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1 **Long term effects of tillage practices and N fertilization in rainfed Mediterranean cropping**
2 **systems: durum wheat, sunflower and maize grain yield.**

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20
21 **Abstract**

22 Long term investigations on the combined effects of tillage systems and other agronomic practices
23 such as mineral N fertilization under Mediterranean conditions on durum wheat are very scanty and
24 findings are often contradictory. Moreover, no studies are available on the long term effect of the
25 adoption of conservation tillage on grain yield of maize and sunflower grown in rotation with

durum wheat under rainfed Mediterranean conditions. This paper reports the results of a 20-years experiment on a durum wheat-sunflower (7 years) and durum wheat-maize (13 years) two-year rotation, whose main objective was to quantify the long term effects of different tillage practices (CT=conventional tillage; MT=minimum tillage; NT=direct drilling) combined with different nitrogen fertilizer rates (N0, N1, N2 corresponding to 0, 45 and 90 kg N ha⁻¹ for sunflower, and 0, 90 and 180 kg N ha⁻¹ for wheat and maize) on grain yield, yield components and yield stability for the three crops. In addition, the influence of meteorological factors on the interannual variability of studied variables was also assessed. For durum wheat, NT did not allow substantial yield benefits leading to comparable yields with respect to CT in ten out of twenty years. For both sunflower and maize, NT under rainfed conditions was not a viable options, because of the unsuitable (i.e. too wet) soil conditions of the clayish soil at sowing. Both spring crops performed well with MT. No significant N x tillage interaction was found for the three crops. As expected, the response of durum wheat and maize grain yield to N was remarkable, while sunflower grain yield was not significantly influenced by N rate. Wheat yield was constrained by high temperatures in January during tillering and drought in April during heading. The interannual yield variability of sunflower was mainly associated to soil water deficit at flowering and air temperature during seed filling. Heavy rains during this latter phase strongly constrained sunflower grain yield. Maize grain yield was negatively affected by high temperatures in June and drought in July, this latter factor was particularly important in the fertilized maize. Considering both yield and yield stability, durum wheat and sunflower performed better under MT and N1 while maize performed better under both CT and MT and with N2 rates. The results of this long term study are suitable for supporting policies on sustainable Mediterranean rainfed cropping systems and also for cropping system modeling.

Keywords: no tillage, minimum tillage, silty-clay soil, yield stability, recursive partitioning analysis, rainfed cropping systems.

1. Introduction

Rainfed cereal cropping systems based on rotations between wheat and a spring crop are widespread in Mediterranean Europe. In the southern Mediterranean countries, winter cereals are grown as monoculture or in rotation with other autumn-spring crops such as pulses, fallow pasture, hay crops or other minor cereals. In the northern Mediterranean countries, the rainfall regime and the high water holding capacity of the arable soils allow the cultivation of spring-summer crops such as sunflower, sorghum or maize under rainfed conditions.

Conservation agricultural practices (CA) such as reduced or no tillage, characterized by a low disturbance of soil, coupled with crop residues retention, are increasingly widespread for cultivating cereals and industrial crops in the regions with dry Mediterranean climate (Kassam et al., 2012). CA in the Mediterranean dry areas can have positive effects on crop productivity due to increased soil moisture and nutrient availability (Lopez Garrido et al., 2011) and can contribute to reduce soil erosion, nitrate leaching, greenhouse gas emissions and fuel costs (Kassam et al., 2012). Site specific effects of CA (i.e. related to soil and climate types) on soil water retention (e.g. De Vita et al., 2007), soil aggregation stability (e.g. Hernanz et al., 2002), microbial activity (Pastorelli et al., 2013) and weed dynamics (De Sanctis et al., 2012) can largely explain the various impacts of CA on crop yields. However, evidences on long term effects of CA practices on crop yield and stability are less frequent and sometimes contradictory.

