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Switching from conventional tillage to no-tillage: Soil N availability, N uptake, 15N fertilizer recovery, and grain yield of durum wheat

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Switching from conventional tillage to no-tillage: Soil N availability, N uptake, 15N fertilizer recovery, and grain yield of durum wheat / Giambalvo, D., Amato, G., Badagliacca, G., Ingraffia, R., Di Miceli, G., Frenda, A.S., Plaia, A., Venezia, G., Ruisi, P.. - In: FIELD CROPS RESEARCH. - ISSN 0378-4290. - 218:218(2018), pp. 171-181. [10.1016/j.fcr.2018.01.018]

*Availability:*

This version is available at: <https://hdl.handle.net/20.500.12318/46860> since: 2020-11-16T16:28:05Z

*Published*

DOI: <http://doi.org/10.1016/j.fcr.2018.01.018>

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***Giambalvo D., Amato G., Badagliacca G., Ingraffia R., Di Miceli G., Frenda A.S., Plaia A., Venezia G., Ruisi P., 2018. Switching from conventional tillage to no-tillage: Soil N availability, N uptake, <sup>15</sup>N fertilizer recovery, and grain yield of durum wheat. Field Crops Research, Volume 218, Pages 171-181, ISSN: 0378-4290***

which has been published in final doi <https://doi.org/10.1016/j.fcr.2018.01.018>  
(<https://www.sciencedirect.com/science/article/abs/pii/S037842901731287X>)

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1 **Switching from conventional tillage to no-tillage: soil N availability, N uptake, <sup>15</sup>N fertilizer**  
2 **recovery, and grain yield of durum wheat**

3

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27 **Abstract**

28 This 2-year study, performed in a typical Mediterranean environment on three soil types (two  
29 Inceptisols and one Vertisol), aimed to improve understanding of the factors that play a major role  
30 in determining crop response when soil management shifts from conventional tillage (CT) to no-  
31 tillage (NT). The effects of NT on the soil nitrogen (N) availability, N uptake,  $^{15}\text{N}$  fertilizer  
32 recovery, and grain yield of durum wheat were evaluated in comparison to CT under five different  
33 N fertilization rates (0, 40, 80, 120, and 160 kg N ha<sup>-1</sup>).

34 Compared to CT, NT negatively affected grain yield in one of the two years but only in the two  
35 Inceptisols. On average, a considerable grain yield advantage of CT over NT (approximately +0.6  
36 Mg ha<sup>-1</sup> of grain) was observed with no N fertilization. This benefit decreased progressively when  
37 N fertilizer rate increased to the point that at 120 kg ha<sup>-1</sup> of N applied differences between CT and  
38 NT were negligible. The differences between the two tillage systems in both grain yield and N  
39 uptake were attributable more to differences in the native soil mineral N (that materialized already  
40 during the vegetative phase of the crop cycle) than to differences between CT plants and NT plants  
41 in efficiency in taking up N from fertilizer. The differences between CT and NT for many of the  
42 traits observed in durum wheat plants increased with decreasing soil fertility and in particular with  
43 decreasing soil total N. In conclusion, the shift from CT to NT, which should be accompanied in  
44 any case by an increase in the N fertilization rate to take into account the reduction in soil N  
45 available for the crop, was less problematic in the Vertisol, which is more fertile and better  
46 structured than the two Inceptisols.

47

48 **Keywords:** Conventional tillage; No-tillage; N fertilization; Soil N availability;  $^{15}\text{N}$ -fertilizer  
49 recovery

50

51 **Abbreviations:** NT, no-tillage; CT, conventional tillage; OM, organic matter; % $^{15}\text{N}_{\text{REC}}$ , percentage  
52 of  $^{15}\text{N}$  fertilizer recovery; CNRG, contribution of N remobilization to grain N yield; N0, no N

53 fertilization; N40, N80, N120, and N160 fertilization with 40, 80, 120, and 160 kg N ha<sup>-1</sup>; CDA,

54 canonical discriminant analysis

55

## 56 **1. Introduction**

57 No-tillage (NT) is widely recognized as a viable soil management technique in sustainable  
58 agriculture (Derpsch, 2008). Compared to conventional tillage (CT; usually based on moldboard  
59 plowing), NT helps to protect the soil from erosion (Scopel et al., 2005); enhances aggregation and  
60 aggregate stability (Madari et al., 2005); improves soil hydraulic characteristics (Kay and  
61 VandenBygaart, 2002); preserves soil macro- and microfauna (Uri et al., 1999); enhances soil  
62 microbial activity (Sharifi et al., 2008); reduces fuel consumption, and saves labor and time  
63 (Kirkegaard, 1995). Moreover, NT tends to preserve soil water better than CT, which results in  
64 huge advantages for the cropping systems in arid and semiarid areas; this is generally attributed to  
65 the change in the soil porosity (into more small pores and fewer large pores), to the creation of a  
66 more continuous pore system (from decaying roots and soil macrofauna activity), and above all to  
67 the minor soil water evaporation in NT as a consequence of both the presence of crop residues on  
68 the soil surface and the minor soil surface roughness generated by soil cultivation (Blevins and  
69 Frye, 1993; Lampurlanés and Cantero-Martínez, 2006). Such potential benefits suggest that NT is  
70 advantageous for cereal-based systems in Mediterranean environments, where water scarcity during  
71 the spring is often the main factor limiting the growth and productivity of rainfed crops  
72 (Lampurlanés et al., 2002) and where soils are particularly prone to erosion because of their  
73 characteristics and morphology (45% of the Mediterranean region has slopes greater than 8%), of  
74 cultivation even in steep slopes, and of the high frequency of intense rainfall events in fall and  
75 winter (García-Ruiz et al., 2013; Raclot et al., 2016). Several studies carried out under  
76 Mediterranean conditions have confirmed the benefits of NT over CT in terms of both a reduction  
77 in soil erosion (García-Orenes et al., 2009) and a crop yield advantage, particularly in dry  
78 areas/years (Amato et al., 2013; Ruisi et al., 2014). Despite these benefits, however, NT systems are  
79 used rarely in the Mediterranean, being practiced on approximately 2% of the total cropland (FAO  
80 AQUASTAT, 2013). There are several reasons for this, such as a lack of policies encouraging the  
81 adoption of NT and likely also the resistance on the part of farmers, as its positive effects are often

82 not immediately apparent but can only be seen after a new equilibrium in the soil has been  
83 established (Stubbs et al., 2004). Such benefits in fact are directly or indirectly attributable to the  
84 increase in soil carbon sequestration and storage that, under NT, occurs gradually over time (West  
85 and Marland, 2002; West and Post, 2002; González-Sánchez et al., 2012; Badagliacca et al., 2018)  
86 depending on several factors, including climatic conditions, soil characteristics, crop rotation, and  
87 other crop management practices. As a consequence, the shift from CT to NT can be thorny; the  
88 farmer often has to completely reorganize the production system to resolve the problems that will  
89 inevitably arise before a new equilibrium is reached. For example, application of NT can markedly  
90 affect the population of weeds (Sosnoskie et al., 2006; Giambalvo et al., 2012; Ruisi et al., 2015)  
91 and the incidence of pests and diseases (Paulitz et al., 2002), requiring adjustments to control  
92 strategies. At the same time, even from the first years of application, NT can result in considerable  
93 changes in organic matter (OM) mineralization rates, nitrogen (N) immobilization, N availability,  
94 and N-use efficiency of the crop (Gao et al., 2009; Stagnari et al., 2014). Obviously, these effects  
95 can vary greatly depending on the context in which NT is implemented (e.g., in terms of climatic  
96 conditions, soil type and fertility, crop rotation, crop management, and duration of application); this  
97 explains the inconsistent findings in the literature (Franzluebbers et al., 1995; McCarty et al., 1998;  
98 Peigné et al., 2007).

99 Although several studies have been conducted in the Mediterranean environment on the effects of  
100 the continuous application of NT over a high number of years on soil N dynamics and the crop  
101 response (e.g., Ruisi et al., 2016), relatively few studies have evaluated the effects of NT on soil N  
102 dynamics and the fate of the N fertilizer applied during the first year switch from CT to NT, which,  
103 as already said, can be thorny so much to induce in some cases the farmer to abandon NT. This  
104 knowledge is important to plan cropping management strategies sustainable from both the  
105 agronomic and environmental standpoints. Thus, the present study aimed to address the following  
106 questions: i) How, and to what extent, does switching from CT to NT alter the availability of soil N  
107 for crops and the fate of the N fertilizer applied? ii) How much do these changes vary by soil type

108 and climatic conditions? To this end, we studied the effects of NT on soil N dynamics and crop  
109 growth and yield in comparison with CT by applying these two techniques to three soil types  
110 differing in physical and chemical characteristics. The experiment was conducted in a semiarid  
111 Mediterranean environment and replicated over 2 years. Durum wheat (*Triticum durum* Desf.) was  
112 used as the model plant because of its importance as a crop plant in arid and semiarid areas of the  
113 Mediterranean basin.

