56% at 100% WFPS as a consequence of the resulting decline in oxygen
169 availability (Khalil et al., 2004).

170 Denitrification is calculated as the product of a soil dependent potential rate and
171 functions expressing the effects of nitrate concentration, soil temperature and soil water
172 content. Denitrification rate increases with NO₃⁻ content following a Michaelis-Menten
173 kinetics with a half maximum constant of 215 mg NO₃-N l⁻¹ which, depending on soil water
174 content, corresponds to 20-60 mg NO₃-N kg⁻¹ (Bessou et al., 2010). Denitrification rate also
175 increases with temperature over most of the typical range of temperature as the optimum rate
176 is 47°C (Benoit et al., 2015). As in the NEMIS model (Hénault and Germon, 2000),
177 denitrification rate is null when WFPS is below a threshold which default value is 62% and
178 then increases exponentially with WFPS. N₂O emission from denitrification is calculated as a
179 variable fraction of the denitrification rate which mainly depends on pH and WFPS. Acid pH
180 strongly inhibits N₂O reduction to N₂ (Rochester, 2003). In the model, the N₂O end-product
181 ratio of denitrification increases with pH decreasing from 9.2 to 5.6. For pH values below 6,

182 denitrification has N₂O as main end-product. Finally, soil water content values close to
183 saturation favor N₂O reduction to N₂. This is due to the development of anoxia (Vieten et al.,
184 2008) and to the increase in the residence time of N₂O into the soil associated to lower gaseous
185 diffusion rates. This effect is taken into account through a linear decrease of the denitrification
186 end-product ratio between the threshold WFPS for the onset of denitrification and maximal soil
187 saturation (Bessou et al., 2010).

188 Observed data from the multi-year MicMac low input cropping systems experiment
189 located in Auzeville (SW France), which includes intensive (i.e. daily) N₂O emissions
190 measurements, were used to evaluate the ability of the STICS model in simulating N₂O
191 emissions, in complement to simple comparison of the range of values of emissions for the two
192 other sites. The Auzeville experiment compares three cropping systems which differ in nitrogen
193 rates, pesticide use and cover crops frequency in a randomized design with three blocks.
194 Further details of the experiment can be found in Peyrard et al. (2016) and Plaza-Bonilla et al.
195 (2015). We focused on N₂O emissions data obtained during the 2010 to 2014 period under 12
196 winter wheat and faba bean (*Vicia faba* L.) phases of the rotation. These crops are
197 representative of the production under Mediterranean dryland conditions (i.e. winter growing
198 cycle) (López-Bellido et al., 1992; Loss and Siddique, 1994). For each crop, the daily N₂O
199 emissions observation period covered the entire growing season, from sowing until harvest,
200 except in 2012 when the measurements were stopped after the top-dressing fertilization of
201 wheat (Table 2). Crop management practices carried out during the experimental period during
202 the observed growing seasons are reported in Tables S1 and S2 (Supplementary material). N₂O
203 emission data for each crop cycle were obtained from a set of three automatic chambers (0.70
204 x 0.70 m) inserted into the soil to a depth of 5-10 cm. Four times a day (i.e. each 6-hr) N₂O
205 concentration in the headspace of each chamber was quantified over a 20 min period with a 10
206 s time step. Fluxes at the time of chamber closure were calculated from the initial increase of

207 the concentration vs. time, using a linear or exponential model fit. A linear model was used if
208 the rate constant of the exponential model was lower than 0.01 min^{-1} or the quality of fit of the
209 exponential was not better than that of the linear ($\text{RMSE}_{\text{exp}}/\text{RMSE}_{\text{lin}} > 0.975$) (Peyrard et al.
210 2016). Daily emissions were then calculated from the average of the 4 fluxes measured per
211 day. The soil temperature at 10 cm depth was monitored with the use of two T107 soil probes
212 (Campbell Scientific Inc, Logan, UT, USA). Monthly soil samplings were carried out at the 0-
213 15 and 15-30 cm soil layers to quantify soil water and mineral N contents. A continuous flow
214 autoanalyzer (Skalar 5100, Skalar Analytic, Erkelenz, Germany) was used for mineral N
215 quantification (NH_4^+ and NO_3^-) after 1 M KCl extraction. Values were transformed to a
216 gravimetric basis using soil bulk density, which was quantified at the beginning and at the end
217 of each N_2O measurement period (i.e. at sowing and crop harvest) by taking two replicate
218 samples of the 0-15 and 15-30 cm soil depths using a 500 cm^3 metal cylinder.

219 Climatic data (i.e. maximum and minimum air temperatures, global radiation, rainfall,
220 wind, vapor pressure and Penman evapotranspiration) and soil characteristics of each plot (i.e.
221 soil depth, clay proportion, organic N, C:N ratio, CaCO_3 , pH, albedo, bulk density, water
222 content at field capacity and permanent wilting point) were used to run the STICS model. The
223 average of soil bulk density values at sowing and at harvest was used for the simulations. Five
224 soil layers were considered for simulations: 0-15, 15-30, 30-60, 60-90 and 90-120 cm. The
225 ploughed layer was divided into two layers (0-15 and 15-30 cm) given its key importance for
226 the nitrification and denitrification processes and its consistency with soil layers used for
227 measurements. The model was run without changing the standard parameters controlling the
228 soil physical and biological processes, except the potential rate of N_2O emission from
229 denitrification and threshold WFPS for the onset of denitrification which were modified to
230 improve the quality of fit at Auzeville. They were set at $2.0 \text{ kg NO}_3^- \text{-N ha}^{-1} \text{ d}^{-1}$ over 0-20 cm
231 and 50%, respectively. Because of the limited availability of measured data on the two other

232 sites and the proximity of these values to the default ones, these parameters were kept constant
233 for all the three sites considered in the study. Simulated and observed N₂O cumulative
234 emissions were compared and the r^2 value, the efficiency of the model (EF), the relative root
235 mean square error (rRMSE) and the mean difference (MD) were calculated according to Eq.
236 S1 (Supplementary material).

237 2.3. *Simulation scenarios*

238 The choice of the simulation scenarios aimed at meeting the requirements of the
239 Mediterranean conditions of the transect: (i) the preponderance of cereals in the rotations given
240 their adaptation to water scarcity (López-Bellido, 1992; Álvaro-Fuentes et al., 2009); (ii) the
241 sole use of winter cash crops, since summer crops would rely on irrigation in the sites with
242 highest water deficit (i.e. HWD-Senés and MDW-Selvanera) and cover crops can result in
243 competition for water with cash crops in dryland semiarid areas (Vigil and Nielsen, 1998;
244 Unger and Vigil, 1998); and (iii) the use of tillage, given the low degree of adoption of no-till
245 techniques in the area of the site with the lowest water deficit (LWD-Auzeville) (DRAAF,
246 2014). Soil characteristics (Table 1) and the 2005-2014 climatic data obtained at or close to
247 each site (Fig. 1) were introduced as model inputs. In order to compare between sites, the same
248 values of bulk density were taken for the three sites: 1.4 g cm⁻³ for the 0-15 and 15-30 cm soil
249 depths and 1.5 g cm⁻³ for the soil horizons below 30 cm depth, close to actual observed values.

250 The capacity of different management practices to mitigate N₂O emissions were tested
251 by simulating scenarios differing in: (i) form of N fertilizer (ammonium nitrate AN, calcium
252 nitrate CN, or urea), (ii) rotation, either three cycles of a 3-yr winter cereal rotation (wheat-
253 wheat-barley, called Cer) or three cycles of a mixed rotation (winter pea-wheat-barley, called
254 CerLeg) reducing synthetic N dependence, and (iii) crop residue management (incorporated or
255 removed residues).

256 A simulation of 9 growing seasons was chosen to (i) represent the climatic variability
257 of the Mediterranean conditions, and (ii) to take into account the carry over effect of the
258 preceding crop of the rotations. Moreover, all the phases of each rotation were simulated each
259 year to take into account the climate x crop interaction. Thus, when not specifically mentioned
260 in the text, annual values correspond to the mean of the three phases. Simulated management
261 practices for the different crops are described in Table 3. For N fertilizer applications, different
262 rates were used on each site according to their yield potential (Table 3). In the rotation including
263 winter pea, N fertilizer applied to the succeeding wheat crop was reduced by 55 kg N ha⁻¹ for
264 LWD-Auzeville, taking into account the values measured in the experiment (Plaza-Bonilla et
265 al., 2015). For MWD-Selvanera and HWD-Senés sites a reduction of 35 and 10 kg N ha⁻¹ was
266 considered according to the site-specific potential yield compared to LWD-Auzeville. The
267 model was run continuously, i.e. without re-initialization, for each scenario (i.e. from 2006 to
268 2014). Simulated wheat yield was used as an agronomical indicator of productivity.

269 The results of the simulation of scenarios were statistically analyzed using the JMP 11
270 Pro statistical package (SAS Institute Inc, 2014). Normality of data was tested using the W test
271 of Shapiro-Wilk and non-normal data were log-transformed when needed before analysis.
272 Analysis of variance was used to detect significant differences between sites, or management
273 practices or the interaction between the two. When significant, differences were identified at
274 the 0.05 probability level of significance using the Tukey test. N₂O emissions and crop yields
275 were defined as the dependent variables. The site effect mainly represented the precipitation
276 gradient influence. Fertilizer, crop rotation and crop residue management type effects
277 represented management options. The year effect represented the influence of interannual
278 climatic variability. Finally, the interactions (especially site-management practice) allowed
279 detecting the dependence of a management option on the climatic context.

280

281 **3. Results**

282 *3.1. STICS model performance*

283 The STICS model performed quite well at simulating the different N₂O-driving
284 variables in the LWD experiment, consistently with previous results obtained for similar
285 cropping systems (Plaza-Bonilla et al., 2015). Soil temperature and soil moisture dynamics (0-
286 15 cm) were generally well reproduced, as illustrated by results from the 2010-11 faba bean
287 (Fig. 2a and 2b) and the 2013-14 durum wheat (Fig. 3a and 3b) growing seasons. The
288 simulation of soil nitrate performed generally better for the durum wheat, especially after the
289 application of N fertilizer, than for faba bean, as shown in Fig. 3c. For example soil nitrate (0-
290 15 cm depth) was simulated correctly during winter months (from January to March 2011, Fig.
291 2c), while the model failed at simulating correctly the decrease in nitrate content during the
292 period of active growth of faba bean (from April to June 2011). However, observed and
293 simulated values were close during the bare fallow period after harvest, being 9.7 and 15.9 in
294 August, 19.3 and 15.2 in September and 29.7 and 33.8 kg NO₃⁻-N ha⁻¹ in October, respectively.
295 Soil ammonium (0-15 cm) was simulated acceptably for both crops, for a range of low values
296 (i.e. from 1.4 to 4.8 kg NH₄⁺-N ha⁻¹) in the non-fertilized grain legume and a greater one (i.e.
297 from 0.2 to 28.3 kg NH₄⁺-N ha⁻¹) after the AN applications in durum wheat (Fig. 2d and 3d,
298 respectively).