More than 50% of durum wheat cultivated worldwide lies in the Mediterranean region (Bozzini, 1988) where it represents one of the most important crops in rainfed cropping systems. In these areas, wheat grain yield is characterized by a high interannual variability due to erratic seasonal weather patterns, particularly irregular rainfall distribution and high temperatures during the grain filling stage (Lopez-Bellido et al., 1996). Under rainfed semiarid Mediterranean conditions, Amato et al. (2013) and Ruisi et al. (2014) showed that durum wheat yield was higher under no tillage than

76 conventional tillage only when water stress was high and that N fertilizer requirements increase
77 with no tillage compared with conventional tillage, because of changes in N cycling that lead to a
78 reduction in plant-available soil N. Sunflower, together with other oilseed crops, is recently drawing
79 a renewed commercial and scientific attention because of its role as energy crop in the cereal-based
80 cropping systems (Barontini et al., 2015 and references therein). Under Mediterranean rainfed
81 conditions, sunflower production is heavily constrained by summer water stress, hence it is
82 practiced as a rainfed crop only in the clayey soil of the northern areas, where the spring-summer
83 rainfall regime is favorable and soil water holding capacity can buffer crop water availability.
84 Under Mediterranean rainfed conditions in southern Spain, CA did not exert a beneficial influence
85 on sunflower grain yields (Lopez-Bellido et al., 2003; Murillo et al., 1998), although a high
86 interannual variability was observed, mainly influenced by soil water conditions throughout the
87 crop cycle.

88 CA practices may have site-specific impacts on rainfed grain maize yields. CA practices in well
89 drained soils and under high N fertilization inputs and crop rotation may improve maize yield, and
90 yield stability seems to be not significantly affected by reduced tillage (Rusinamodzi et al., 2011).
91 Rainfall was confirmed as the most important determinant of maize yield under rainfed conditions.
92 The meta analysis of Rusinamodzi et al. (2011) clearly revealed that the success of CA in
93 improving maize yields depends on the adoption of other good agronomic practices such as targeted
94 site-specific fertiliser application, timely weeding and crop rotations.

95

96 To our knowledge, no studies are available on the long term effect of conservation tillage on the
97 productivity of rainfed maize and sunflower under Mediterranean conditions. The duration of such
98 studies on sunflower ranged from one (Lopez-Garrido et al., 2014) to four years (Lopez-Bellido et
99 al., 2003). In the case of grain maize, the available long term studies on the role of tillage systems
100 on yields are referred to a range of climate conditions, from a typical Northern-Central USA climate
101 (Karlen et al., 2013), to the subhumid temperate climate in the Pampas of Argentina (Diaz-Zorita et

102 al., 2002), to the semi-arid, subtropical climate of highlands of Central Mexico (Verhulst et al.,
103 2011) and to the cold semi-arid and humid subtropical climate of Northern China (Wang et al.,
104 2012), none of which comparable to the Mediterranean climate type.

105 The long-term impact of conservation tillage practices for durum wheat under Mediterranean
106 conditions was instead analysed by several scholars (e.g., Amato et al., 2013; Lopez-Bellido et al.,
107 1996, 2000, 2001; Mazzoncini et al., 2008). However, findings were often contradictory due to
108 differences among the experimental sites in terms of climatic conditions, soil type, management
109 practices, agronomic history and duration of experiments. Hence the effectiveness of various tillage
110 systems is highly site specific and the impact of yield-limiting factors may vary significantly
111 depending on the environmental conditions and on the interactions between them and the
112 management practices (Subedi and Ma, 2009)

113 Moreover, very few long term investigations have been conducted to study the combined effects of
114 tillage systems and other agronomic practices such as mineral N fertilization under Mediterranean
115 conditions (Lopez-Bellido et al., 1996, 2001).