114

## 115 **2. Materials and Methods**

### 116 *2.1. Site characteristics*

117 Field experiments were performed during two growing seasons (2011–2012 and 2012–2013;  
118 hereafter referred to as 2012 and 2013, respectively) at three sites (highly representative of arable  
119 soils of the Sicilian inland), all located within the Pietranera farm, which is located about 30 km  
120 north of Agrigento, Sicily, Italy (37°30'N, 13°31'E; 178 m a.s.l.). The farm covers approximately  
121 700 ha and includes a variety of soil types, morphologies, and orographies. The cropping systems of  
122 the farm are based on cereal crops (mainly durum wheat) in rotation with legumes (grain and fodder  
123 crops). Soil tillage management is based on moldboard plowing (followed by secondary tillage  
124 operations) for cereal crops or on minimum tillage for legume crops. Soil characteristics (referring  
125 to the 0- to 0.40-m layer) of the three experimental sites are reported in Table 1. The first soil,  
126 classified as Typic Calcixerept (Soil Survey Staff, 2006), is deep, with a clayey texture and a low to  
127 moderate OM content; it has a sub-angular structure and a sub-alkaline reaction. The second soil is  
128 a Vertic Haploxerept evolved on recent alluvial deposits. The soil is deep, with a sandy clay texture  
129 and a very low OM content; it has a granular structure, good drainage, and a sub-alkaline reaction.  
130 The third soil, classified as Chromic Haploxerert, is a fine-clayey, calcareous, mixed, xeric Vertisol  
131 that developed on Mio-Pliocenic clayey substrata. It is especially rich in montmorillonitic clays that  
132 promote swelling and shrinking in the soil; it can be considered the most productive soil because of  
133 its high natural fertility.

134 The climate is semiarid Mediterranean, with a mean annual rainfall of 581 mm, mostly in  
135 autumn/winter (74%) and in spring (18%), and a mean annual PET of about 1100 mm (calculated  
136 using the Penman–Monteith method). The dry period is from May to September. The mean air  
137 temperature is 15.9°C in autumn, 9.8°C in winter, and 16.5°C in spring. The average minimum and  
138 maximum annual temperatures are 10.0°C and 23.3°C, respectively.

139

140

141 **Table 1.** Physical and chemical characteristics of the top layer (0–40 cm) of the three soil types  
 142 where the experiment was conducted.

	Unit	Soil type (St)		
		St 1	St 2	St 3
		Typic Calcixerept (Inceptisol)	Vertic Haploxerept (Inceptisol)	Chromic Haploxerert (Vertisol)
Altitude	m a.s.l.	245	150	175
Particle size analysis:				
Clay	g kg <sup>-1</sup>	558	267	525
Silt	g kg <sup>-1</sup>	197	247	227
Sand	g kg <sup>-1</sup>	245	486	248
pH (1:2.5 H <sub>2</sub> O)	—	8.0	8.0	8.2
Total C (Walkley Black)	g kg <sup>-1</sup>	10.6	6.3	16.8
Total N (Kjeldahl)	g kg <sup>-1</sup>	0.61	0.86	1.78
Available P (Olsen)	mg kg <sup>-1</sup>	28.8	55.9	40.1
Cation exchange capacity	cmol+ kg <sup>-1</sup>	28.1	26.8	35.0
Water content at:				
field capacity	cm <sup>3</sup> cm <sup>-3</sup>	0.35	0.28	0.37
permanent wilting point	cm <sup>3</sup> cm <sup>-3</sup>	0.19	0.19	0.20

143

144

145

## 146 2.2. Experimental design and crop management

147 The experiments were set up as a split-plot design with four replications. The main plots (90 m<sup>2</sup>  
 148 each) were the soil tillage techniques: CT or NT. Each subplot received a different level of N  
 149 fertilizer: 0, 40, 80, 120 or 160 kg N ha<sup>-1</sup> (hereafter referred to as “N0”, “N40”, “N80”, “N120” and  
 150 “N160,” respectively). The size of each subplot was 18 m<sup>2</sup> (16 rows, each 6.0 m long, spaced at  
 151 0.1875 m). In both 2012 and 2013, the previous crop was berseem clover (*Trifolium alexandrinum*  
 152 L.) in all three sites; before berseem clover was sown, soils were always managed with one shallow  
 153 harrowing operation to prepare a proper seedbed. Berseem clover was managed by cutting plants to  
 154 an ~8 cm stubble height in the first decade of April and allowing plant regrowth to produce seeds.  
 155 Standing straws were always left in the soil, and loose residues (3–4 Mg DM ha<sup>-1</sup>, on average) were

156 spread uniformly throughout the plot. In 2013, the experiments were performed in the same three  
157 sites in surfaces adjacent to those used in 2012, to maintain “first year switch conditions”.

158 CT consisted of one moldboard plowing to a depth of 0.30 m in the summer, followed by two  
159 shallow harrowing operations before sowing to control weeds and prepare a suitable seedbed. NT  
160 consisted of sowing by direct drilling; before sowing, weeds were controlled with glyphosate (N-  
161 [phosphonomethyl] glycine) at rates of 720 to 1440 g a.i. ha<sup>-1</sup> depending on the development of the  
162 weeds; sowing was performed by direct drilling with a no-till seed drill. In CT treatments, residues  
163 of previous crops were incorporated into the soil, whereas in NT treatments they were left on the  
164 soil surface (to ensure that soil coverage was always more than 30%). Cultivation and tillage  
165 treatments were performed with commercial farm equipment. Phosphorus fertilizer was applied to  
166 the surface of each plot before planting as triple superphosphate at a rate of 69 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>.  
167 Nitrogen fertilization was done by hand-applying in each plot the appropriate amount of N fertilizer  
168 (as [NH<sub>4</sub>]<sub>2</sub>SO<sub>4</sub>) according to the experimental design. The total amount of N fertilizer was always  
169 split applied, with 50% applied at crop emergence and 50% applied at the end of tillering. Durum  
170 wheat (cv Vertola) was planted (for all treatments) at 350 viable seeds m<sup>-2</sup> always in the second  
171 decade of December. Vertola (released in 2003) is characterized by short plant height, very early  
172 heading and maturity, a high yield potential, and good pasta-making quality. Spontaneous weeds  
173 were controlled at an early growth stage with application of thifensulfuron-methyl (25 g a.i. ha<sup>-1</sup>)  
174 and tribenuron-methyl (12.5 g a.i. ha<sup>-1</sup>).

175 Each year and at each site, soon after crop emergence, two sampling areas of 2.25 m<sup>2</sup> each (8 rows  
176 1.5 m long) were identified within each subplot for subsequent measurements. In N80 treatments, a  
177 <sup>15</sup>N fertilizer (as [NH<sub>4</sub>]<sub>2</sub>SO<sub>4</sub>) with an isotopic enrichment of 1.33 atom% was added to the two  
178 sampling areas (50% at crop emergence and 50% at the end of tillering) following the application  
179 procedure described by Høgh-Jensen and Schjoerring (1994); the rest of the subplots outside of the  
180 <sup>15</sup>N-labeled areas received equivalent amounts of unlabeled fertilizer.

181 Soil samples (0- to 0.40-m layer) were collected from each subplot immediately before sowing and  
 182 soon after the harvesting of wheat and analyzed for 2M KCl-extractable  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  (10 g  
 183 of soil in 100 mL of extractant) using a Bran+Luebbe AutoAnalyzer 3 (Norderstedt, Germany).  
 184 In both years, heading (stage 59, Zadoks scale; Zadoks et al., 1974) was reached in the third decade  
 185 of April. Both at heading and at maturity (stage 92, Zadoks scale), a sample of total aboveground  
 186 plant material from a 0.50 m segment of the two central rows of each sampling area was taken,  
 187 oven-dried at 60°C for 48 h, weighed, ground to a fine powder (sieved using a 0.1-mm mesh) in a  
 188 fast-running mill, and analyzed for total N and, limited to N0 and N80, for  $^{15}\text{N}$  enrichment.  
 189 Concentrations of total N were assessed using the Dumas method (flash combustion with automatic  
 190 N analyzer; DuMaster D-480, Büchi Labortechnik AG, Flawil, Switzerland), and  $^{15}\text{N}$   
 191 concentrations were determined using a Roboprep-CN and 20-20 isotope ratio mass spectrometer  
 192 (Europa Scientific Ltd, Crewe, UK). In the rest of each sampling area, biomass production was  
 193 determined. All samples were oven-dried at 60°C for 48 h and weighed. For each subplot, at  
 194 harvest, grain yield was recorded after hand-cutting plants from a sampling area of 2.25 m<sup>2</sup> and  
 195 threshing with a laboratory thresher for cereals. Grain N content (g kg<sup>-1</sup>) was also recorded. The  
 196 weather data were collected from a weather station located within 500 m of the sites.

197

### 198 2.3. Calculations and statistical analyses

199 Data on  $^{15}\text{N}$  enrichment of biomass, taken both at heading and at maturity, were used to calculate  
 200 labeled-fertilizer N recovery ( $^{15}\text{N}_{\text{REC}}$ ) on an area basis (kg N ha<sup>-1</sup>) and percentage basis according to  
 201 Hauck and Bremner (1976):

202

$$203 \quad {}^{15}\text{N}_{\text{REC}} = N_t \times \frac{{}^{15}\text{N}_{fp} - {}^{15}\text{N}_{nfp}}{{}^{15}\text{N}_{fert} - {}^{15}\text{N}_{nfp}} \quad [1]$$

204 and

$$205 \quad \% \text{ } N_{\text{REC}} = \frac{{}^{15}\text{N}_{\text{REC}}}{f} \times 100 \quad [2]$$

206

207 where  $N_t$  is the plant N uptake ( $\text{kg N ha}^{-1}$ ),  $^{15}\text{N}_{\text{fp}}$  is the atom%  $^{15}\text{N}$  in the fertilized plants (N80  
208 treatments),  $^{15}\text{N}_{\text{nfp}}$  is the atom%  $^{15}\text{N}$  in the nonfertilized plants (N0 treatments),  $^{15}\text{N}_{\text{fert}}$  is the atom%  
209  $^{15}\text{N}$  in the fertilizer, and  $f$  is the fertilizer rate ( $\text{kg N ha}^{-1}$ ).