299 The average values of cumulative emissions during the 12 growing seasons were 0.71
300 and 0.82 kg N₂O-N ha⁻¹ for observed and simulated fluxes, respectively. The coefficient of
301 variation (CV) of observed values for each growing season (n = 3) varied between 6 and 37%,
302 which is in the low range of values reported in the literature for N₂O measurements. Observed
303 cumulative N₂O-N ranged between 0.28 and 1.44 kg ha⁻¹ while simulated fluxes ranged
304 between 0.46 and 1.72 kg ha⁻¹ (Fig. 4). The r^2 , EF, rRMSE and MD of the comparison between

305 the cumulative observed and simulated N₂O-N emissions were 0.40, 0.24, 45.6% and 0.1 kg
306 N₂O-N ha⁻¹, respectively.

307 Overall, simulated N₂O emissions were rather low. However, the ability of the model
308 to reproduce the N₂O dynamics was acceptable. For instance, the mean observed and simulated
309 N₂O-N flux was 2.48 and 3.0 g ha⁻¹ d⁻¹ for the faba bean growing season of 2011, and 4.46 and
310 3.66 g ha⁻¹ d⁻¹ for the durum wheat growing season of 2014, which represents a +21% and -
311 18% difference between observed and simulated values. Similar magnitudes were found
312 between observed and simulated of N₂O fluxes in the faba bean growing season (Fig. 2e). In
313 that example, observed data exceeded simulated ones only during some days in March, with
314 high variability between chambers. However, differences were less than one order of
315 magnitude in all cases. During the wheat crop, the observed and simulated N₂O fluxes varied
316 similarly in most cases (Fig. 3e). The increase in the emissions after wheat top-dressing N
317 fertilization was captured by the model, although there was a tendency to overestimate N₂O
318 peaks (Fig. 3e). Difficulties appeared in simulating late emissions occurring far from N
319 fertilization events. However, the dynamics of observed and simulated cumulative N₂O-N
320 emissions was similar in both crops (Fig. 2f and Fig. 3f).

321 3.2. *Precipitations and crop yields simulated in scenarios*

322 Precipitation values and their distribution over the nine growing seasons used for the
323 simulations (i.e. from 2006 to 2014) presented large differences between sites (Fig. 1). During
324 these 9 growing seasons (i.e. defined as the period from July to June of the subsequent year)
325 precipitation varied between 166 and 434 mm, 315 and 559 mm and 516 and 823 mm in HWD-
326 Senés, MWD-Selvanera and LWD-Auzeville, with average values of 303, 460 and 637 mm,
327 respectively (Figs. 1a, 1b and 1c). The CV of annual precipitation was high and similar between
328 sites: 23, 15 and 18% for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively. A
329 decrease in the duration of water deficit occurs in the south-to-north direction of the transect:

330 monthly water deficit (calculated as PET – precipitation) exceeded 100 mm during the May-
331 to-August, June-to-August and July-to-August periods in the HWD, MWD and LWD sites,
332 respectively. The frequency of daily rainfall events ≥ 30 mm increased from the south-to-north
333 direction with 9, 12 and 14 days for the HWD, MWD and LWD sites, respectively.

334 Simulated grain yield was significantly affected by water deficit, with significant
335 differences between sites on wheat production, with higher yields when decreasing water
336 deficit (Table S3, Supplementary material; Fig. 5b), a trend that was also observed in barley
337 and winter pea (Fig. 5c and 5d). Simulated yields of winter pea showed an increase according
338 to the potential of each site with an average of 0.5, 1.7 and 3.9 Mg ha⁻¹ for HWD-Senés, MWD-
339 Selvanera and LWD-Auzeville, respectively. Cereals showed larger simulated productions,
340 with an average of 1.1, 4.1 and 7.5 Mg ha⁻¹. In MWD-Selvanera, the scenario with the
341 incorporation of winter pea in the rotation, the production of wheat increased significantly by
342 15%. In the two other sites, HWD-Senés and LWD-Auzeville, there was no significant
343 difference in wheat production between rotations. The yields simulated by the STICS model
344 were sensitive to the climatic conditions of the year (Fig. 5b, 5c and 5d).

345 3.3. Cumulative N₂O emissions simulated in scenarios

346 The effect of the different factors on N₂O cumulative emissions is presented at Table
347 S3 (Supplementary material). Site, and thus climatic gradient, had a strong effect on the
348 production of N₂O from nitrification and denitrification and total N₂O emissions, with an
349 increase from high to low water deficit. As an average of all the scenarios taken into account,
350 cumulative N₂O losses were 0.26, 0.65 and 2.51 kg N₂O-N ha⁻¹ yr⁻¹ for HWD-Senés, MWD-
351 Selvanera and LWD-Auzeville, respectively (Table 4). However, the contribution of
352 denitrification to total N₂O emissions did not follow the same relationship, being largest in
353 LWD-Auzeville and smallest in MWD-Selvanera with intermediate values in HWD-Senés.

354 Most of the management scenarios simulated, when analyzed as single effects,
355 significantly affected the cumulative N₂O emissions and/or the N₂O producing processes (i.e.
356 nitrification and denitrification) and the relative contribution of the denitrification to total N₂O
357 emission (Table S3, Supplementary material). The type of N fertilizer affected total N₂O losses,
358 with higher N losses (+6 and +8%) for urea compared to AN or CN. This effect was mainly
359 associated to an increase in N₂O produced through the nitrification process. As a consequence,
360 the relative importance of denitrification on N₂O losses was also impacted by the nature of the
361 fertilizer. The effect of fertilizer form on total N₂O emissions was not site (or climate)
362 dependent as shown by the lack of interaction between site and fertilizer type.

363 On the contrary, the effect of the other management options depended on the site of
364 study and thus the climate gradient. The type of rotation had no significant effect on total N₂O
365 emissions although it significantly affected the amount of N₂O derived from nitrification which
366 was slightly larger for the rotation based on cereals than that with winter pea (Table 4). The
367 site x rotation interaction was however significant: in HWD-Senés, the Cer rotation showed
368 larger total N₂O losses due to a larger contribution from both nitrification and denitrification
369 processes when compared to the rotation including a grain legume (CerLeg). Crop residue
370 management significantly affected total N₂O losses irrespective of the site, but the presence of
371 an interaction with the site indicates that its effect was dependent on the climatic context: it
372 was larger in the wetter sites, e.g. 20% higher in LWD-Auzeville when returning crop residues
373 compared to their removal. This was due to a larger contribution of both nitrification and
374 denitrification processes (11 and 22% increase, respectively). The climate x residue
375 management interaction is also illustrated by the exponential relationship between N₂O losses
376 and soil water accumulation during the growing season (Fig. 6).

377 A significant interaction between rotation and N fertilization type was found (Table S3,
378 Supplementary material). N₂O emissions did not differ between fertilizer types in the CerLeg

379 rotation, whereas in the Cer rotation larger total and nitrification-driven N₂O emissions
380 occurred with urea as fertilizer (Table 4). In the Cer rotation, the relative proportion of N₂O
381 resulting from denitrification decreased in the order CN > AN > urea. A significant interaction
382 was found between residue management and N fertilizer form on total and nitrification-driven
383 emissions: N₂O emissions were not affected by the fertilizer form when returning crop residues,
384 but were elevated with urea fertilization in combination with crop residue removal.

385 Finally, the year had a strong effect on N₂O emissions, both as main effect and through
386 interaction with other factors. This is a clear indication of the strong influence of precipitation
387 variability which is analyzed in the next section.

388 3.4. N₂O emissions affected by precipitation variability

389 Simulated N₂O fluxes were highly sensitive to the annual climatic conditions as shown
390 by i) the role played by rainfall between sites (Fig. 6) and between years for a given site (Fig.
391 5a), ii) the significance of the year single effect and its interactions with the rest of effects tested
392 (Table S3, Supplementary material). The inter-annual variability (represented by the CV) of
393 N₂O emissions averaged over the scenarios simulated with STICS reached 52, 49 and 27% for
394 HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively. Despite a lower CV,
395 Auzeville site exhibited important inter-annual variation of N₂O fluxes and cumulative
396 emissions ranged from 1 to almost 4 kg N₂O-N ha⁻¹ yr⁻¹ (Fig 6a). Another example of the
397 influence of precipitation variability is found at MWD-Selvanera in 2014 in the barley-pea-
398 wheat sequence (BPW, CerLeg rotation). The wheat following winter pea resulted in a
399 cumulative N₂O emission of 2.79 kg N₂O-N ha⁻¹ yr⁻¹, which is much larger than the average of
400 the rest of the years (2006-2013) of the same sequence (0.61 kg N₂O-N ha⁻¹ yr⁻¹) and the 2014
401 value of the pea-wheat-barley (PWB) and wheat-barley-pea (WBP) sequences (0.79 and 0.94
402 kg N₂O-N ha⁻¹ yr⁻¹, respectively). Cumulative N₂O emissions in the 2009-2010 growing season
403 in LWD-Senés were also much lower than in the rest of the years due to the dry conditions

404 from June to September 2009 (Fig. 1a). For a given site and management scenario, the dynamic
405 features of N₂O emissions were also highly sensitive to the conditions of the year considered,
406 with increases in the cumulative N₂O emissions after N fertilizer applications (Fig. 7a-l) or
407 incorporation of low C:N ratio winter pea residues in soil (e.g. 2009-2010 season in Fig. 7g-l)
408 which was exacerbated under wet soil conditions.