116 In the context of rainfed cereal cropping systems of the clayey hills of central Italy, in
117 approximately 300,000 ha of arable hill-slope land, the rotation of wheat and a spring-summer crop
118 such as sunflower or maize implies about 8-9 months of intercropping period between the wheat
119 harvest (early July) and the seeding of sunflower (March) or maize (April). Because of the high soil
120 clay content (up to 50%) and the seasonal rainfall/evapotranspiration regime, the main tillage under
121 the conventional practice (i.e. 30-40 cm deep ploughing) is made in the summer, in order to exploit
122 the structuring effect of thermal and water regimes in the soil during autumn-winter. Moreover,
123 tillage practices during autumn may be difficult due to the high plasticity of the clayey soils when
124 autumn is wet. Further harrowing is practiced during intercropping to prepare the maize or
125 sunflower seedbed. Therefore, the conventional practice exposes the bare soil to soil erosion
126 (Roggero and Toderi, 2002) and nitrate leaching (De Sanctis et al., 2009) during the wet and cool
127 season. CA techniques including no tillage and reduced N fertilization rates can provide options to

128 mitigate such undesirable processes, but are considered by farmers as not reliable enough to ensure
129 yield targets and stability, particularly in the case of the spring-summer crops.

130 In this paper we explore the implications for adopting CA practices from a Long Term Experiment
131 (LTE) based on a two-year rotation of durum wheat and sunflower or maize under rainfed
132 Mediterranean conditions and heavy clayey soils.

133 The aims of this study were to (i) assess the long term influence of tillage systems and N
134 fertilization rates on yield, yield components and stability of durum wheat, sunflower and maize
135 under Mediterranean rainfed conditions of the hilly areas of Central Italy and (ii) analyse at what
136 extent the meteorological factors can influence the interannual variability of yield for the three
137 crops.

138

139 **2. Materials and Methods**

140 *2.1. Experimental site*

141 The LTE is located at the “Pasquale Rosati” experimental farm of the Polytechnic University of
142 Marche in Agugliano, Italy (43°32' N, 13°22' E, 100 m a.s.l.), on a silty-clay soil classified as
143 Calcaric Gleyic Cambisols (FAO, 2006), almost free of gravel, with a high clay (49%) and calcium
144 carbonate (31%) content, pH of 8.3, a low soil organic carbon (SOC) content (0.7%) and a slope of
145 about 10%.

146 The climate of the experimental site is Mediterranean (Fig. 1), with a mean annual rainfall of 820
147 mm, mostly distributed in the autumn and winter (54%) and in the spring (24%). The mean air
148 temperature is 15.3°C, with monthly means ranging from 6.2°C in January to 25°C in August. The
149 mean annual evapotranspiration (ET₀), estimated at daily basis over the 20-years period with the
150 FAO Penman-Monteith formula by using the computer tool ET₀ Calculator (Annandale et al.,
151 2002), was 1068 mm (standard deviation (SD) = 75 mm), producing an average aridity index
152 (Rain/ET₀) of 0.76 (SD=0.16).

153

154 2.2. *Experimental Design and Crop Management*

155 The LTE was established in 1994 and is still on-going consisting on a rainfed 2-years rotation with
156 durum wheat (*Triticum durum* L. cv. Grazia, ISEA) in rotation with sunflower (*Helianthus annuus*,
157 L., cv. Starsol, ISEA) until 2001 or maize (*Zea mays* L., DK440 hybrid, Dekalb Monsanto, FAO
158 class 300) from 2002 onwards. The crop rotation was duplicated in two adjacent fields to allow for
159 all crops to be present each year. Within each field, three tillage (T, main plot, 1500 m²) and three
160 nitrogen fertilizer (N, sub-plot, 500 m²) treatments were repeated in the same plots every year and
161 arranged according to a split plot experimental design with two replications.

162 The conventional tillage (CT), that is representative of the business as usual tillage practice in the
163 study area, and the minimum tillage (MT) plots were ploughed along the maximum slope every
164 year by a mouldboard (with 2 plows) at a depth of 40 cm or a chisel at a depth of 25 cm respectively
165 in autumn for wheat and in summer for maize. The seedbed was prepared with double harrowing
166 before the sowing date. The no tillage (NT) soil was left undisturbed except for crop residues and
167 weed chopping and total herbicide spraying prior to direct seed drilling. The three N fertilizer
168 treatments (N0, N1 and N2) corresponded to 0, 90 and 180 kg N ha⁻¹ distributed in two rates for
169 wheat and at seeding for maize, while sunflower received 0, 45 and 90 kg N ha⁻¹ about one month
170 after sowing. The N1 treatment was compliant with the agri-environmental measures adopted
171 within the Rural development Plans at local scale. The N2 treatment was the business as usual N
172 rates in the study area at the start of the experiment. The N0 treatment was chosen as a control.
173 Dates of the agronomic management practices for all the three crops are reported in Table 1.