210 According to Huggins and Pan (1993), the soil N potentially available for the crop (i.e., N supply,  
211  $N_s$ ,  $\text{kg N ha}^{-1}$ ) was estimated as the amount of applied N ( $f$ ) plus  $N_t$  plus residual postharvest N in  
212 the soil ( $\text{kg N ha}^{-1}$ ), the latter two determined from control subplots (no applied N).

213 Moreover, the following parameters related to N accumulation and remobilization were calculated  
214 according to Cox et al. (1986) and Arduini et al. (2006):

- 215 - postheading N accumulation ( $\text{kg N ha}^{-1}$ ), as the difference between the amount of N uptake ( $\text{kg}$   
216  $\text{N ha}^{-1}$ ) in the aboveground biomass at heading and at maturity ;
- 217 - N remobilization ( $\text{kg N ha}^{-1}$ ), as the amount of N uptake ( $\text{kg N ha}^{-1}$ ) in the aboveground biomass  
218 at heading minus the difference between the amount of N uptake ( $\text{kg N ha}^{-1}$ ) in the aboveground  
219 biomass and the grain N yield ( $\text{kg N ha}^{-1}$ ) at maturity;
- 220 - N remobilization efficiency, as the ratio of the amount of N remobilization ( $\text{kg N ha}^{-1}$ ) to the  
221 amount of N uptake ( $\text{kg N ha}^{-1}$ ) in the aboveground biomass at heading;
- 222 - contribution of N remobilization to grain N yield (CNRG), as the percentage ratio of N  
223 remobilization ( $\text{kg N ha}^{-1}$ ) to grain N yield ( $\text{kg N ha}^{-1}$ ).

224 Data were analyzed using a linear model for split-plot design (Montgomery, 1997), with tillage  
225 system as the main plot and N fertilization rate as the subplot, replicated four times and in three  
226 different sites. Besides the site, two more factors could be considered—soil and year—but these and  
227 their interaction were confounded with site. To establish which of the two (soil or year) primarily  
228 influenced the variability in site and its interaction with tillage system and N fertilization rate, we  
229 used two different models to analyze the data with respect to each output variable: i) a model with  
230 site, tillage system, and N fertilization rate and their interactions; and ii) a model with soil, year,  
231 tillage system, and N fertilization rate and their interactions. In comparing the analysis of variance

232 tables of the two models, we partitioned the effect of site and of its interaction with tillage system  
233 and N fertilization rate between a part corresponding to year and a part corresponding to soil.  
234 Means differences were compared using the Tukey test ( $P < 0.05$  and  $0.01$ ). The entire analysis was  
235 carried out using R (2011).

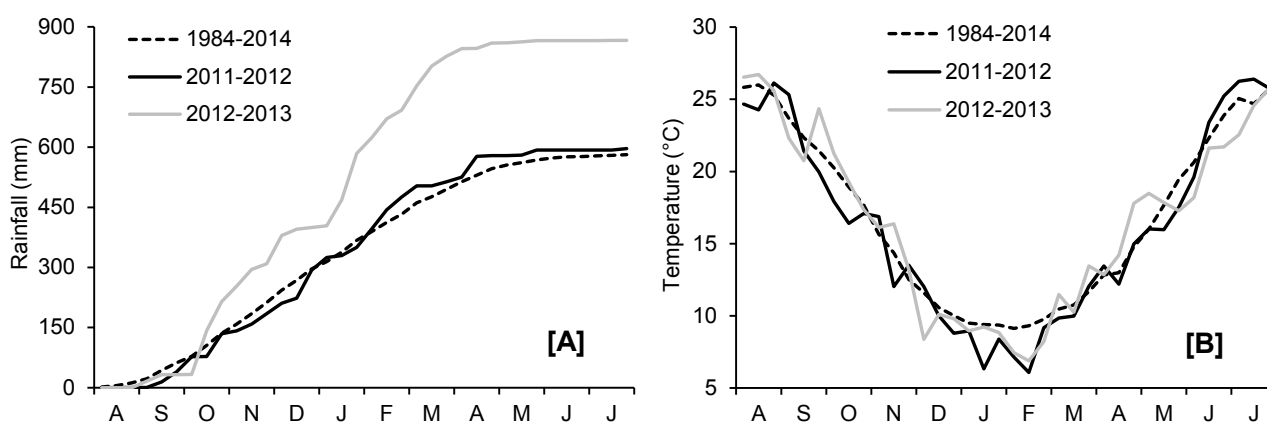
236 Finally, canonical discriminant analysis (CDA) was performed (SAS Institute, 2008) to determine i)  
237 whether multivariate statistically significant differences existed between tillage systems across year,  
238 N fertilization rate, and site based on some selected plant traits; and ii) which of these traits  
239 accounted the most for these differences. Canonical variable means (centroid values) were  
240 calculated for each combination (tillage system/year, tillage system/N fertilization rate, and tillage  
241 system/site), and the significance between means was determined using the Mahalanobis distance.

242

243 **3. Results**

244 The total rainfall during the first growing season was 596 mm (Fig. 1), which was very close to the  
245 long-term average. Rainfall was well distributed over the growing season and allowed for  
246 satisfactory plant growth and yield for the trial environment. The mean temperature for the year was  
247 slightly lower than the normal mean temperature, especially during the winter season. During the  
248 second growing season, the total rainfall was 866 mm, about 50% greater than the long-term  
249 average. Rainfall mainly occurred in October (180 mm) and between January and March (430 mm),  
250 with a peak in January (185 mm), causing severe water logging during the vegetative phase of the  
251 crop cycle. The mean temperature was similar to the normal mean temperature.

252



253

254 **Fig. 1.** Accumulated rainfall [A] and 10-day mean air temperature [B] at the experimental site  
255 during the two growing seasons (2011–2012 and 2012–2013). 30-year average 10-day temperatures  
256 and accumulated rainfall are also included.

257

258 Table 2 shows the results of the statistical analysis of the effects of the applied treatments (and their  
259 interactions) on wheat yield and N parameters. The great variability in the climatic conditions  
260 between the two experimental years markedly influenced crop growth and productivity, with the  
261 grain yield approximately twice as great in 2012 as in 2013 (on average 4.61 and 2.34 Mg ha<sup>-1</sup>,  
262 respectively). The effects of tillage system on most of the observed traits varied greatly by site. The  
263 greatest contribution to the significance of this interaction was almost always attributable to year; in

264 contrast, the contribution of soil type was generally low. For some traits, the effects of tillage  
265 system also varied by N fertilization.

266 In 2012, compared to CT, NT negatively affected grain yield in the two Inceptisols (–32% and –  
267 17%, respectively, in St1 and St2) but not in the Vertisol (St3; Fig. 2), whereas in 2013 no  
268 differences were observed between CT and NT in grain yield.

269

270 **Table 2.** Analysis of variance: *P*-values for the effects of the applied treatments on the traits measured on durum wheat plants. Percentage values in  
 271 brackets represent the proportion of the variance explained by the factor.