409 The interaction between year and management options was always significant, which
410 indicates that the potential of mitigation associated to a practice is strongly dependent on the
411 climate of the year considered. For instance, during the 2006 to 2014 period, cumulative N₂O
412 emissions for the Cer rotation varied between 0.13 and 0.66, 0.26 and 0.97 and 1.03 and 3.67
413 kg N₂O-N ha⁻¹ yr⁻¹ for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively; in the
414 CerLeg rotation, the emissions ranged between 0.12-0.51, 0.20-1.51 and 1.93-3.21 kg N₂O-N
415 ha⁻¹ yr⁻¹, respectively.

416 **4. Discussion**

417 *4.1. Rainfall variability, crop yields and N₂O emissions*

418 Tier 1 methodology proposed by the IPCC (2006) does not take into account explicitly
419 pedoclimatic and agricultural management influences on N₂O emissions. The results of the
420 present work highlight the potential large variability of N₂O emissions under Mediterranean
421 conditions, both along an aridity gradient and from year to year. As a consequence, the use of
422 models (i.e. Tier 3) seems especially relevant in the Mediterranean context for a more precise
423 quantification of N₂O emissions taking into account its typical strong variability (Conen et al.,
424 2000).

425 The ability of the STICS model to simulate N₂O emissions was first evaluated using
426 data observed in the LWD-Auzeville for which daily measurements were available. The test
427 indicated a reasonable consistency between observed and simulated cumulative values which
428 varied between 0.28-1.44 and 0.46-1.71 kg N₂O-N ha⁻¹ yr⁻¹, respectively. The mean cumulative

429 N₂O emissions predicted by the STICS model in the two other sites, HWD-Senés and MWD-
430 Selvanera, were 0.26 and 0.65 kg N₂O-N ha⁻¹ yr⁻¹, which falls in the range of published values
431 for semiarid dryland Mediterranean conditions. For instance, Plaza-Bonilla et al. (2014a)
432 measured the effect of different tillage and N fertilizer management practices on N₂O emissions
433 in one experimental site close to HWD-Senés and another slightly drier than MWD-Selvanera
434 (i.e. with an annual water deficit of 425 mm compared to the 350 mm of the MWD site), both
435 under winter cereal production in dryland conditions. In the site close to HWD-Senés, they
436 measured an emission of 0.16, 0.21 and 0.58 kg N₂O-N ha⁻¹ for three rates of fertilizer (0, 75
437 and 150 kg N ha⁻¹) as ammonium sulphate and AN under conventional tillage (i.e. disk plough
438 and chisel). In the site drier than MWD-Selvanera, the emission was 0.08, 0.41 and 0.38 kg
439 N₂O-N ha⁻¹ yr⁻¹ when applying 0, 60 and 120 kg N ha⁻¹ as ammonium sulphate and AN with a
440 full inversion tillage based on moldboard ploughing. Similar magnitudes were measured in a
441 semiarid area in Central Spain with 315 mm of annual water deficit (calculated as ETo minus
442 precipitation); cumulative N₂O emissions of 0.35 kg N ha⁻¹ during a spring barley growing
443 season (i.e. from January to June) fertilized with urea were reported (Meijide et al., 2009). At
444 the same site, Ábalos et al. (2013) measured the N₂O emissions under a rainfed barley crop.
445 They found a cumulative emission of 0.67 and 1.30 kg N₂O-N ha⁻¹, respectively, after removing
446 or incorporating the previous corn residues, during the period from the incorporation of
447 residues to the harvest (i.e. mid-November to end of June). A similar range of emission (0.32-
448 0.68 kg N₂O-N ha⁻¹ yr⁻¹) was reported by Kessavalou et al. (1998) in the semiarid High Plains
449 of the USA in a wheat-fallow rotation. This range is consistent with that obtained in the
450 simulations, which broadens the confidence in simulated results despite the usual difficulties
451 in simulating the dynamics of N₂O emissions.

452 As pointed out before, the significant interannual variability of rainfall had a clear
453 influence on cumulative N₂O emissions simulated by the model in the three sites analyzed. In

454 temperate semiarid areas and at the landscape scale, fluctuation of N₂O emission is mainly
455 influenced by precipitation and irrigation, and when soil moisture is favorable, soil mineral N,
456 temperature and labile C availability become important (Corre et al., 1996; Rowlings et al.,
457 2015). The CV of the simulated cumulative N₂O emissions reached 52, 49 and 27% for HWD-
458 Senés, MWD-Selvanera and LWD-Auzeville respectively, showing the strong interannual
459 variability of N₂O fluxes in the Mediterranean conditions. Similar high interannual variability
460 was reported in the few multiyear greenhouse gas datasets published in the literature. In the
461 site equivalent to HWD-Senés, Plaza-Bonilla et al. (2014a) found a CV of 20% for cumulative
462 emissions measured over two seasons (2011-13) and five fertilization treatments. Du et al.
463 (2006) reported an interannual CV of 71% when measuring N₂O emissions in a cold semi-arid
464 grassland in inner Mongolia.

465 The STICS model predicted that water deficit exerted a large impact on crop yields,
466 with a winter cereal yield varying between 0.5 and 9.5 Mg ha⁻¹ along the transect. Such a
467 variation is commonly observed under Mediterranean conditions depending on the amount of
468 water available for the crop (Cantero-Martínez et al., 2003, 2007). Plaza-Bonilla et al. (2014b)
469 compared three sites with different yield potentials along the semiarid Ebro valley (NE Spain).
470 They found that winter cereal production ranged from 0.4 to 8.2 Mg ha⁻¹ in the 2009-10
471 growing season. Simulated winter pea yields were very low in HWD-Senés, between 0.1 and
472 1.4 Mg ha⁻¹, demonstrating the probability of crop failure and associated economic risk when
473 establishing grain legumes in the most extreme locations under Mediterranean conditions, as
474 reported by Álvaro-Fuentes et al. (2009).

475 4.2. *Management scenarios for N₂O mitigation*

476 We compared the potential to reduce N₂O emissions in Mediterranean dryland field
477 crops production by different scenarios of management practices. All driving variables (i.e.
478 proportion of O₂ in the soil pores, temperature, mineral N and labile C) were directly affected

479 by agricultural management practices (e.g. N fertilization, crop residues incorporation, soil
480 management, etc.), in interaction with the soil water status. The simulations carried out showed
481 the sensitivity of N₂O emissions to the nature of the fertilizer used (including substitution of
482 legumes in the rotation instead of mineral N fertilizer) and residue management, effects well
483 documented in the existing literature (e.g. Bouwman et al., 2002; Ábalos et al., 2013).

484 The introduction of one winter grain legume (i.e. winter pea) in the traditional cereal-
485 based rotations reduced significantly the emissions of N₂O only in the driest site (HWD-Senés),
486 given the low amount of winter pea residues produced susceptible of being decomposed during
487 the successive phase of the rotation (i.e. wheat phase). In LWD-Auzeville and MWD-
488 Selvanera, the reduction of N₂O emissions simulated as a result of the N fertilizer savings in
489 durum wheat preceded by winter pea, was offset by an increase in emissions due to the
490 decomposition of the crop residues from the winter pea crop. The simulated N₂O emissions
491 during the wheat phase preceded by winter pea in the CerLeg rotation were 35 and 48% larger
492 than the corresponding wheat phase of the Cer rotation in MWD-Selvanera and LWD-Senés,
493 respectively. In a recent meta-analysis, Basche et al. (2014) reported that the incorporation of
494 legume cover crop residues to the soil increased N₂O emissions when compared to the
495 incorporation of cereal crop residues with a larger C:N ratio. The incorporation of low C:N
496 ratio residues to the soil usually increases net N mineralization contributing to higher nitrate
497 availability, and concomitantly to larger N₂O emissions (Firestone and Davidson, 1989).

498 Contradictory results were obtained by De Antoni-Migliorati et al., (2015) when using
499 the DayCent model in a simulation study carried out in irrigated Oxisols under subtropical
500 conditions. The authors tested the interest of introducing legume pastures in summer cereal-
501 based (i.e. sorghum) cropping systems. They simulated a reduction in N₂O emissions when
502 introducing legume pastures and lowering sorghum N-fertilization by 30%. However, under
503 those subtropical conditions sorghum is planted right after the incorporation of the legume,

504 improving the synchrony between crop demand and N availability due to legume residues
505 decomposition, reducing the susceptibility to N₂O emissions. Unfortunately, under dryland
506 Mediterranean conditions, the establishment of two crops per year (i.e. a cash and cover crop
507 succession or a double cropping) is impeded by water scarcity, being only possible in the
508 wettest sites and/or with irrigation. As a consequence, N₂O emissions associated to residue
509 decomposition and mineral N release can occur during the fallow period between grain legume
510 harvest (i.e. June) and subsequent crop sowing (i.e. November) as already observed at the LWD
511 site (Peyrard et al. 2016). However, Barton et al. (2014) suggested that it is unlikely that grain
512 legume cropping would increase soil N₂O emissions in semi-arid conditions. These
513 contradictory findings suggest the need to carry out more field-based measurements of N₂O
514 emissions under semi-arid conditions when diversifying cereal-based cropping systems, which
515 could be designed with the help of model simulations.

516 According to our simulations, the removal of crop residues would reduce the emissions
517 of N₂O by 0.45 kg N₂O-N ha⁻¹ yr⁻¹ in LWD-Auzeville, the most productive site. After
518 compiling studies carried out in eastern Canada and northeastern US, Gregorich et al. (2005)
519 reported larger N₂O emissions when incorporating stubble residues in soil instead of leaving
520 crop residues on the soil surface: 2.41 vs. 1.19 kg N₂O-N ha⁻¹ yr⁻¹. Abalos et al. (2013) also
521 found a marked increase (+105%) in N₂O emissions when incorporating maize stover in a non-
522 irrigated barley crop compared to crop residues removal. They attributed the increase to a larger
523 amount of dissolved organic carbon, nitrate availability and more anaerobic microsites
524 enhancing denitrification due to the maize stover. However, the removal of crop residues
525 represents a significant loss of soil organic carbon and soil quality which could counteract the
526 lower N₂O emissions and increase the C footprint of the system. The input of C to the soil as
527 crop residues is of a paramount importance to maintain the stock of soil organic C under
528 dryland conditions (Plaza-Bonilla et al., 2016). Taking into account a GWP of 265 (IPCC,

529 2013) the emission of $0.45 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ would be equivalent to the sequestration of 50
530 $\text{kg C ha}^{-1} \text{ yr}^{-1}$ in the soil, a value of C sequestration which can be reached under dryland
531 conditions when returning the crop residues to the soil (Lal, 2004).