174

175 2.3. *Measurements*

176 At crop maturity, grain yield for all the studied crops was measured in each plot through combine
177 harvesters and it was expressed on a dry matter content basis. Twenty (1995-2014), seven (1995-
178 2001) and thirteen (2002-2014) years of grain yield data were collected respectively for durum
179 wheat, sunflower and maize. Yield components were determined on thirteen (1995-2001, 2007-

2008, 2011-2014), seven (1995-2001) and nine (2002-2003, 2006-2008, 2011-2014) years respectively for durum wheat, sunflower and maize. For durum wheat, the number of spikes m^{-2} was determined by counting the number of spikes along two adjacent 1-m long rows. The grain weight per spike and the 100 grains weight were estimated on 30 spikes randomly collected per subplot. For sunflower and maize, yield components were assessed on three random samples per subplot of 10 plants each for a total of 30 plants sampled in each subplot. For each plant the grains weight per inflorescence and the 100 grains weight were determined. Plant density of sunflower and maize was determined by counting the number of plants along two adjacent 10-m long rows. Meteorological data were obtained from the Agugliano (43°32' N, 13°22' E, elevation: 140 m) weather station of the Agrometeorological Regional Service of Marche (ASSAM) that is located nearby the experimental site. E-OBS dataset (Haylock et al., 2008) from the EU-FP6 project ENSEMBLES (<http://ensembles-eu.metoffice.com>) was used for retrieval of the missing data related to daily precipitations, minimum and maximum temperatures.

193

194 2.4. Data analyses

195 All data were submitted to the PROC MIXED procedure in SAS (SAS Institute, 1999), suitable for
196 analyzing mixed effects and repeated measures with non-constant variance and any covariance
197 structure models. The independence assumption on the error terms required for the ANOVA of a
198 factorial model (Montgomery, 1997) was in fact likely not met. The appropriate mixed model was
199 built following Onofri et al. (this issue) and considering "year" as a repeated factor and for each
200 year, tillage (T) and N fertilisation (N) as randomised treatment factors. The appropriate variance-
201 covariance structure for this particular model was selected fitting all possible models and making an
202 'a posteriori' selection, based on those statistics which put a penalty on 'complexity', such as the
203 Akaike Information Criterion (AIC: Akaike, 1974). For assessing the yield stability over the
204 experimental years, the Shukla's (1972) stability variance was calculated by applying the R code
205 reported by Onofri et al. (this issue). The closer to zero is the Shukla's stability variance the more

206 stable is the yield. We tested the null hypothesis of any grain yield trend over time associated to the
 207 repeated T and N fertilization treatments by fitting a simple linear regression of yield vs. years as
 208 suggested by Piepho et al. (2014) The treatment (T x N) effect was regarded as fixed as well as the
 209 treatment-dependent slopes, while the year effect and the year x treatment interactions as random.
 210 The robustness of this analysis increases with the duration of the experiment (Onofri et al., this
 211 issue), hence is higher for the durum wheat experiment than for maize (13-years trial). For this
 212 reason, this analysis was not performed for sunflower.