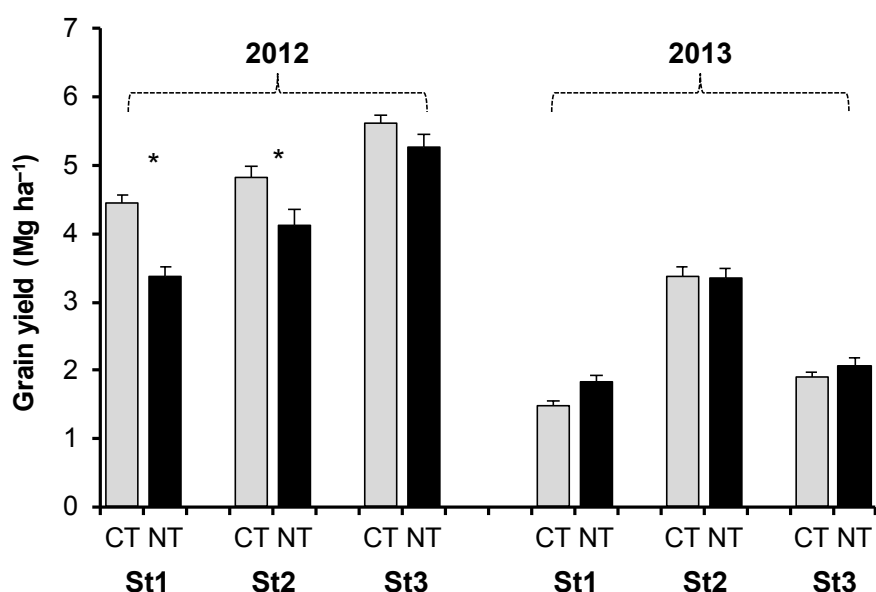
	D.f.	Grain yield	N uptake at heading	N uptake at maturity	N uptake heading to maturity	Grain N content	Grain N yield	<sup>15</sup> N <sub>REC</sub> at heading <sup>¶</sup>	<sup>15</sup> N <sub>REC</sub> at maturity <sup>¶</sup>	N remob.‡	N remob. efficiency	N supply <sup>¶</sup>	CNRG <sup>§</sup>
		Mg ha <sup>-1</sup>	kg N ha <sup>-1</sup>	kg N ha <sup>-1</sup>	kg N ha <sup>-1</sup>	g kg <sup>-1</sup>	kg N ha <sup>-1</sup>	%	%	kg N ha <sup>-1</sup>	—	kg N ha <sup>-1</sup>	%
Site	5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
Year (Y)	1	*** (73%)	*** (96%)	*** (84%)	*** (31%)	*** (78%)	*** (77%)	*** (90%)	*** (89%)	*** (89%)	ns (4%)	*** (75%)	** (39%)
Soil type (St)	2	*** (14%)	** (2%)	*** (6%)	*** (24%)	** (11%)	*** (10%)	*** (9%)	*** (9%)	*** (11%)	*** (81%)	*** (13%)	* (33%)
Y × St	2	*** (13%)	* (2%)	*** (10%)	*** (45%)	ns (11%)	*** (13%)	ns (1%)	† (2%)	ns (0%)	† (15%)	*** (12%)	* (28%)
Tillage (T)	1	<0.001	0.004	0.012	ns	ns	<0.001	ns	ns	0.018	ns	<0.001	ns
T × Site	5	<0.001	0.003	0.009	ns	ns	<0.001	0.049	0.056	0.049	ns	0.013	0.068
T × Y	1	*** (77%)	*** (93%)	*** (77%)	ns (13%)	ns (65%)	*** (75%)	** (75%)	** (88%)	** (74%)	ns (2%)	** (71%)	ns (0%)
T × St	2	ns (7%)	ns (4%)	ns (6%)	† (78%)	ns (16%)	ns (9%)	ns (0%)	ns (2%)	ns (11%)	† (57%)	ns (17%)	* (90%)
T × Y × St	2	* (16%)	ns (3%)	* (17%)	ns (9%)	ns (19%)	* (16%)	ns (25%)	ns (10%)	ns (10%)	ns (41%)	ns (12%)	ns (10%)
Fertilization (F)	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	—	—	<0.001	0.002	—	ns
F × T	4	0.002	0.001	0.013	ns	0.043	ns	—	—	ns	0.037	—	ns
F × Site	20	0.098	<0.001	<0.001	ns	0.003	<0.001	—	—	<0.001	<0.001	—	<0.001
F × Y	4	* (33%)	*** (91%)	*** (86%)	ns (31%)	*** (55%)	*** (60%)	—	—	*** (47%)	ns (9%)	—	* (18%)
F × St	8	* (53%)	ns (5%)	ns (4%)	ns (33%)	ns (26%)	* (29%)	—	—	** (40%)	*** (71%)	—	*** (59%)
F × Y × St	8	ns (14%)	ns (4%)	ns (10%)	ns (36%)	ns (19%)	ns (11%)	—	—	ns (13%)	† (20%)	—	ns (23%)
Site × T × F	20	ns	ns	ns	ns	ns	ns	—	—	ns	ns	—	ns
Y × T × F	4	ns (24%)	ns (44%)	ns (25%)	ns (14%)	ns (20%)	ns (12%)	—	—	ns (36%)	ns (15%)	—	ns (8%)
St × T × F	8	ns (24%)	ns (26%)	ns (20%)	ns (38%)	ns (19%)	ns (25%)	—	—	ns (8%)	ns (39%)	—	ns (38%)
Y × St × T × F	8	ns (52%)	ns (30%)	ns (55%)	ns (47%)	† (60%)	ns (63%)	—	—	ns (55%)	ns (46%)	—	ns (54%)

272 †, \*, \*\*, and \*\*\* indicate that the factor is significant at  $P \leq 0.1$ , 0.05, 0.01, and 0.001, respectively; ns, not significant at  $P \leq 0.1$ . ¶ For the <sup>15</sup>N  
 273 fertilizer recovery (both at heading and maturity) and for the N supply the analysis of variance was performed only on the data obtained from N80

274 and N<sub>0</sub>, respectively. ‡N remob. is N remobilization. § CNRG is the contribution of N remobilization to grain N yield (as percentage ratio of N  
275 remobilization to grain N yield).

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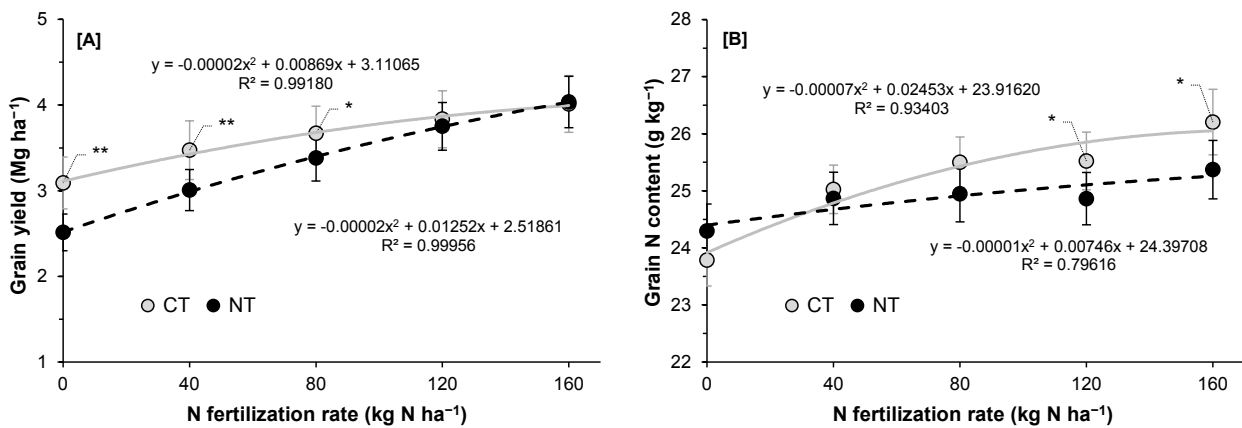
279 **Fig. 2.** Grain yield of wheat as affected by tillage system and soil type, separately for year. CT,  
280 conventional tillage; NT, no-tillage. St1= Typic Calcixerept; St2= Vertic Haploxerept; St3=  
281 Chromic Haploxerept (see Table 1). Each value is a mean of 4 data (4 replicates). Vertical bars  
282 indicate standard errors of each mean value. Asterisks in the top of the histograms indicate that  
283 tillage system effect was significant at  $P \leq 0.05$ .  
284

285 On average, a strong grain yield advantage of CT over NT (approximately 0.6 Mg ha<sup>-1</sup> of grain)  
286 was observed with no N fertilization (Fig. 3A). This benefit decreased progressively with increases  
287 in the N fertilizer rate, to the point that at 120 kg ha<sup>-1</sup> of N differences between CT and NT were  
288 negligible. On average, grain N content increased with the N fertilization rate (from 24.0 g kg<sup>-1</sup> in  
289 N0 to 25.8 g kg<sup>-1</sup> in N160); the effects on N fertilization were higher in CT compared to NT, and  
290 the differences between the two tillage systems were significant at the higher N fertilizer rates  
291 (N120 and N160; Fig. 3B). On the whole, grain N yield varied in the same way as the grain yield,  
292 but, unlike the latter, CT and NT showed a similar response to the increase in the N fertilizer rate  
293 (Tillage System  $\times$  N Fertilization Rate not significant).

294 N supply was on average markedly higher in 2012 than in 2013 (141 vs. 65 kg N ha<sup>-1</sup>, respectively).  
295 Nitrogen supply was significantly higher under CT than NT only in 2012 (Fig. 4). In this year, the

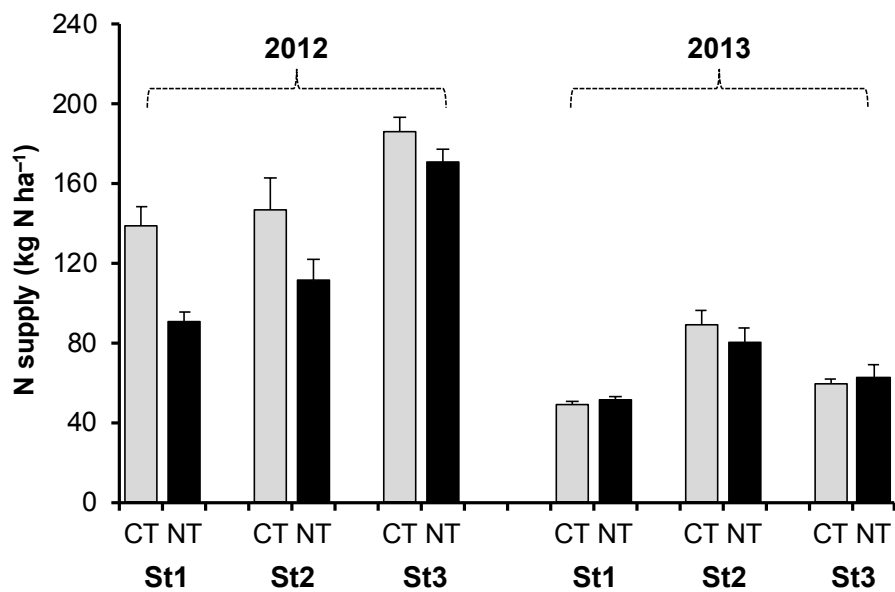
296 superiority of CT over NT was clear in the two Inceptisols (+52% and +32% in St1 and St2,  
 297 respectively) and moderate in the Vertisol (i.e., St3; +9%).. The grain yield of wheat increased  
 298 proportionally with increasing N supply, with no significant differences observed in this  
 299 relationship by tillage system (Fig. 5A). Moreover, the variation in N supply due to the tillage  
 300 system adopted explained about 90% of the variation observed in the grain yield between NT and  
 301 CT systems in N0 (Fig. 5B).