532 Given its lower price, urea is one of the most commonly used nitrogenous fertilizers by
533 farmers in the Mediterranean basin (FAOSTAT; Ryan et al., 2009). However, the simulation
534 predicted an increase in N_2O emissions when applying urea compared to ammonium nitrate,
535 due to greater losses of N_2O by nitrification. Decock (2014) analyzed data collected in corn
536 cropping systems of the Midwestern US and South-East Canada and found a tendency of larger
537 N_2O emission for ammonium nitrate than for urea. However, she pointed out that fertilizer N-
538 forms different from nitrate would enhance N_2O emissions in dry conditions that favor
539 nitrification. Urea can also lead to larger NH_3 losses to the atmosphere than other N fertilizers,
540 particularly in the Mediterranean region where soils are commonly basic (Sanz-Cobena et al.,
541 2008; Ryan et al., 2009). One technological option for the reduction of N_2O losses from
542 synthetic fertilizers is the use of nitrification inhibitors. Although it has received much
543 attention, such chemicals are unlikely to be used extensively, due to its high cost and the low
544 productivity of field crops under dryland Mediterranean conditions (Ryan et al., 2009).

545

546

547 **5. Conclusions**

548 Results from this simulation work indicate that N₂O emissions from rainfed field crop
549 production in a water deficit transect, range from 0.3 to 2.5 kg N₂O-N ha⁻¹ yr⁻¹, covering a large
550 panel of agricultural dryland production under Mediterranean conditions. The lower N₂O
551 emissions in the driest sites were not only related to lower N fertilization rates but also to other
552 factors associated with the Mediterranean characteristics, particularly, the dryer water regime.
553 The interannual variability of rainfall, which is an intrinsic characteristic of the Mediterranean
554 climate, strongly influenced the simulated emissions of N₂O during the 9-yr period considered,
555 with an inter-annual variability ranging between 27 and 52% (depending on the site). Thus,
556 when designing experiments, emission measurements over at least a complete rotation and/or
557 several years should be favored. Simulated seasonal N₂O emissions were driven by N
558 fertilization events and low C:N ratio of crop residues (i.e. legumes) decomposing after harvest.

559 All management options aiming at soil N₂O emissions mitigation were affected by
560 climate. According to the model, the application of urea would increase N₂O emissions when
561 compared to other fertilizers partially or totally based on nitrate. This effect was observed in
562 all cases but its intensity varies with the water deficit gradient. This model output, which
563 remains to be demonstrated experimentally, can be explained by winter crops growing in the
564 specific conditions of the Mediterranean climate, which favor nitrification N₂O losses. The
565 introduction of winter pea in the traditional cereal-based rotation only reduced N₂O emissions
566 in the driest site. In the sites with greater yield potential, the decomposition of pea residues
567 (with low C:N ratio) could have counteracted the N₂O emissions associated with the reduction
568 in N fertilizer applied to the succeeding crop. Crop residue removal reduced N₂O emissions in
569 the most productive site with the lowest water deficit, i.e. LWD-Auzeville. However, reducing
570 crop residues return to soil could lead to soil carbon losses which is negative both for the overall
571 C footprint of the system, soil quality and future yields. Our work demonstrates the usefulness

572 of modelling approaches combined with experimental data, to take into account climatic
573 variability and explore how the efficiency of mitigation practices is affected by the agro-pedo-
574 climatic conditions.

575

576

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746 **Figure captions**

747 **Fig. 1** Mean monthly precipitation (black columns) and potential evapotranspiration
748 temperature (PET, red columns) at each site: a) HWD-Senés, b) MWD-Selvanera and c)
749 LWD-Auzeville (HWD, MWD and LWD, high, medium and low water deficit,
750 respectively) 30-yr average values (in italics) and 2005 to 2014 growing seasons (i.e. shown
751 from July to June). For each site and growing season mean precipitation is reported within
752 the sub-figures.

753 **Fig. 2** Observed and simulated soil temperature (a), water content (b), nitrate content (c) and
754 ammonium content (d) in the 0-15 cm soil layer, daily N₂O fluxes (e) and cumulative N₂O
755 losses (f) during a faba bean growing season in 2011 in LWD-Auzeville. Vertical bars
756 correspond to the standard deviations.

757 **Fig. 3** Observed and simulated soil temperature (a), water content (b), nitrate content (c) and
758 ammonium content (d) in the 0-15 cm soil layer, daily N₂O fluxes (e) and cumulative N₂O
759 losses (f) during a durum wheat growing season in 2014 in LWD-Auzeville. Vertical bars
760 correspond to the standard deviations. Vertical arrows indicate the applications of
761 ammonium nitrate fertilizer.

762 **Fig. 4** Observed and simulated cumulative N₂O emissions of different cropping seasons (10-
763 11, 11-12, 12-13 and 13-14) of faba bean (FB) and durum wheat (DW) crops in LWD-
764 Auzeville. Horizontal bars indicate the standard deviations of measurements (n = 3). The
765 previous cover crops (bc, berseem clover, oat, vetch+mu, vetch and mustard mixture) and
766 bare fallow (bf) phases are shown in brackets.

767 **Fig. 5.** Simulated annual N₂O emissions (a), and wheat, barley and winter pea grain yield (b, c
768 and d, respectively) in each site versus rotation type (Cer ,or CerLeg) and crop sequence

769 (WWB, WBW, BWW and PWB, WBP, BPW) during the 2006-2014 period. Values are the
770 mean of the three fertilizer types and the two crop residues managements.

771 **Fig. 6** Relationship between annual N₂O emissions (simulated) and a water availability
772 indicator (soil water content at the beginning of soil water recharge period (July) + annual
773 rainfall). Two exponential relationships were fitted, depending on crop residues
774 management (incorporated vs. removed). Values are the mean of two rotation types and
775 three N fertilizer types. HWD, MWD and LWD correspond to high (Senés), medium
776 (Selvanera) and low (Auzeville) water deficit sites.

777 **Fig. 7** Simulated cumulative N₂O emissions in a cereal (a-f) and cereal-legume rotation (g-l)
778 with three N fertilizer (AN, ammonium nitrate, CN, calcium nitrate and Urea) and two crop
779 residues management (No residues, residues removed; Residues, residues incorporated)
780 scenarios during the 2006-2014 period at each site. The wheat-W/wheat-W/barley-B and the
781 winter pea-P/wheat-W/barley-B sequences of the Cer and CerLeg rotations are shown.
782 Arrows indicate the first N fertilizer application on each crop and the incorporation of pea
783 residues to the soil. (For interpretation of the legend the reader is referred to the web version
784 of this article.)

785 **Table 1.** Site and general soil characteristics in the 0–30 cm soil depth of the three experimental
786 sites. HWD, MWD and LWD indicate high, medium and low water deficit, respectively. PET
787 = potential evapotranspiration.
788

	Site		
	Senés (HWD)	Selvanera (MWD)	Auzeville (LWD)
Country/Region	Spain/Aragón	Spain/Catalonia	France/Midi-Pyrénées
Latitude	41° 54' N	41° 49' N	43° 31' N
Longitude	0° 30' W	1° 17' E	1° 30' E
Elevation (m)	395	470	150
Annual precipitation (mm)	327	450	685
Annual PET (mm)	1197	800	905
Annual water deficit (mm) ^a	870	350	220
Soil classification ^b	Typic Calcixerept	Fluventic Xerochrept	Typic Hapludalf
pH	8.0	8.3	7.0
Soil organic carbon (g kg ⁻¹)	15.6	10.5	8.7
EC _{1:5} (dS m ⁻¹)	1.04	0.16	0.0
CaCO ₃ eq. (%)	29.5	35.0	0.3
Water retention (% vol.) at			
-33 kPa	26.8	27.3	30.7
-1500 kPa	13.9	12.1	12.8
Particle size distribution (%)			
Sand (2,000-50 µm)	6.2	36.5	37.6
Silt (50-2 µm)	63.3	46.4	36.8
Clay (2 µm)	30.5	17.1	25.6
Rooting depth (m)	0.6-0.9	0.9-1.0	1.2

789

790 ^a Calculated as the difference between annual precipitation and annual evapotranspiration.

791 ^b According to the USDA classification (Soil Survey Staff, 2014).

792 **Table 2.** Summary of the growing seasons and duration of the daily N₂O emission
 793 measurements used to test the model in the durum wheat and faba bean phases (in bold)
 794 depending on the rotation carried out in Auzeville (SW France).

Rotation	Crop analyzed	Growing season	N ₂ O measurements	
			Beginning	End
SR* – (bf) – SF – (bf) – DW – (bf)	Durum wheat	2010-11	12/10/2010	06/26/2011
	Durum wheat	2012-13	11/21/2012	07/13/2013
SR – (vol.) – SF – (bc) – DW – (vetch+phac.)	Durum wheat	2010-11	12/10/2010	06/26/2011
	Durum wheat	2012-13	11/21/2012	07/13/2013
	Durum wheat	2013-14	12/16/2013	06/28/2014
SF – (bf) – FB – (bf) – DW – (bf)	Faba bean	2010-11	12/16/2010	06/28/2011
	Durum wheat	2010-11	12/16/2010	06/26/2011
	Durum wheat	2011-12	10/17/2011	04/24/2012
SF – (oat) – FB – (vetch+mu) – DW – (vetch+oat)	Faba bean	2010-11	12/16/2010	06/28/2011
	Durum wheat	2010-11	12/16/2010	06/26/2011
	Durum wheat	2011-12	10/17/2011	04/24/2012
	Durum wheat	2012-13	11/30/2012	06/12/2013

795

796 *bc, bf, DW, FB, mu, phac., SF, SR and vol. stand for berseem clover, bare fallow, durum wheat, faba bean,
 797 mustard, phacelie, sunflower, sorghum and sorghum volunteers, respectively.