213 For all the studied crops, three agro-meteorological variables were calculated and analysed on
 214 monthly basis starting from sowing until crop harvest: mean temperature (Tmean), rainfall amount
 215 (Rain) and cumulated reference evapotranspiration (ET0). Linear correlation coefficients (Pearson
 216 r) were then used to determine the effect of each meteorological variable on yields considering both
 217 yields of all treatments and yields related to each singular management factor (CT, MT, NT and N0,
 218 N1, N2). Only the meteorological variables that were statistically significant in at least one
 219 treatment, together with the categorical factors T and N, were submitted as inputs in a recursive
 220 partitioning analysis. The inter-annual variability of these variables is shown in Table 2. The
 221 recursive partition explores the structure of a dataset, developing decision rules for predicting a
 222 categorical (classification tree) or continuous (regression tree) variable (Rokach and Maimon, 2008;
 223 Strobl et al., 2009). In our study, we used the regression tree function *ctree* available in the *party* R
 224 package (Hothorn et al., 2006) to explore the variation of yield as influenced by several explanatory
 225 (meteorological and management) variables. Regression trees are constructed by recursively
 226 splitting the response variable (i.e. grain yield) into two groups on the basis of the explanatory
 227 variables (Tmean, Rain, ET0) so as to minimize variability within a group and maximizing
 228 variability between groups. At the end, the terminal node (leaves) is characterized by the mean
 229 values of the response variable. *Ctree* function bases its node splitting on statistical tests providing a
 230 P value for the significance of its splitting. Although *ctree* was used in this study just to explore the
 231 interactions among explanatory variables and not as a predictive tool, we estimated anyway the

232 performance of the regression using the root-mean-square error (RMSE) and the mean absolute
233 error (MAE).

234

235 RMSE was calculated as:

236
$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_{obs,i} - y_{model,i})^2}{n}}$$

237 and MAE was given by:

238
$$MAE = \frac{\sum_{i=1}^n |y_{obs,i} - y_{model,i}|}{n}$$

239 where y_{obs} is the observed crop yield, y_{model} is the modelled yield at year_i and n is the number of
240 observations.

241

242 **3. Results**

243

244 *3.1. Durum wheat yield, yield components and yield stability*

245 Significant year x T and year x N interactions were observed, while no significant T x N interaction
246 was observed (Table 3). Grain yields ranged from 1.3 (CT 2004) to 5.0 t ha⁻¹ (CT 2013) and from
247 0.6 (N0 2007) to 5.9 t ha⁻¹ (N2 2004). Grain yield under NT was significantly higher than CT in one
248 out of twenty years, while CT and NT were not significantly different in ten out of twenty years
249 (Table 4). MT differed significantly from CT in eight out of twenty years being significantly higher
250 and lower in three and five years respectively. Wheat grain yields were higher under MT than NT in
251 seven out of twenty years throughout the experiment. N2 showed higher grain yields than N1 in
252 sixteen out of twenty years. Among the four years with no significant differences between N2 and
253 N1, two years were the least productive ones.

254 On average, NT resulted in lower spikes m^{-2} than MT and CT by about -13% (313 vs. 359). A
 255 significant relationship was found between spikes m^{-2} and grain yield independently of the tillage
 256 treatment averaged for all N levels, while the same relationship was significant only for N2 (Fig. 2).
 257 The number of kernels per spike and the 100 kernels weight were significantly influenced by the
 258 tillage x year and nitrogen x year interactions (Table 3). The number of kernels per spike ranged
 259 between 21 and 42 with NT showing a slight higher value than CT and MT (33 vs. 29). In 70% of
 260 the years when the number of kernels per spike was determined, N2 had about 6 kernels per spike
 261 more (+20%) than N1.
 262 In about half of the years, 100 kernels weight showed significant higher values under NT than CT.
 263 The stability analysis (Fig. 3) showed that the most productive treatment (CT_N2) was the least
 264 stable in terms of grain yield, while CT_N1 and, even more, MT_N1 characterized by intermediate
 265 yields were the most stable. Also NT_N0 had very stable grain yields that were however associated
 266 to low yields. No significant time trend was found for grain yield for any of the T x N fertilization
 267 combinations.
 268 The correlation analysis between the meteorological variables and grain yield selected the following
 269 significant variables (Table 5): mean temperature of January (M1_Tmean), mean temperature
 270 (M3_Tmean) and rainfall (M3_RAIN) of March, mean temperature (M4_Tmean), rainfall
 271 (M4_RAIN) and reference evapotranspiration (M4_ET0) of April and mean temperature of May
 272 (M5_Tmean).
 273 The decision tree obtained considering these significant meteorological variables, together with T
 274 and N factors, is reported in Fig. 4. The first important factor was N fertilization, with N0
 275 associated to the lowest yields. M1_Tmean was the second most important factor independently of
 276 the N fertilization rate, and 6.5 °C represented the partitioning threshold. The group identified by
 277 N2 and N1 and $\text{M1_Tmean} \leq 6.5$ °C was further split according to the N fertilization rate and both
 278 subgroups obtained were divided by a M4_ET0 value of 91 mm. Other important meteorological
 279 factors were M4_Rain for the group firstly identified by N2 and N1 and $\text{M1_Tmean} > 6.5$ °C, and