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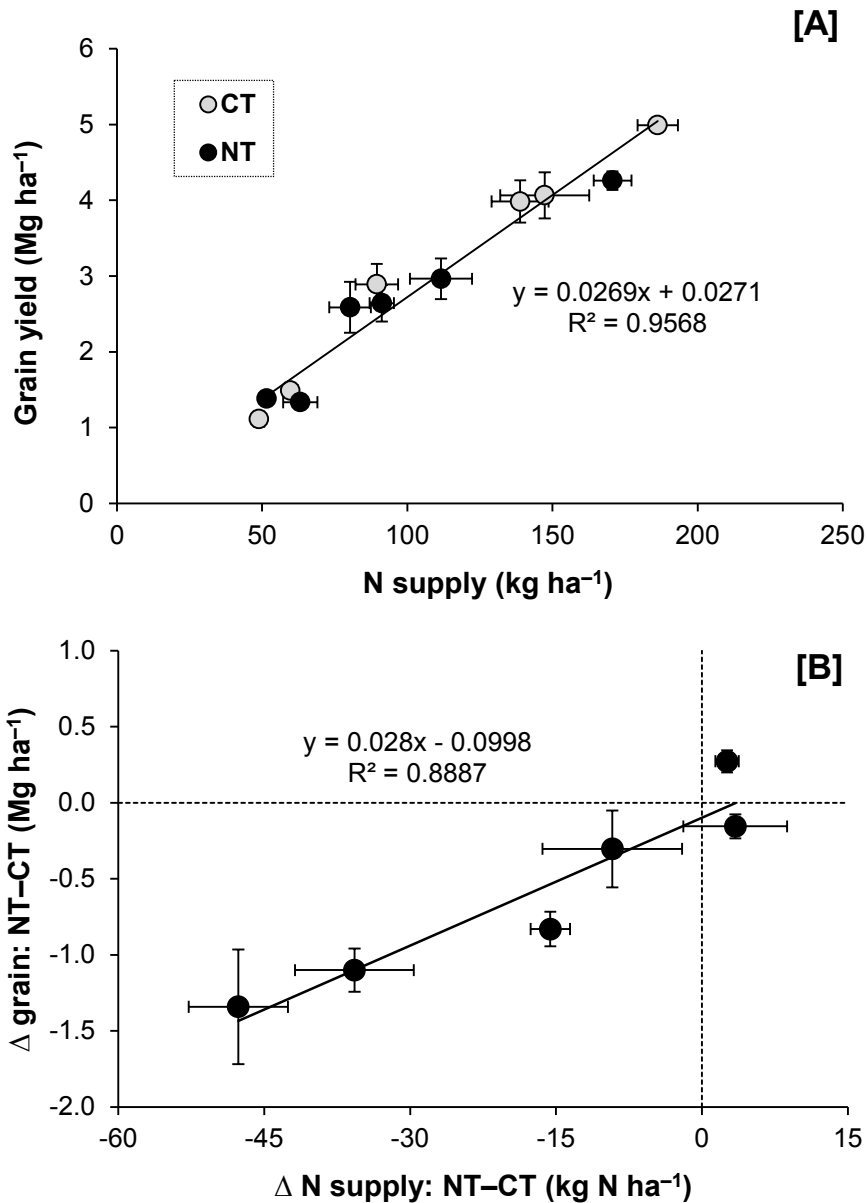
**Fig. 3.** Grain yield [A] and grain N content [B] in wheat grown under conventional tillage (CT) and no-tillage (NT) at five N fertilization levels (0, 40, 80, 120, and 160 kg N ha<sup>-1</sup>). Each value is a mean of 24 data (2 years × 3 soil types × 4 replicates). Vertical bars indicate standard errors of each mean value. Asterisks indicate that tillage system effect was significant at  $P \leq 0.05$  (\*) or  $P \leq 0.01$  (\*\*).



313

314 **Fig. 4.** N supply measured in non-N fertilized plots (N0) as affected by tillage system and soil type,  
 315 separately for year. CT, conventional tillage; NT, no-tillage. St1= Typic Calcixerept; St2= Vertic  
 316 Haploxerept; St3= Chromic Haploxerept (see Table 1). Each value is a mean of 4 data (4 replicates).  
 317 Vertical bars indicate standard errors of each mean value.

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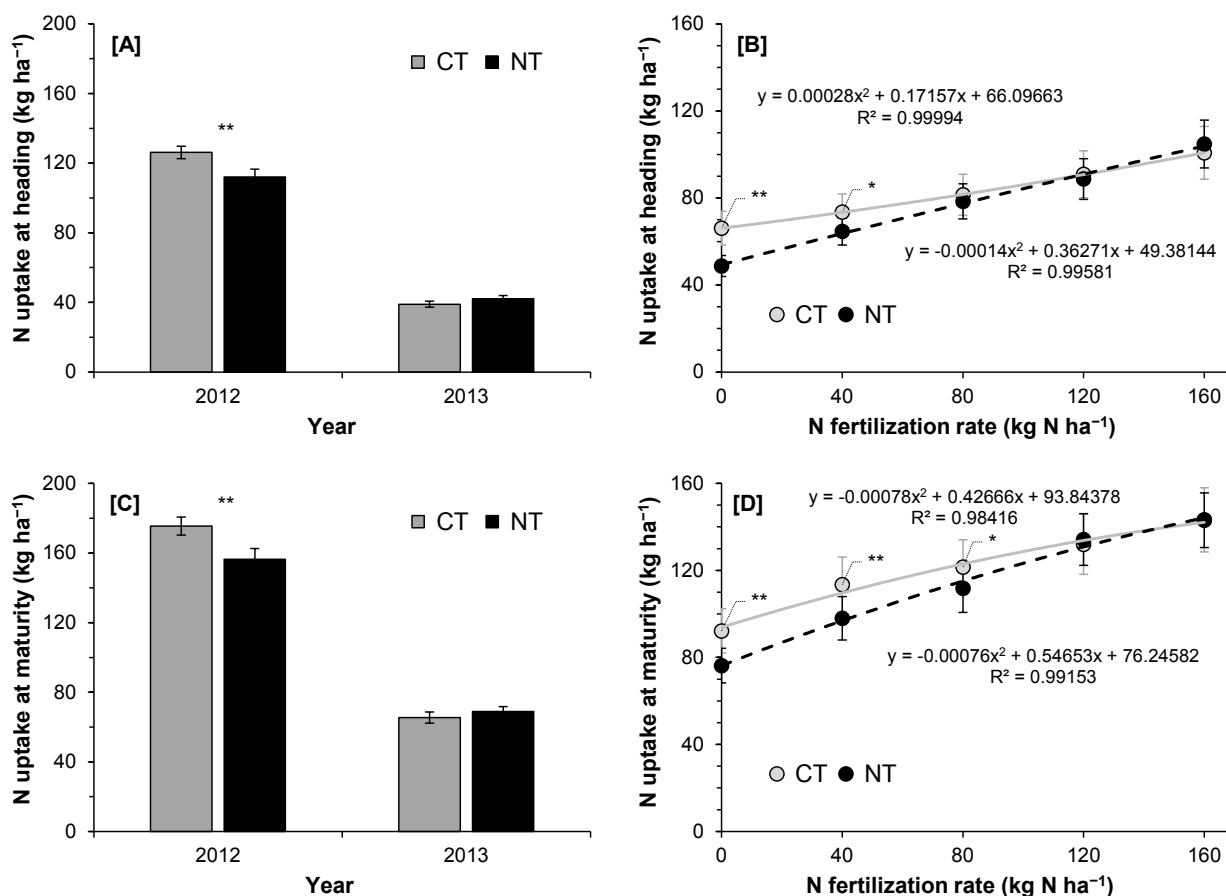
320 **Fig. 5.** [A]: Relationship between the N supply and the grain yield of wheat; each value is a mean of  
 321 24 data (2 years  $\times$  3 soil types  $\times$  4 replicates); since no significant differences between NT and CT  
 322 were found in the regression equations obtained, a unique regression line (and relative equation)  
 323 was reported. [B]: Relationship between the differences in the N supply between no-tillage (NT)  
 324 and conventional tillage (CT) and the differences in the grain yield of wheat between NT and CT in  
 325 the various trial conditions (n = 24; 2 years  $\times$  3 soil types  $\times$  4 replicates). Both the relationships  
 326 displayed refer to the non-N fertilized condition (N0). In both figures, horizontal and vertical bars  
 327 indicate the standard errors of each mean value.

328

329 Tillage system influenced N uptake (both at heading and at maturity) differently in the 2 years (Fig.  
 330 6A and 6C). In 2012, application of NT instead of CT led to a decrease in N uptake (on average

331 -11% both at heading and at maturity), whereas in 2013, no differences between NT and CT were  
 332 observed for N uptake (both at heading and at maturity). On average, the advantage for CT over NT  
 333 for N uptake, large and significant under N0 conditions, decreased progressively as the rate of N  
 334 fertilizer increased so that starting from N80 and from N120 no significant differences were  
 335 observed between the two tillage systems, respectively at heading and at maturity (Fig. 6B and 6D).  
 336 For N uptake at maturity the effects of tillage varied by soil type, but only in 2012 (Fig. 7).  
 337 Differences due to tillage system were not observed in the amount of N taken up by wheat from  
 338 heading to maturity (Table 2).