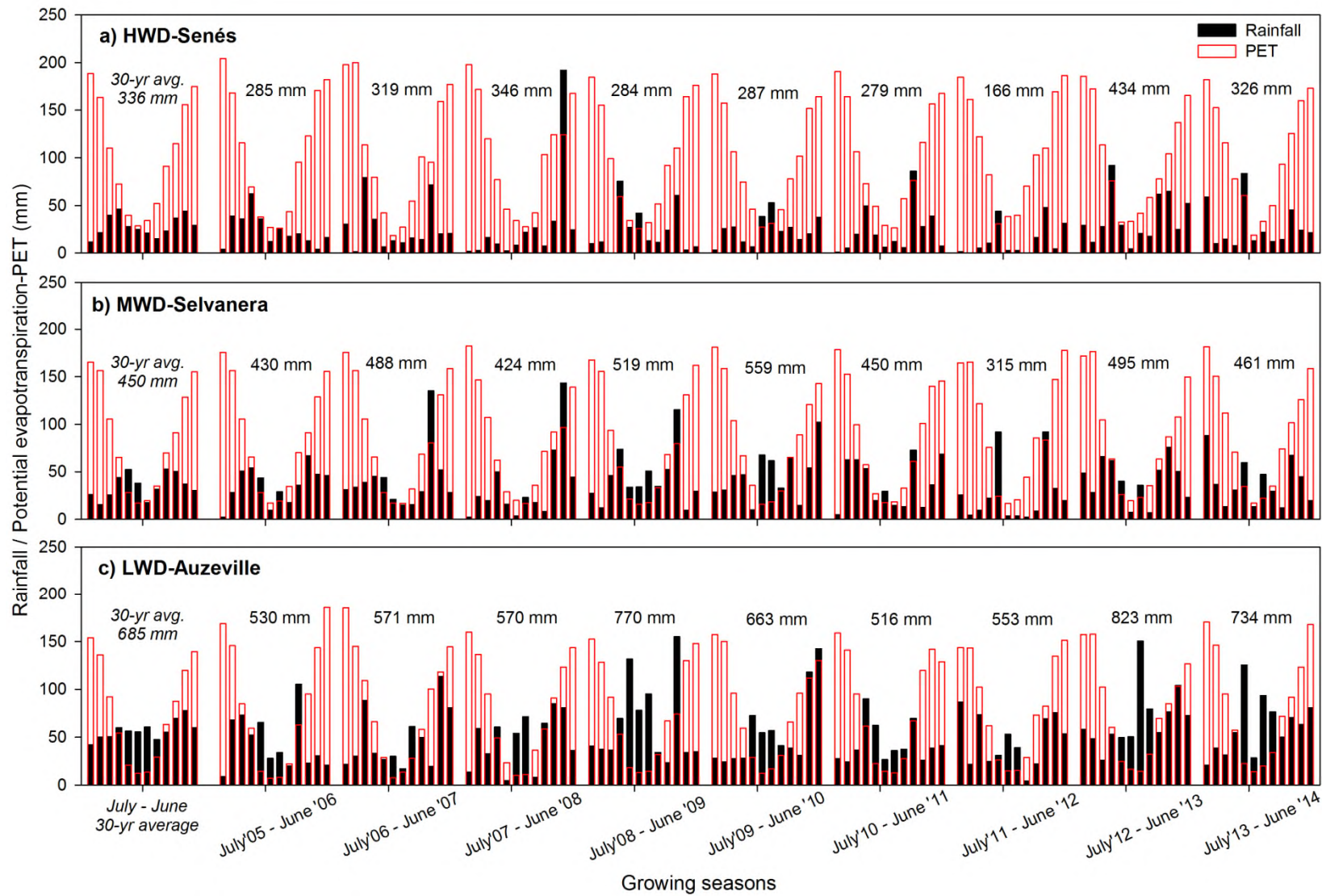
798 **Table 3.** Simulated crop management practices carried out in a Mediterranean transect (HWD, MWD and LWD, high, medium and low water deficit,
799 respectively) to analyze the impact of different management scenarios (in italics) (cereal vs. cereal+grain legume rotation, N fertilizer type: urea, AN, ammonium
800 nitrate and CN, calcium nitrate, crop residue management: removed vs. incorporated, and their interactions) on N₂O emissions.
801

Rotation phase	Management practice	Date	Tillage implement and input type	Nitrogen fertilizer applied (kg N ha ⁻¹)		
				HWD	MWD	LWD
<i>Winter cereal rotation (wheat-wheat-barley)</i>						
Wheat	Tillage Sowing N fertilization Harvest	15th Sept. and 20th Oct. 1st Nov. 4th and 27th April 1st July	Disk tandem – Rotary harrow 400 seeds m ⁻² . <i>Urea, AN and CN</i> <i>Crop residues incorporated vs. removed</i>	60+0	70+40	100+70
Wheat	Tillage Sowing N fertilization Harvest	15th Sept. and 20th Oct. 1st Nov. 4th and 27th April 1st July	Disk tandem – Rotary harrow 400 seeds m ⁻² . <i>Urea, AN and CN</i> <i>Crop residues incorporated vs. removed</i>	60+0	70+40	100+70
Barley	Tillage Sowing N fertilization Harvest	15th Sept. and 20th Oct. 15th Nov. 4th and 27th April 1st July	Disk tandem – Rotary harrow 400 seeds m ⁻² . <i>Urea, AN and CN</i> <i>Crop residues incorporated vs. removed</i>	50+0	60+30	100+50
<i>Winter cereal-legume rotation (winter pea-wheat-barley).</i>						
Winter pea	Tillage Sowing Harvest	15th Sept. and 20th Oct. 20th Nov. 1st July	Disk tandem – Rotary harrow 70 seeds m ⁻² Crop residues incorporated			
Wheat	Tillage Sowing N fertilization Harvest	15th Sept. and 20th Oct. 1st Nov. 4th and 27th April 1st July	Disk tandem – Rotary harrow 400 seeds m ⁻² . <i>Urea, AN and CN</i> <i>Crop residues incorporated vs. removed</i>	50+0	45+30	65+50
Barley	Tillage Sowing N fertilization Harvest	15th Sept. and 20th Oct. 15th Nov. 4th and 27th April 1st July	Disk tandem – Rotary harrow 400 seeds m ⁻² . <i>Urea, AN and CN</i> <i>Crop residues incorporated vs. removed</i>	50+0	60+30	100+50

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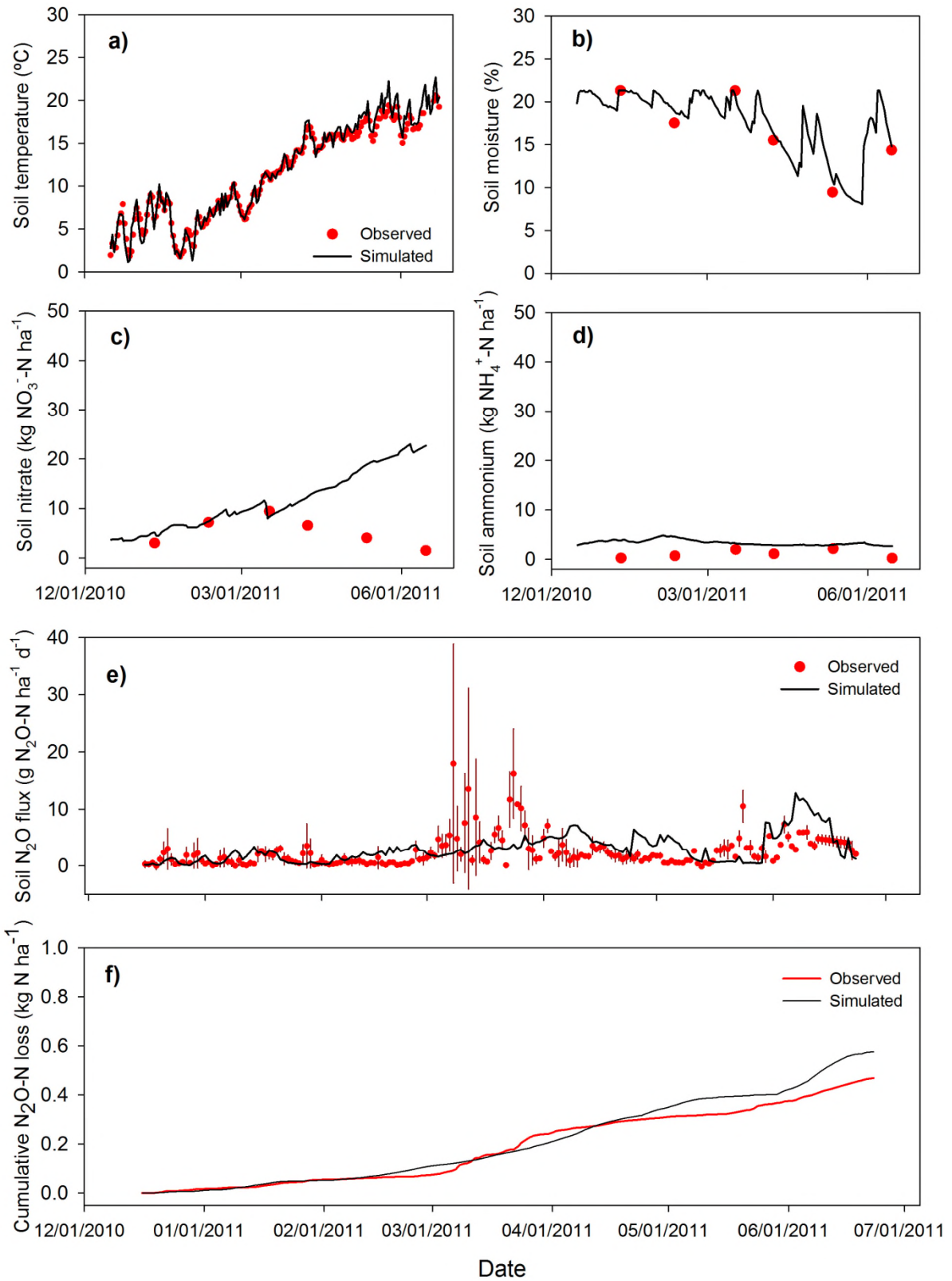
803 **Table 4.** Simulated annual N₂O emissions from nitrification and denitrification, total N₂O emissions and
804 N₂O ratio in two rotation types (cereal-based, Cer rot; cereal-legume, CerLeg) with different crop residue
805 management (Res. Rem., residues removed, Res. Incorp., residues incorporated) and N fertilizer types (AN,
806 ammonium-nitrate, CN calcium nitrate, Urea) in three sites. Values correspond to the average of 9 years
807 (2006-2014) and the three phases of each rotation. Different letters indicate significant differences between
808 treatments at $P < 0.05$. std. dev is shown between brackets.