280 the M5_Tmean for the group identified by N0 and M1_Tmean ≤ 6.5 °C. The lowest wheat grain
281 yield was associated to N0 and M1_Tmean > 6.5 °C, while the highest yield to M1_Tmean ≤ 6.5 °C,
282 N2 and M4_ET0 ≤ 91 mm. The two indicators of the model performance RMSE and MAE were
283 respectively 694 kg ha⁻¹ and 525 kg ha⁻¹. Similarly to what found with the mixed model analysis,
284 the effect of tillage on wheat grain yield was not significant also for the decisional tree approach.
285

286 3.2. Yield, yield components and yield stability in sunflower

287 Sunflower grain yield showed a high interannual variability ranging from 0.6 to 2.8 t ha⁻¹ (Table 6).
288 A significant year x T interaction was found while no effect of N was observed (Table 6). Grain
289 yield under NT was always significantly lower than CT (Table 7) except for one year out of seven
290 (1997). In the last four years of sunflower cultivation, MT showed similar yields to CT and higher
291 than NT.

292 Plants m⁻², achenes weight per flower head and the 1,000 achenes weight showed a significant T x
293 year interaction (Table 6). On average (data not shown), under NT the number of plants per m⁻²
294 were lower by 54% than CT (2.6 vs 5.6). In two out of seven years (1996 and 1998), the number of
295 plants per m⁻² under NT was more than 80% lower than under CT. Under MT, plant density was
296 significantly lower than under CT in six out of seven years, on average -12% (from -3 to -18%),
297 while it was slightly higher only in 1998.

298 The achenes weight per flower head (data not shown) ranged from 8.6 to 67.7 g under NT in 1995
299 and CT in 1999 respectively. However, on average, NT showed a +13% higher achenes weight per
300 flower head with respect to CT.

301 The results of the stability analysis (Fig. 3) showed that CT_N2 and MT_N2 were on average the
302 most productive treatments and, at the same time, with the least unstable yields. All the NT
303 treatments independently of the N fertilizer rate had the lowest stability.

304 The correlation analysis between sunflower grain yields and the meteorological variables selected
305 the following significant variables (Table 8): mean temperature (M4_Tmean) and precipitation

306 (M4_Rain) of April, the reference evapotranspiration of May (M5_ET0), the mean temperature
307 (M6_Tmean) and reference evapotranspiration of June (M6_ET0), mean temperature of July
308 (M7_Tmean), mean temperature (M8_Tmean), precipitation (M8_Rain) and reference
309 evapotranspiration (M8_ET0) of August.

310 The significant meteorological variables together with N and T factors were used as input in the
311 regression tree analysis illustrated in Fig. 5. The first most important factor was M7_Tmean
312 followed by the T factor with higher sunflower yields associated to CT and MT. This group was
313 further split according to a threshold value of 39.2 mm for the M8_Rain, while the NT group was
314 split according to the M6_ET0. The highest sunflower grain yield was associated to $M7_Tmean \leq$
315 $25.1\text{ }^{\circ}\text{C}$, CT or MT and $M8_Rain \leq 39.2\text{ mm}$, while the lowest yield to $M7_Tmean \leq 25.1\text{ }^{\circ}\text{C}$, NT
316 and $M6_ET0 > 156.7\text{ mm}$. The performance indicators RMSE and MAE were respectively 475 kg
317 ha^{-1} and 398 kg ha^{-1} . According to what found with the mixed model analysis, the N fertilization
318 rate was not considered a significant explanatory variable also in the recursive partition approach.