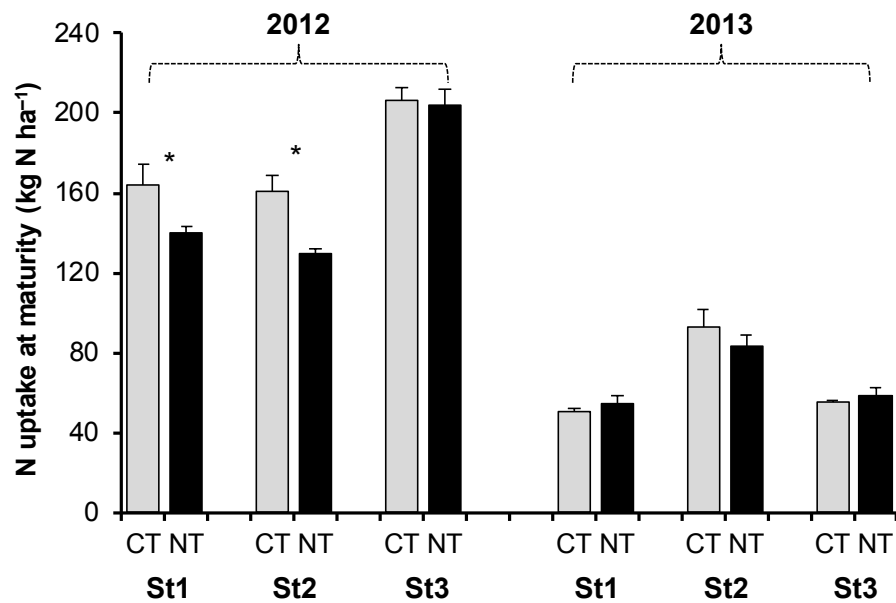
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341 **Fig. 6.** Nitrogen uptake at heading [A] and maturity [B] of durum wheat as affected by tillage  
 342 system (CT, conventional tillage; NT, no-tillage, NT), year (2012 and 2013), and N fertilization rate  
 343 (0, 40, 80, 120, and 160 kg N ha<sup>-1</sup>). Each value is a mean of 60 data (5 N fertilizer rates × 3 soil  
 344 types × 4 replicates) in [A] and [C], and of 24 data (2 years × 3 soil types × 4 replicates) in [B] and  
 345 [D]. Vertical bars indicate standard errors of each mean value. Asterisks indicate that tillage system  
 346 effect was significant at P ≤ 0.05 (\*) or P ≤ 0.01 (\*\*).

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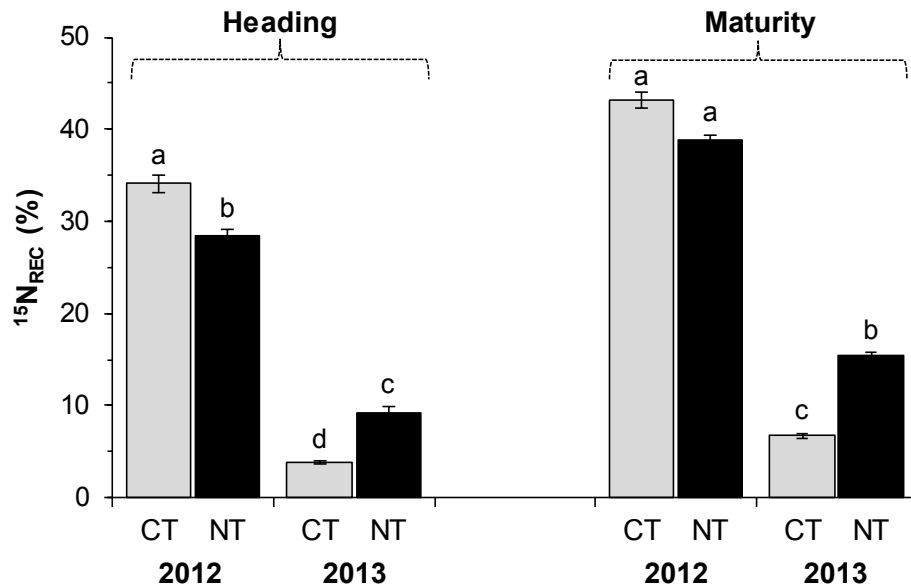
350 **Fig. 7.** N uptake of wheat at maturity as affected by tillage system and soil type, separately for year.  
 351 CT, conventional tillage; NT, no-tillage. St1= Typic Calcixerept; St2= Vertic Haploxerept; St3=  
 352 Chromic Haploxerept (see Table 1). Each value is a mean of 4 data (4 replicates). Vertical bars  
 353 indicate standard errors of each mean value. Asterisks in the top of the histograms indicate that  
 354 tillage system effect was significant at  $P \leq 0.05$ .

355

356 On average, the recovery of  $^{15}\text{N}$  fertilizer ( $\%^{15}\text{N}_{\text{REC}}$ ) was markedly higher in 2012 than in 2013  
 357 (Fig. 8); at heading  $\%^{15}\text{N}_{\text{REC}}$  was 31.2% and 6.5% in 2012 and 2013, respectively, whereas at  
 358 maturity it was 41.0% and 11.1%, respectively. The  $\%^{15}\text{N}_{\text{REC}}$  at heading was significantly lower in  
 359 NT than in CT in 2012. The opposite was observed in 2013, when  $\%^{15}\text{N}_{\text{REC}}$  was significantly higher  
 360 in NT than CT both at heading and at maturity. Moreover, the advantage for CT over NT for  
 361  $\%^{15}\text{N}_{\text{REC}}$  was canceled out in 2012 from heading to maturity, whereas in 2013 the advantage for NT  
 362 over CT increased from heading to maturity.

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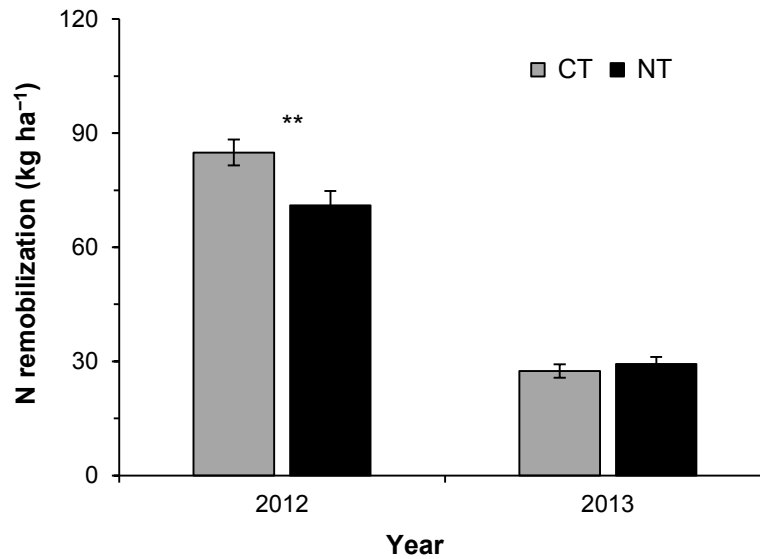


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366 **Fig. 8.** Percentage of the recovery of the  $^{15}\text{N}$ -fertilizer ( $\%^{15}\text{N}_{\text{REC}}$ ) at heading and maturity by durum  
 367 wheat as affected by tillage system in the two experimental years. CT, conventional tillage; NT, no-  
 368 tillage. Each value is a mean of 12 data (3 soil types  $\times$  4 replicates). Vertical bars indicate standard  
 369 errors of each mean value. Within each phenological stage, different letters denote significant  
 370 differences ( $P \leq 0.05$ ).

371

372 The amount of N remobilized during the grain filling was markedly higher in 2012 than in 2013 (on  
 373 average 78.0 vs. 28.4 kg N ha $^{-1}$ , respectively). Application of NT instead of CT resulted in an  
 374 important decrease in N remobilization only in 2012 (Fig. 9). The effects of tillage system on both  
 375 N remobilization efficiency and CNRG varied by soil type, being slightly higher in CT than NT  
 376 only in the Vertisol (St3) (data not shown).



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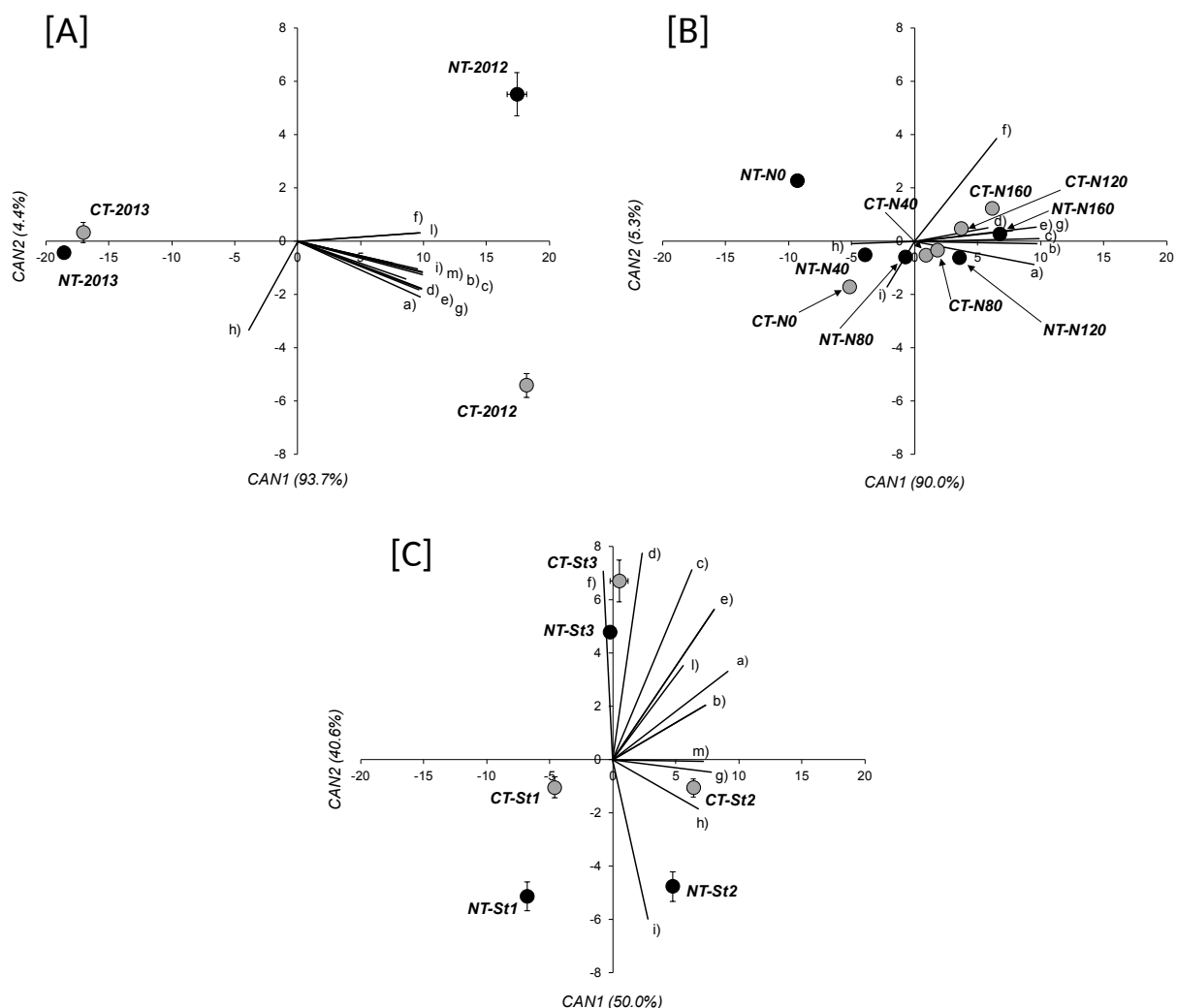
378 **Fig. 9.** Nitrogen remobilization in wheat grown under conventional tillage and no-tillage in the two  
 379 experimental years. CT, conventional tillage; NT, no-tillage. Each value is a mean of 60 data (5 N  
 380 fertilizer rates  $\times$  3 soil types  $\times$  4 replicates). Vertical bars indicate standard errors of each mean  
 381 value. Asterisks in the top of the histograms indicate that tillage system effect was significant at  $P \leq$   
 382 0.01.