Selected treatments	Nitrification N ₂ O-N (kg N ₂ O-N ha ⁻¹ yr ⁻¹)	Denitrification N ₂ O-N (kg N ₂ O-N ha ⁻¹ yr ⁻¹) (1)	Total N ₂ O-N (kg N ₂ O-N ha ⁻¹ yr ⁻¹) (2)	(1):(2)
HWD	0.08 (0.05) c	0.19 (0.14) c	0.26 (0.16) c	0.69 (0.15) b
MWD	0.27 (0.14) b	0.38 (0.31) b	0.65 (0.43) b	0.56 (0.11) c
LWD	0.58 (0.18) a	1.92 (0.80) a	2.51 (0.90) a	0.75 (0.09) a
Cer rot.	0.32 (0.25) a	0.82 (0.90)	1.13 (1.12)	0.67 (0.14)
CerLeg rot.	0.30 (0.24) b	0.84 (0.95)	1.15 (1.16)	0.67 (0.14)
AN	0.31 (0.23) b	0.82 (0.91)	1.13 (1.13) b	0.66 (0.11) b
CN	0.25 (0.22) c	0.85 (0.94)	1.10 (1.13) b	0.73 (0.14) a
Urea	0.37 (0.28) a	0.82 (0.92)	1.19 (1.17) a	0.62 (0.14) c
Res. Rem.	0.30 (0.24) b	0.76 (0.81) b	1.06 (1.02) b	0.67 (0.14)
Res. Incorp.	0.33 (0.61) a	0.90 (1.02) a	1.22 (1.25) a	0.67 (0.14)
HWD Cer rot.	0.09 (0.05) c	0.21 (0.14) c	0.29 (0.16) c	0.69 (0.15)
CerLeg rot.	0.07 (0.04) d	0.16 (0.14) d	0.23 (0.16) d	0.69 (0.15)
MWD Cer rot.	0.27 (0.12) b	0.34 (0.16) b	0.61 (0.25) b	0.56 (0.11)
CerLeg rot.	0.28 (0.16) b	0.42 (0.40) b	0.70 (0.55) b	0.57 (0.10)
HWD Cer rot.	0.60 (0.20) a	1.90 (0.80) a	2.50 (0.91) a	0.74 (0.09)
CerLeg rot.	0.57 (0.16) a	1.95 (0.80) a	2.52 (0.90) a	0.76 (0.08)
HWD Res. Rem.	0.08 (0.05) d	0.19 (0.15) d	0.27 (0.17) d	0.70 (0.15) b
Res. Incorp.	0.08 (0.05) d	0.18 (0.13) d	0.26 (0.16) d	0.68 (0.15) b
MWD Res. Rem.	0.26 (0.14) c	0.36 (0.28) c	0.62 (0.38) c	0.57 (0.10) c
Res. Incorp.	0.28 (0.15) c	0.40 (0.33) c	0.68 (0.45) c	0.56 (0.11) c
LWD Res. Rem.	0.55 (0.17) b	1.73 (0.68) b	2.28 (0.77) b	0.74 (0.09) a
Res. Incorp.	0.61 (0.19) a	2.12 (0.86) a	2.73 (0.97) a	0.76 (0.08) a
Cer rot. AN	0.32 (0.23) b	0.79 (0.88)	1.11 (1.09) b	0.65 (0.11) c
CN	0.20 (0.17) d	0.85 (0.94)	1.05 (1.09) b	0.78 (0.10) a
Urea	0.43 (0.29) a	0.80 (0.89)	1.23 (1.17) a	0.57 (0.12) d
CerLeg rot. AN	0.31 (0.24) bc	0.84 (0.95)	1.14 (1.16) b	0.66 (0.12) bc
CN	0.30 (0.25) c	0.84 (0.94)	1.15 (1.17) b	0.68 (0.15) b
Urea	0.31 (0.25) c	0.85 (0.95)	1.15 (1.17) b	0.67 (0.14) b
Res. Rem. AN	0.30 (0.22) cd	0.75 (0.80)	1.04 (1.0) bc	0.66 (0.11) c
CN	0.21 (0.18) e	0.78 (0.82)	0.99 (0.98) c	0.77 (0.11) a
Urea	0.38 (0.27) a	0.76 (0.82)	1.14 (1.07) ab	0.57 (0.13) d
Res. Incorp. AN	0.33 (0.25) bc	0.89 (1.01)	1.21 (1.24) a	0.65 (0.12) c
CN	0.30 (0.25) d	0.91 (1.04)	1.21 (1.25) a	0.69 (0.15) b
Urea	0.35 (0.29) b	0.89 (1.01)	1.24 (1.26) a	0.65 (0.15) c



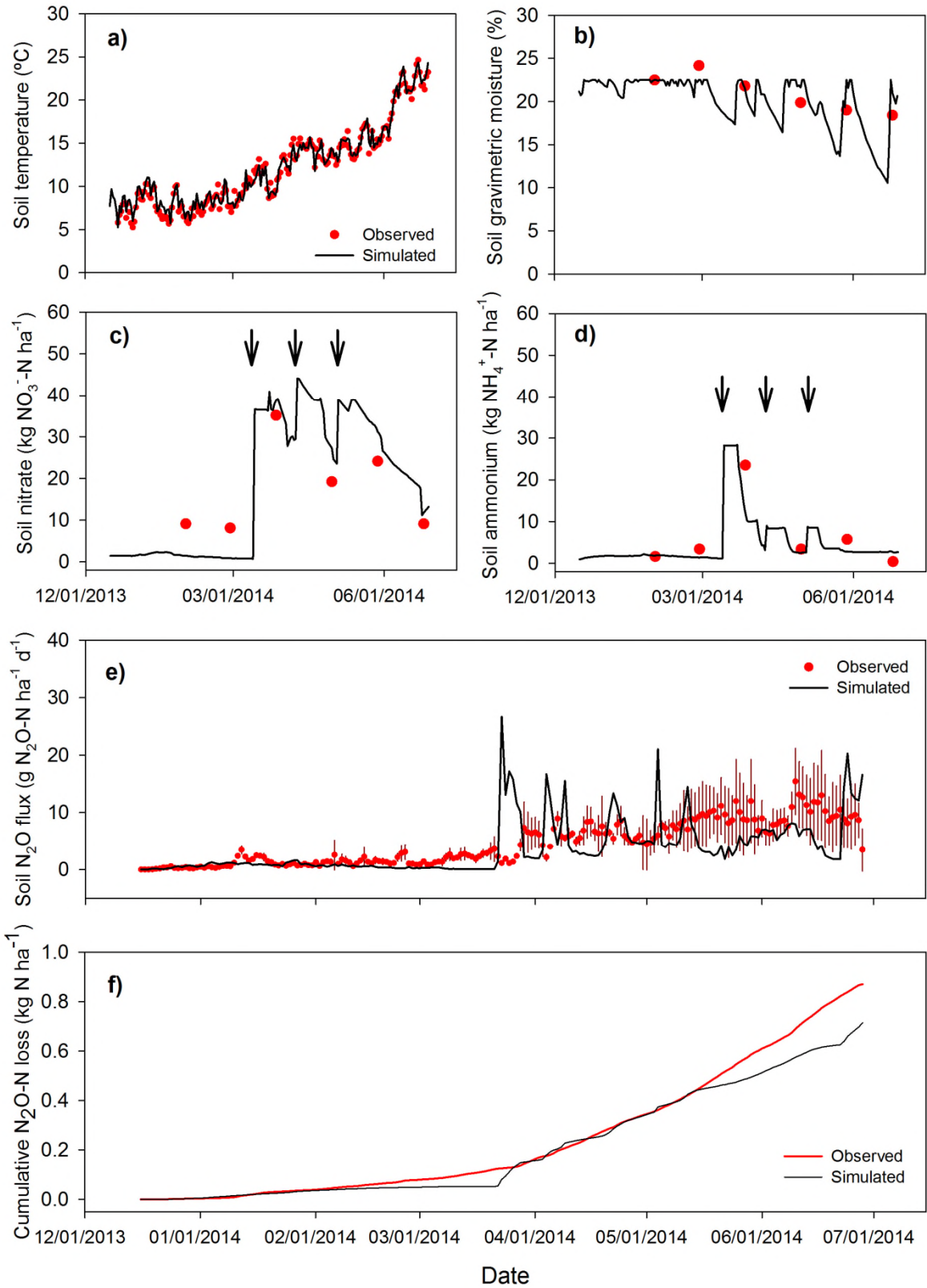
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811 **Fig. 1**