319

320 3.3. Yield, yield components and yield stability in maize

321 Maize grain yield showed an irregular pattern over the thirteen years period ranging from very low
322 values (2003 and 2007 for NT) up to 5.0 t ha^{-1} (2012 for MT). The interactions between both year x
323 T and year x N were significant (Table 9). In 2003 and 2007, grain yields under NT were almost
324 zero, due to the very low plant density that did not allow mechanical harvest (Table 10). In more
325 than half of the years, NT showed a lower yield than CT (-40%). MT differed significantly from CT
326 in eight out of thirteen years being significantly higher and lower in four years respectively.
327 N2 showed comparable grain yields to N1 in 30% of years. N1 in none of the years showed
328 significantly higher yield than N2.
329 In terms of plants m^{-2} , NT showed always lower values (3.4 plants m^{-2}) by about -45% (from -20%
330 to -96%) compared to CT and MT (data not shown). Plant density was positively correlated with

331 grain yield (Fig. 6) with data grouped by T treatments. By considering the relationship with data
332 grouped by N treatments, a weaker correlation was found ($r = 0.54$, $P = 0.003$).

333 The 100 grains weight was significantly influenced by T x year interaction (Table 9) and ranged
334 from 7.7 g (MT 2014) to 24.1 g (NT 2008) with a mean of 18.5 g. No significant differences were
335 found among T treatments along the experimental period with the exception of 2008 when 100
336 grains weight was +11% higher in NT than in CT and MT.

337 The results of the stability analysis (Fig. 3) showed that the most productive treatment (CT_N2)
338 was the least stable in terms of grain yield, while the highest yield stability was found for MT_N1
339 and NT_N1. Unfertilized treatments had intermediate stability. MT and NT combined with N2 or
340 N1 showed a significant positive trend in terms of grain yield over time (NT_N1: slope $231 \text{ kg ha}^{-1} \text{ y}^{-1}$;
341 P -value 0.02; MT_N2: slope $301 \text{ kg ha}^{-1} \text{ y}^{-1}$; P -value 0.01).

342 Through the correlation analysis between the meteorological variables and maize yield, the
343 following significant variables were identified (Table 11): mean temperature (M4_Tmean) and
344 reference evapotranspiration (M4_ET0) of April, mean temperature (M6_Tmean), precipitation
345 (M6_Rain), and reference evapotranspiration (M6_ET0) of June, rain of July (M7_Rain) and
346 reference evapotranspiration of August (M8_ET0).

347 The significant meteorological variables and the management factors (T and N) were used for
348 obtaining the conditional regression tree for maize yield reported in Fig. 7. The meteorological
349 variables explaining most the yield performances in maize were M6_Tmean (threshold values
350 ranging from 22.0 to 23.3 °C) and M7_Rain (50.2 mm). Both management factors were found to be
351 significant. The lowest maize grain yield was associated to $\text{M6_Tmean} > 23.2 \text{ °C}$ and MT and NT
352 practices, while the highest values to $\text{M6_Tmean} \leq 23.2 \text{ °C}$, N2 or N1 and $\text{M7_Rain} > 50.2 \text{ mm}$.

353 RMSE and MAE obtained with the regression tree for maize were respectively 936 kg ha^{-1} and 785
354 kg ha^{-1} . According to the mixed model analysis, also this decisional tree found that both T
355 management and N fertilization rates were significant for maize yield.