383

384 The CDA performed for tillage system and year and based on data for eleven selected traits clearly  
 385 discriminated the treatments (Fig. 10A). First canonical variable (CAN1) mostly varied according to  
 386 grain yield, N uptake (both at heading and at maturity), and the  $\%^{15}\text{N}_{\text{REC}}$  (both at heading and at  
 387 maturity), whereas CAN2 was mostly influenced (negatively) by N remobilization efficiency and  
 388 grain yield. CAN1 discriminated clearly 2012 by 2013, whereas CAN2 discriminated NT by CT  
 389 only for 2012. Specifically, NT-2012 and CT-2012 plotted in the upper right and bottom right  
 390 quadrants, respectively (highly significant differences based on Mahalanobis squared distances),  
 391 whereas NT-2013 and CT-2013 plotted near each other with no significant differences. In the CDA  
 392 based on tillage system and N fertilization (Fig. 10B), distances between NT and CT systems  
 393 decreased as the N fertilizer rate increased, so that differences based on Mahalanobis squared  
 394 distances were significant only at N0 and N40. Both CAN1 (which was influenced by grain and  
 395 grain N yields, N uptake both at heading and at maturity) and CAN2 (which varied mainly  
 396 according to the grain N content and the CNRG) contributed to discriminating the treatments.

397 Finally, the CDA based on tillage system and soil type also discriminated the treatments (Fig. 10C).  
 398 CAN1 was positively influenced by grain and grain N yields and N remobilization, whereas the  
 399 traits with the greatest influence on CAN2 were the N uptake (both at heading and at maturity) and  
 400 the grain N content. As can be seen from the figure, distances between CT and NT systems varied  
 401 according to soil type (St1 > St2 > St3).

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406 **Fig. 10.** Canonical discriminant analysis (CDA). Canonical variable means (centroid values) were  
 407 calculated for each combination: [A]= tillage system/year; [B]= tillage system/N fertilization rate;  
 408 and [C]= tillage system/soil type. CAN1, first canonical variable; CAN2, second canonical variable.  
 409 CT, conventional tillage; NT, no-tillage. N0, N40, N80, N120, and N160 represent the following  
 410 fertilization rates: 0, 40, 80, 120, and 160 kg N ha<sup>-1</sup>, respectively. St1, Typic Calcixerept; St2,

411 Vertic Haploxerept; St3, Chromic Haploxerert (see Table 1). CDAs were performed on the basis of  
412 only 11 selected traits measured on plants: a) grain yield; b) N uptake at heading; c) N uptake at  
413 maturity; d) N uptake from heading to maturity; e) grain N yield; f) grain N content; g) N  
414 remobilization; h) N remobilization efficiency; i) ratio between N remobilization and grain N  
415 yield(CNRG); l) recovery of <sup>15</sup>N-fertilizer at heading; m) recovery of <sup>15</sup>N-fertilizer at maturity.  
416 Within each diagram, the direction and length of each line indicate the canonical loadings of the  
417 measured traits on the first two canonical variables.  
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#### 420 **4. Discussion**

421 The results of the present study suggest that switching from CT to NT influences crop response  
422 through effects on soil N dynamics and in particular on the soil N potentially available for the crop.  
423 Soil cultivation, which increases soil aeration and mixes and incorporates crop residues into the soil,  
424 generally increases the decomposition of OM by altering the soil structure and temperature, by  
425 modifying the degree of physical protection of OM from microorganisms (or their enzymes), and by  
426 stimulating microbial activity and modifying the rate of microbial biomass turnover (Silgram and  
427 Shepherd, 1999; Watson et al., 2002; Mikha and Rice, 2004). This leads to a faster release of N  
428 from both the native soil OM and the crop residues under CT compared to NT systems and thus to  
429 an increase in the N supply. The decrease in N supply in NT compared to CT can also be the result  
430 of an increased N immobilization rate under NT (Rice and Smith, 1984; Drinkwater et al., 2000). In  
431 fact, many studies have shown that surface-managed crop residues (such as those generally found in  
432 NT systems) have a greater potential for N immobilization than incorporated residues (Holland and  
433 Coleman, 1987; Van Den Bossche et al., 2009).

434 In the present study, N supply was markedly lower in NT than CT in 2012 (on average about 125  
435 and 160 kg N ha<sup>-1</sup> in NT and CT, respectively), whereas no differences were observed by tillage  
436 system in 2013 (about 65 kg N ha<sup>-1</sup> for both CT and NT). The differences in N supply between CT  
437 and NT affected durum wheat grain yield and N uptake, which both varied significantly in 2012  
438 (with higher values in CT than NT) but not in 2013 (CT = NT). Moreover, we found a strong  
439 positive relationship between the differences in N supply and the differences in grain yield between  
440 CT and NT, showing that a high proportion (about 90%) of the variation observed for grain yield  
441 between NT and CT was explained by the variation in N supply between these two tillage systems.  
442 The hypothesis that the lower N supply under NT was the determining factor in reducing grain yield  
443 and N uptake is corroborated by the fact that the differences between CT and NT for these two traits  
444 progressively decreased as the N fertilizer rate increased. This was confirmed by the results from  
445 the CDA that showed how the distances between NT and CT, which were significant in N0 and

446 N40, decreased as the N fertilizer rate increased, so much so that starting from N80 the distances  
447 between the two tillage systems were canceled out. Our data are in line with the findings of Lundy  
448 et al. (2015), who performed a meta-analysis to evaluate the influence of crop and environmental  
449 variables on NT productivity and found that N fertilization reduces yield declines following the  
450 adoption of NT.

451 The detrimental effects of the adoption of NT on durum wheat varied according to soil type as  
452 highlighted by the CDA and, in particular, these detrimental effects seemed to increase with  
453 decreasing soil fertility and in particular when soil total N decreased (St1 > St2 > St3). The  
454 differences between CT and NT for grain yield and N uptake were indeed much lower in the  
455 Vertisol (the N-richest soil with a total N content > 1.5 g kg<sup>-1</sup> of soil) than in the two Inceptisols  
456 (both with a total N content < 1 g kg<sup>-1</sup> of soil). Compared to NT, CT promotes an increase in soil  
457 OM decomposition (and hence the release of N) through increase in soil aeration (Six et al., 2000),  
458 in addition to the mechanisms listed above. Thus, in the Vertisol, which was characterized by a  
459 good structure due to the high contents of montmorillonitic clays and soil OM, the omission of soil  
460 cultivation likely did not reduced the soil OM decomposition rate, as was the case for the two  
461 Inceptisols, in which, in the absence of tillage, oxygen could have become a limiting factor for the  
462 soil OM decomposition process. The differences in N supply observed between CT and NT in the  
463 three soils used in the present study, which were significant and consistent in the two Inceptisols but  
464 very low in the Vertisol, support this hypothesis. Clearly, improvements in soil biological activity,  
465 porosity, OM content, and structure induced by the continuous application of NT over a number of  
466 years should progressively counteract the negative effects highlighted during the shift from CT to  
467 NT, as suggested by Rice et al. (1986) and Salinas-García et al. (1997). However, the results of an  
468 experiment carried out in the same environment as present study, in which NT was applied  
469 continuously for several years, while showing a progressive increase in NT with respect to CT for  
470 many of the above mentioned parameters (soil biological activity, OM content, etc.; Badagliacca et

471 al., 2018), they also showed higher values of N supply under CT compared to NT, thus failing to  
472 support the hypothesis of occurrence of a transient effect. (Ruisi et al., 2016).