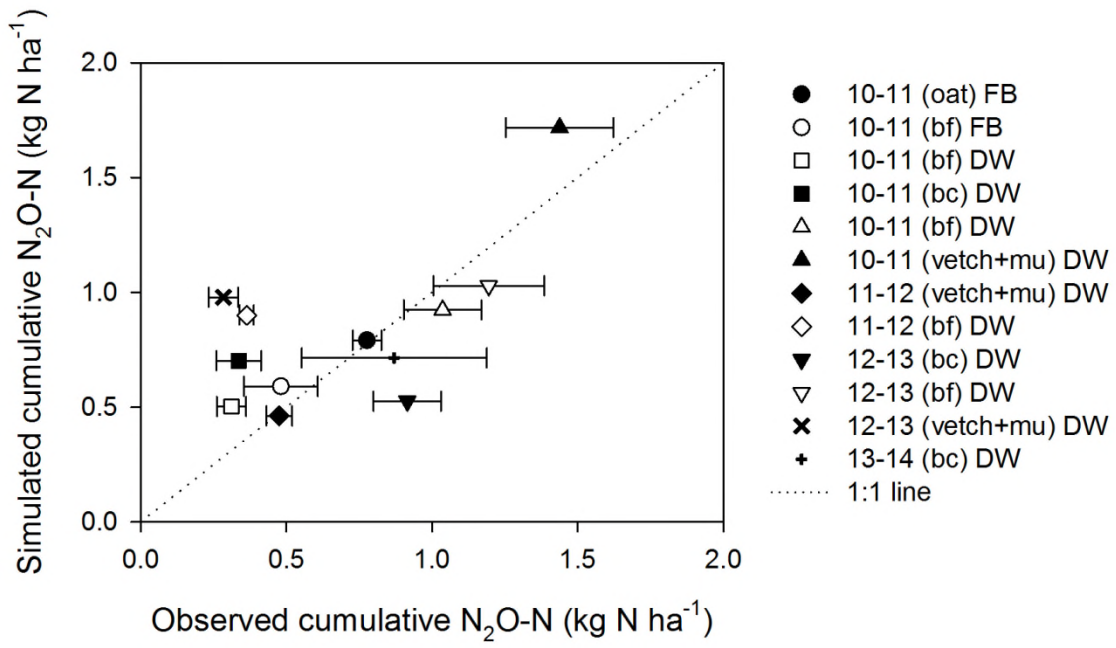


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813 **Fig. 2**



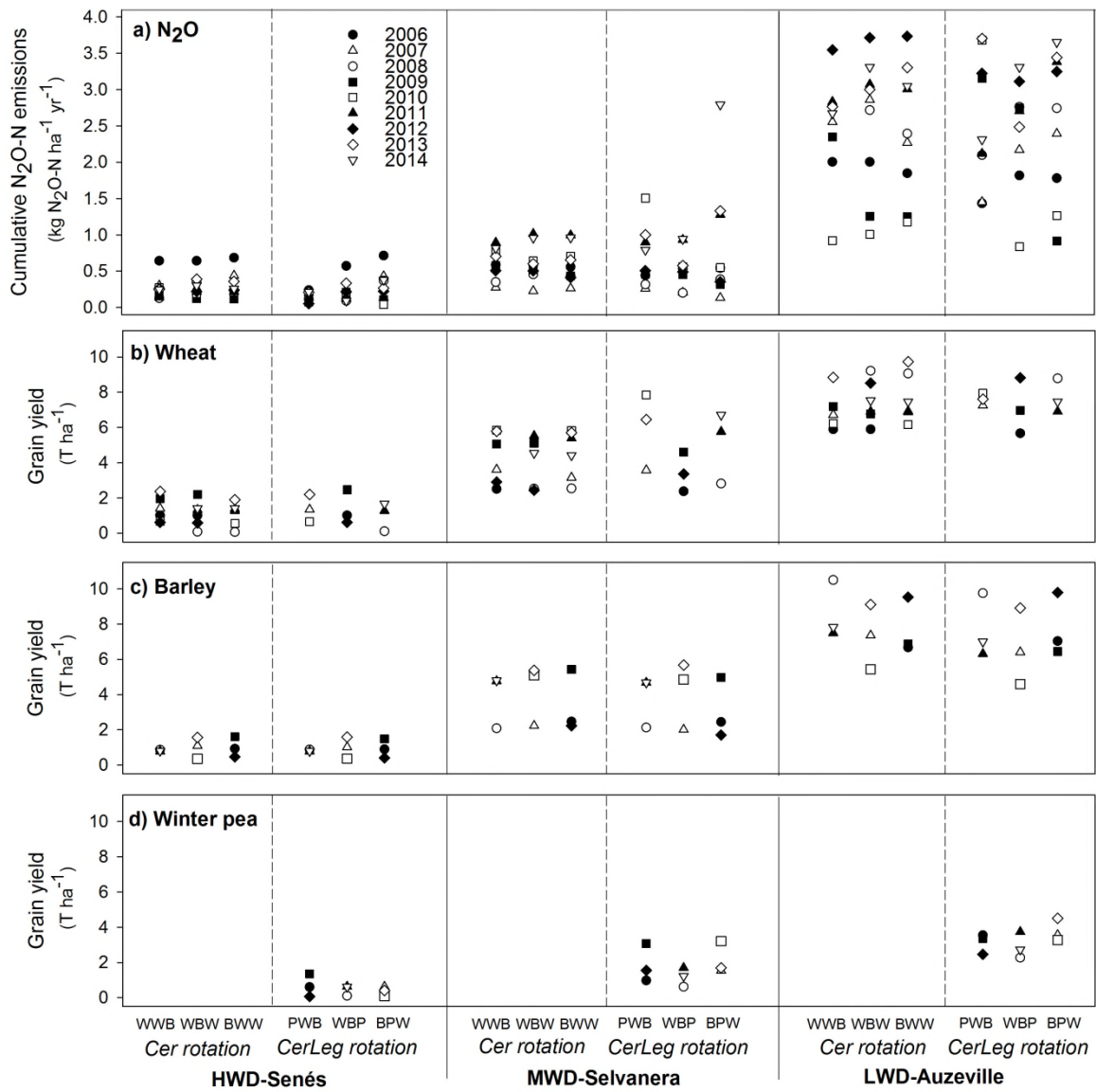
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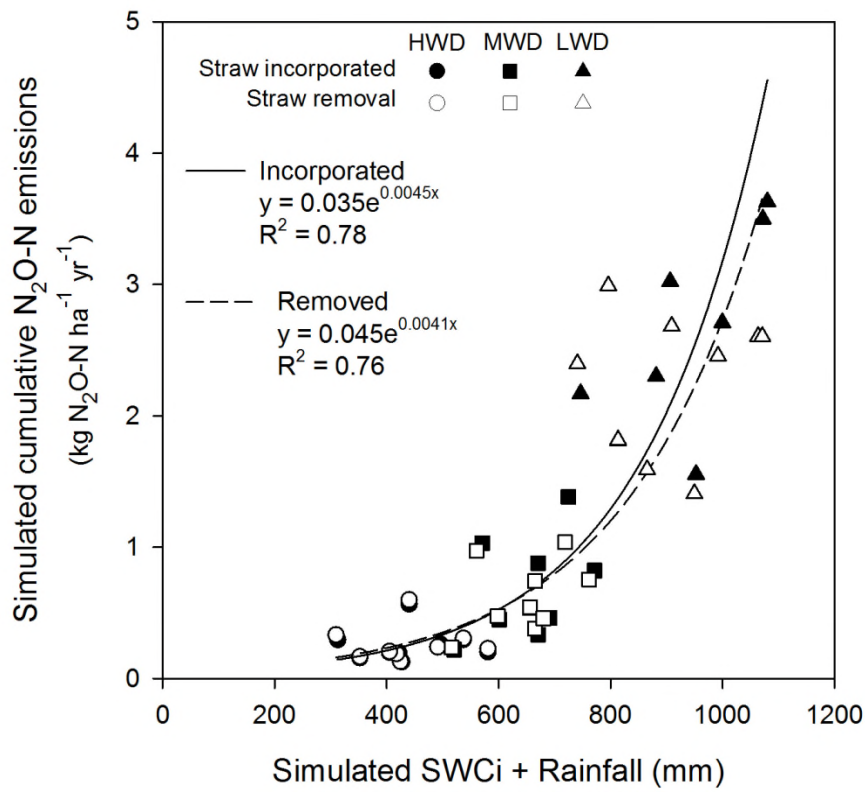
819 **Fig. 4**

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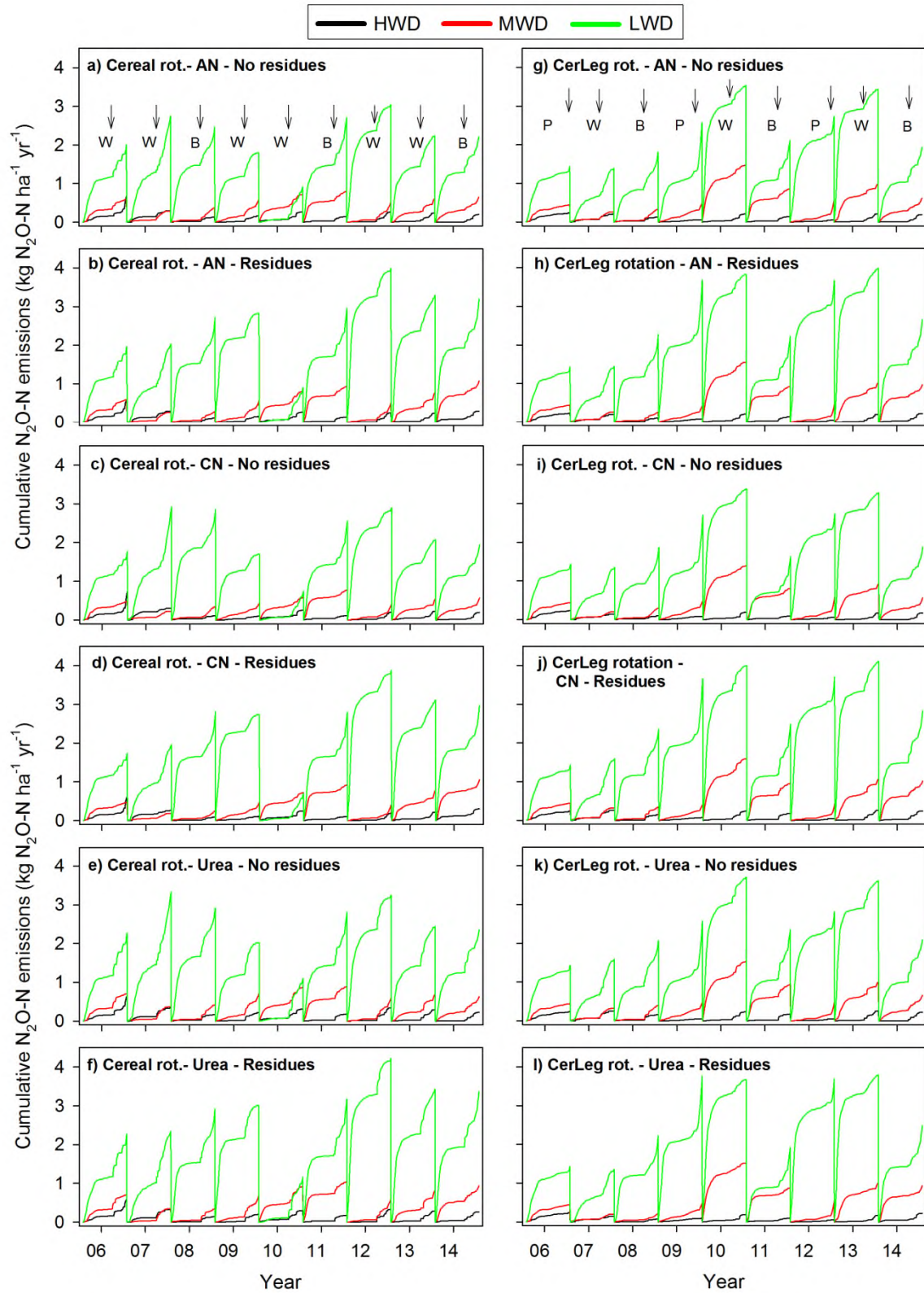
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822 **Fig. 5**



823

824 **Fig. 6**



825

826 **Fig. 7**

827 **Table S1.** Crop management practices carried out in the wheat phase of a wheat – sorghum – sunflower rotation with and without cover crops
828 (BF, bare fallow; CC, cover crops) (per order: vetch+phacelia, sorghum volunteers and berseem clover), where daily N₂O measurements were
829 carried out in LWD-Auzeville (SW, France).