473 Some authors have attributed the differences in grain yield and N uptake between CT and NT to the  
474 differing efficiency of CT plants and NT plants in taking up N and other nutrients from the soil (Fox  
475 and Bandel, 1986; López-Bellido and López-Bellido, 2001). However, our research does not  
476 confirm this hypothesis. In fact, no differences were observed between the two tillage systems in  
477 either the amount of residual N in the soil at harvest (data not shown) or the  $^{15}\text{N}$  fertilizer recovery  
478 fraction ( $\%^{15}\text{N}_{\text{REC}}$ ). Hence, the differences between CT and NT in N uptake have to be attributed to  
479 differences in the N supply between the two tillage systems, similar to what was observed in the  
480 above mentioned long-term tillage experiment (Ruisi et al., 2016).

481 In 2013, no differences were found between CT and NT in any of the observed traits, in contrast  
482 with the findings of 2012. This lack of differences can be explained by the excessive rainfall in the  
483 100 days after sowing (more than 400 mm of rain), which most likely caused abundant leaching of  
484 both native soil N and N from fertilizer applied at crop emergence. Several studies have shown that  
485 in Mediterranean environments N losses through leaching can be considerable, particularly in years  
486 characterized by rainy autumns or winters. As reported by Demurtas et al. (2016) in a study carried  
487 out under Mediterranean conditions, about 70% of total annual  $\text{NO}_3^-$  leaching occurs between  
488 October and February, the period in which about 60% of the annual percolation occurs in  
489 Mediterranean areas as a consequence of the imbalance between rainfall and evapotranspiration  
490 (Arregui and Quemada, 2006; Carneiro et al., 2012). This most likely occurred in our experiment in  
491 2013, and this hypothesis is furthermore supported by the values found for the  $^{15}\text{N}$  fertilizer  
492 recovery fraction ( $\%^{15}\text{N}_{\text{REC}}$  = about 10% on average), which were much lower than both those  
493 observed in 2012 ( $\%^{15}\text{N}_{\text{REC}}$  = about 40% on average) and those usually reported in the literature for  
494 wheat grown in the same environment ( $\%^{15}\text{N}_{\text{REC}}$  = 25%–30%; Giambalvo et al., 2010; Ruisi et al.,  
495 2014, 2015). Previous studies have shown inconsistent findings for the influence of tillage system  
496 on N losses via leaching. In particular, the effect of tillage system seems to be highly dependent on

497 soil N availability and pedo-climatic and agronomic factors (Hansen and Djurhuus, 1997;  
498 Constantin et al., 2010). Some research has highlighted the fact that adoption of NT increases  $\text{NO}_3^-$ -  
499 N drainage losses through leaching, encouraging the formation of continuous soil macro-pores,  
500 which may increase  $\text{NO}_3^-$ -N preferential flow (Paul and Clark, 1989; Patni et al., 1998). In contrast,  
501 other studies have reported less  $\text{NO}_3^-$ -N leaching under NT due to the reduced amount of N  
502 available for leaching because of the lower N mineralization rate compared to CT (Levanon et al.,  
503 1993; Mkhabela et al., 2008). Melero et al. (2011) came to similar conclusions in an experiment  
504 carried out in a Mediterranean Vertisol. We think that in the present study, N leaching was likely  
505 much more intense under CT than under NT during 2013, thus nullifying the advantage of soil  
506 cultivation in terms of increased N supply with respect to NT, so much so that no differences were  
507 observed in crop response between the two tillage techniques. The hypothesis that N leaching could  
508 have been more intense in CT than NT finds further confirmation in the analysis of  $\%^{15}\text{N}_{\text{REC}}$   
509 recorded in 2013, which, although quite low overall, was significantly higher in NT than CT,  
510 implying that a greater amount of N fertilizer could have been lost via leaching in CT compared to  
511 NT.

512 Our results highlight the fact that the advantages for CT over NT for plant growth materialized  
513 already during the vegetative phase of the crop cycle, as shown by the values of N uptake at  
514 heading (on average higher in CT than NT). Thus, the adoption of CT could have led to more  
515 favorable conditions for more rapid plant early growth (tillering and first phases of stem elongation)  
516 compared to NT, with a consequential increase for plants under CT in N crop demand and a greater  
517 chance that the crop would absorb the N provided by the fertilizer. Obviously, in addition to the  
518 higher N supply, other factors, such as the higher soil temperatures and aeration under CT, could  
519 have contributed to this result (Mielke et al., 1986; Giller et al., 2009; Rusinamhodzi et al., 2011).

520 Moreover, it is interesting to note that in the present research no differences between CT and NT  
521 were observed for the amount of N taken up by durum wheat from heading to maturity. The  
522 negative effects on initial crop growth associated with NT were evidently canceled out or partially

523 counteracted by other factors during the reproductive phase of the crop cycle. For instance,  
524 compared to CT, in NT more water is generally available for the crop during the spring (i.e., during  
525 wheat grain filling), a fact that is attributable to reduced soil water evaporation with NT (Blevins  
526 and Frye, 1993; Lampurlanés and Cantero-Martínez, 2006) and to deeper soil water storage under  
527 this tillage system (Lampurlanés et al., 2016). This would also explain the higher N remobilization  
528 efficiency observed under NT compared to CT when N fertilizer was applied. Indeed, Ercoli et al.  
529 (2008) observed in durum wheat that N remobilization efficiency decreased with increasing water  
530 stress during grain filling and also that the magnitude of this effect increased with increasing  
531 availability of N, thus highlighting the fact that plant N status can influence plant tolerance to water  
532 stress. Moreover, it is reasonable to assume that the improved vegetative plant growth under CT  
533 could have led to an increased demand for transpiration and a faster depletion of soil water reserve  
534 in CT compared to NT, thus resulting in an amplification of water stress conditions during grain  
535 filling, which could have adversely affected N remobilization efficiency. On the other hand, in  
536 semiarid Mediterranean environments, which are characterized by low and erratic rainfall patterns  
537 during the growing season, it is particularly important to adopt crop management strategies that  
538 mitigate water stress during grain filling. These strategies should aim to limit excessive water  
539 consumption during the initial phase of crop growth and to maximize the availability of water  
540 during grain filling. From the above, it follows that adopting NT, which influences N and water  
541 availability patterns, represents a solution particularly suitable for Mediterranean environments, as  
542 it can enhance the efficient use of these resources (Cantero-Martínez et al., 2007; Morell et al.,  
543 2011). Therefore, it is not surprising that several studies carried out in Mediterranean areas have  
544 shown that NT generally results in higher grain yields than CT in dry years (Lampurlanés et al.,  
545 2002; Amato et al., 2013). Under these conditions, the adoption of NT instead of CT is often  
546 advantageous because of the benefits of NT in terms of soil water storage and reduced soil water  
547 evaporation (Lampurlanés and Cantero-Martínez, 2006). In our experiment, rainfall was normal or  
548 consistently above the long-term average, so the availability of water was certainly not the key

549 factor that limited crop productivity (thus nullifying the potential advantage of NT over CT),  
550 whereas N supply was. We believe that if the growing seasons had been drier the results could have  
551 been different.

552 On the whole, the results of the present study show that the shift from CT to NT can be problematic,  
553 as it can negatively influence crop performance with effects more or less intense in relation to  
554 climate (mainly the amount and distribution of rainfall) and soil type. The effects of climate (which  
555 in this experiment were large and intense) and soil type (which were less intense) appeared to be  
556 connected to the influence that these two factors exerted on the soil N dynamics (N releases from  
557 the soil OM decomposition, N losses, etc.) and hence on the N supply in the soil, so much so that N  
558 fertilization progressively reduced or even canceled out the differences observed between the two  
559 soil tillage systems.

560 Moreover, results from the present study also show that i) the advantages of CT over NT for N  
561 supply and N uptake by the crop materialized already during the vegetative phase of the crop cycle;  
562 ii) the differences between CT and NT in N recovered by the crop from fertilizer were on average  
563 small but variable over the years; and iii) the shift from CT to NT was less problematic in the  
564 Vertisol, which is more fertile and better structured than the two Inceptisols.

565 In conclusion, switching from CT to NT can induce, already in the first year of transition, a  
566 significant reduction of the soil N potentially available for crops. The magnitude of such a reduction  
567 can vary in relation to climatic conditions and soil type. In particular, the differences between CT  
568 and NT for many of the traits observed in durum wheat plants increased with decreasing soil  
569 fertility and reduced progressively as the rate of N fertilization increased.

570 Our study suggests that the shift from CT to NT, which is desirable given the numerous agronomic  
571 and environmental benefits provided by NT (if continuously applied for a consistent number of  
572 years), must be accompanied by a reorganization of crop management, in particular the strategies of  
573 N fertilization, especially when the soil is poor in N. In particular, compared to CT, under NT  
574 conditions it would be appropriate to increase slightly the rate of N fertilizer applied in the early

575 tillering stage of growth to take into account the reduction in the release of N from OM  
576 decomposition during the first phases of the growing season. Clearly, all of this should be done  
577 keeping in mind that Mediterranean environments can see rainy years leading to increases in N  
578 losses (especially via leaching). Our results may be useful in helping Mediterranean farmers to plan  
579 appropriate N fertilization strategies to make the shift from CT to NT more successful.

580

581

## 582 **Acknowledgements**

583 This study was funded by MIUR (Italian Ministry for Education, University, and Research) to  
584 Università degli Studi di Palermo (Palermo, Italy) and Fondazione A. e S. Lima Mancuso (Palermo,  
585 Italy) in the framework of the Project “Sviluppo tecnologico e innovazione per la sostenibilità e  
586 competitività della cerealicoltura meridionale (PON/01\_01145-ISCOCEM)”.

587

## 588 **Declaration of interest**

589 Conflicts of interest: none.

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