Management practice	Cover crops use		Date	Type of implement or input	Amount of inputs	
	BF	CC			BF	CC
<i>Durum wheat crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)</i>						
Previous cash crop residues incorporation	X	X	09/15/2010	Disk tandem		
Tillage		X	09/16/2010	Rotary harrow		
Sowing		X	09/16/2010	Berseem clover cv. Miriam		18 kg ha ⁻¹
Tillage	X	X	10/29/2010	Rotary harrow		
Sowing	X	X	12/07/2010	Durum wheat cv. Isildur	477 seeds m ⁻²	477 seeds m ⁻²
N fertilization	X	X	04/04/2011	Ammonium nitrate	100 kg N ha ⁻¹	100 kg N ha ⁻¹
N fertilization	X	X	04/27/2011	Ammonium nitrate	60 kg N ha ⁻¹	60 kg N ha ⁻¹
Harvest	X	X	07/05/2011	Medium-sized combine		
<i>Durum wheat crop grown in the 2012-13 season preceded by bare fallow (BF) and cover crop (CC)</i>						
Sowing (undersown)		X	06/06/2012	Berseem clover cv. Miriam		15 kg ha ⁻¹
Previous cash crop residues incorporation	X		09/17/2012	Disk tandem		
Tillage	X	X	10/24/2012	Disk tandem		
Tillage	X	X	11/18/2012	Rotary harrow		
Sowing	X	X	11/19/2012	Durum wheat cv. Isildur	345 seeds m ⁻²	345 seeds m ⁻²
N fertilization	X	X	03/26/2013	Ammonium nitrate	107 kg N ha ⁻¹	107 kg N ha ⁻¹
N fertilization	X	X	04/29/2013	Ammonium nitrate	54 kg N ha ⁻¹	54 kg N ha ⁻¹
Harvest	X	X	07/18/2013	Medium-sized combine		
<i>Durum wheat crop grown in the 2013-14 season preceded by a cover crop (CC)</i>						
Sowing (undersown)		X	05/07/2013	Alfalfa+Clovers mixture		
Cover crop termination		X	12/04/2013	Mower		
Tillage		X	12/05/2013	Disk tandem		
Tillage		X	12/12/2013	Rotary harrow		
Sowing		X	12/12/2013	Durum wheat cv. Isildur		
N fertilization		X	03/14/2014	Ammonium nitrate		90 kg N ha ⁻¹
N fertilization		X	04/09/2014	Ammonium nitrate		30 kg N ha ⁻¹
N fertilization		X	05/04/2014	Ammonium nitrate		31 kg N ha ⁻¹
Harvest		X	07/15/2014	Medium-sized combine		

830 **Table S2.** Crop management practices carried out in the wheat and faba bean phases of a wheat – sunflower – faba bean rotation with and without
831 cover crops (BF, bare fallow, CC, cover crops) (per order: vetch+oat, oat and vetch+mustard), where daily N₂O measurements were carried out
832 in LWD-Auzeville (SW, France).
833

Management practice	Cover crops use		Date	Type of implement or input	Amount of inputs	
	BF	CC			BF	CC
<i>Faba bean crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)</i>						
Previous cash crop residues incorporation	X	X	09/15/2010	Disk tandem		
Tillage		X	09/16/2010	Rotary harrow		
Sowing		X	09/16/2010	Oat cv. Cadence		19 kg seeds ha ⁻¹
Tillage	X		10/29/2010	Rotary harrow		
Cover crop incorporation		X	12/06/2010	Moldboard plough		
Tillage		X	12/09/2010	Rotary harrow		
Sowing	X	X	12/13/2010	Faba bean cv. Iréna	26 seeds m ⁻²	26 seeds m ⁻²
Harvest	X	X	07/05/2011	Medium-sized combine		
<i>Durum wheat crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)</i>						
Previous cash crop residues incorporation	X	X	07/28/2010	Disk tandem		
Tillage		X	08/16/2010	Disk tandem		
Tillage		X	09/06/2010	Rotary harrow		
Sowing		X	09/06/2010	Mustard cv. Ascot		24 kg seeds ha ⁻¹
Irrigation		X	09/09/2010	Large-volume sprinkler		30 mm
Tillage	X		10/29/2010	Rotary harrow		
Cover crop incorporation		X	12/06/2010	Moldboard plough		
Sowing	X		12/07/2010	Durum wheat (mixture of 4 cv.)	404 seeds m ⁻²	
Tillage		X	12/09/2010	Rotary harrow		
Tillage		X	12/12/2010	Rotary harrow		
Sowing		X	12/13/2010	Durum wheat (mixture of 4 cv.)		404 seeds m ⁻²
N fertilization	X	X	04/04/2011	Ammonium nitrate	50 kg N ha ⁻¹	90 kg N ha ⁻¹
N fertilization	X	X	04/27/2011	Ammonium nitrate	50 kg N ha ⁻¹	50 kg N ha ⁻¹
Harvest	X	X	07/05/2011	Medium-sized combine		
<i>Durum wheat crop grown in the 2011-12 season preceded by bare fallow (BF) and cover crop (CC)</i>						
Previous cash crop residues incorporation	X	X	08/01/2011	Disk tandem		
Tillage		X	08/01/2011	Rotary harrow		
Sowing		X	08/01/2011	Vetch cv. Bingo + Mustard cv. Ascot		20+5 kg seeds ha ⁻¹
Tillage	X		09/01/2011	Disk tandem		

Tillage	X		09/30/2011	Disk tandem		
Cover crop termination		X	10/20/2011	Mower		
Tillage		X	10/21/2011	Disk tandem		
Tillage	X	X	11/14/2011	Rotary harrow		
Sowing	X	X	11/14/2011	Durum wheat (mixture of 4 cv.)	316 seeds m ⁻²	316 seeds m ⁻²
N fertilization	X	X	03/13/2012	Ammonium nitrate	52 kg N ha ⁻¹	82 kg N ha ⁻¹
N fertilization	X	X	04/23/2012	Ammonium nitrate	30 kg N ha ⁻¹	51 kg N ha ⁻¹
Harvest	X	X	07/03/2012	Medium-sized combine		

Durum wheat crop grown in the 2012-13 season preceded by a cover crop (cc)

Previous cash crop residues incorporation		X	08/01/2012	Disk tandem		
Tillage		X	08/17/2012	Disk tandem		
Tillage		X	08/23/2012	Rotary harrow		
Sowing		X	08/23/2012	Vetch cv. Bingo + Mustard cv. Ascot		25+5 kg seeds ha ⁻¹
Irrigation		X	09/05/2012	Large-volume sprinkler		23 mm
Cover crop termination		X	10/24/2012	Mower		
Tillage		X	10/24/2012	Disk tandem		
Tillage		X	11/19/2012	Rotary harrow		
Sowing		X	11/19/2012	Durum wheat (mixture of 4 cv.)		316 seeds m ⁻²
N fertilization		X	03/26/2013	Ammonium nitrate		64 kg N ha ⁻¹
N fertilization		X	04/29/2013	Ammonium nitrate		43 kg N ha ⁻¹
Harvest		X	07/18/2013	Medium-sized combine		

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836 **Table S3.** Analysis of variance (*P* values) of the simulated cumulative N₂O emissions from nitrification and denitrification, total N₂O emissions,
837 N₂O ratio (denitrification) and wheat yield in a cereal- (wheat-wheat-barley) and a cereal-legume (winter pea-wheat-barley) based rotation with
838 different crop residue management (removed vs. incorporated) and N fertilizer types (ammonium nitrate, calcium nitrate, and urea) in the three
839 sites over the 2006-2014 period. Note that for each year, the three phases of each rotation were taken into account in the statistical analysis related
840 to N₂O.

Effect	N ₂ O nitrification	N ₂ O denitrification (1)	Total N ₂ O (2)	N ₂ O ratio (1):(2)	Wheat yield
Site (S)	<0.001	<0.001	<0.001	<0.001	<0.001
Rotation (Rot)	<0.001	0.625	0.486	0.187	0.038
Fertilizer (F)	<0.001	0.471	<0.001	<0.001	0.546
Residues (Res)	<0.001	<0.001	<0.001	0.300	0.555
Year (Y)	<0.001	<0.001	<0.001	<0.001	
S*Rot	0.003	0.005	0.003	0.251	0.050
S*F	0.001	0.987	0.704	<0.001	0.993
S*Res	0.006	<0.001	<0.001	0.001	0.924
S*Y	<0.001	<0.001	<0.001	<0.001	
Rot*F	<0.001	0.490	0.003	<0.001	0.531
Rot*Res	0.328	0.649	0.555	0.637	0.757
Rot*Y	0.006	<0.001	<0.001	0.005	
Res*F	<0.001	0.984	0.028	<0.001	0.576
Y*F	0.977	0.999	0.999	0.677	
Y*Res	0.011	<0.001	<0.001	0.169	
S*Rot*Y	<0.001	<0.001	<0.001	<0.001	
S*Rot*Res	0.998	0.910	0.926	0.783	0.961
S*Y*Res	0.975	0.004	0.033	0.010	
S*Rot*F	0.001	0.991	0.801	<0.001	0.995
S*Y*F	1.0	1.0	1.0	0.264	
S*Res*F	0.541	0.978	0.854	0.002	0.997
Rot*Y*F	0.959	1.0	1.0	0.713	
Rot*Y*Res	0.998	0.957	0.974	0.974	
Rot*Res*F	<0.001	0.603	0.345	<0.001	0.857
Y*Res*F	1.0	1.0	1.0	0.980	
S*Rot*Y*F	1.0	1.0	1.0	0.289	
S*Rot*Y*Res	1.0	0.999	1.0	1.0	
S*Rot*Res*F	0.216	1.0	0.997	0.001	0.998
S*Y*Res*F	1.0	1.0	1.0	0.991	
Rot*Y*Res*F	0.997	1.0	1.0	0.847	
S*Rot*Y*Res*F	1.0	1.0	1.0	0.992	

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