356

357 **4. Discussion**

358 *4.1. Effects of tillage and fertilization systems on durum wheat yield traits*

359 Our results show that NT did not provide any substantial advantage or disadvantage to durum wheat
360 grain yield in comparison to CT or MT. This finding is consistent to the evidences reported in the
361 European meta-analysis by Van den Putte et al. (2010), showing an average grain yield of -8.5 %
362 for NT compared to CT. Similarly, in a 16-years long term experiment made in Central Italy on
363 poorly drained silt-loam soil, Mazzoncini et al. (2008) reported a mean loss of wheat grain yield of -
364 8.9% under NT vs. CT. Lopez-Bellido et al. (2000, 2001) and De Vita et al. (2007), in the Vertisols
365 of Spain and Italy respectively, found that wheat under CT performed better only in the wet years,
366 while in the dry years, wheat grain yield was higher under NT. Our results do not confirm these
367 findings and our interpretation is that we rarely experienced extremely dry years (i.e. less than 350
368 mm of rainfall during the wheat cycle) and because the soil of the experimental field was not a
369 Vertisol, which would have been characterized by self-structuring capacity. In a 20-years
370 experiment carried out on a Vertisol, under semiarid Mediterranean conditions, Ruisi et al. (2012)
371 did not observe significant differences between CT and NT, although they also found a tendency for
372 NT to guarantee superior grain yields under water stress conditions during the crop cycle. However,
373 similarly to our findings, Ruisi et al. (2012) found a great interannual variability in durum wheat
374 productivity, that they interpreted as mainly associated to the interactions between tillage and other
375 agronomic factors, in particular crop sequence. A yield superiority of NT compared to CT was in
376 fact observed only when wheat was grown in a 2-years rotation, while, when grown continuously, it
377 performed better under CT. In our experiment, the 2-years rotation of wheat with a spring crop
378 might have contributed to prevent from the potential progressive increased incidence of pests and
379 diseases, which are often the main drivers causing differences between tillage systems under
380 monocropping. It is interesting to highlight that durum wheat grain yield under NT did not show
381 any significant increasing trend over time, although in the same LTE, De Sanctis et al. (2012)
382 measured an increment of soil organic matter in the top soil in the first twelve experimental years.

383 The possible positive effects on soil quality due to no tillage, as improved water retention (De Vita
384 et al., 2007), aggregation stability (Hernanz et al., 2002), improved biological and biochemical soil
385 processes (Acosta-Martínez and Tabatabai, 2001) did not result into a higher crop productivity.
386 Soil compaction is also an important constraint for wheat grain yield under NT, as documented in
387 the same LTE by Pastorelli et al. (2013). The negative effects of soil compaction on root
388 development and tillering are well documented (e.g. Atwell, 1990) and confirmed by the lower
389 number of spikes m^{-2} under NT in our experiment (-14% with respect to CT). However, this seems
390 in contrast to the findings of other scholars who measured similar soil bulk density and root density
391 values under NT and CT (e.g., Munoz-Romero et al., 2010; Plaza-Bonilla et al., 2014) but on
392 Vertisols, where the self-structuring nature and the better soil water conditions allow sufficient
393 conditions for root growth and tillering also under NT (e.g., Lopez-Bellido et al., 2007).
394 The most relevant factor influencing wheat yield was N fertilization, which provided an advantage
395 of about +30% in terms of grain yield when doubling the N rate from 90 to 180 kg ha^{-1} N. In
396 southern Spain, also Lopez-Bellido et al. (2001) reported a more significant impact of N
397 fertilization than tillage on grain yield, with no additional response to N fertilizer at rates above 100
398 kg ha^{-1} . In our study, grain yields were more stable with 90 kg N ha^{-1} than with 180 kg N ha^{-1} .
399 Therefore, the decision about the about the optimal N fertilizer rate to adopt will depend on the
400 specific farming system context and associated trade-offs between productivity and stability targets.
401 The second important driver influencing the grain yield, as resulted from the decisional tree
402 analysis, was the mean temperature of January. Low temperatures at early developmental stages (as
403 it is in January in the experimental site) and in particular when plants are at the tillering stage, might
404 delay the crop development determining an increase of the tillering duration. A greater number of
405 tillers can lead therefore to a greater potential numbers of spikes m^{-2} and, hence, to a higher yield
406 (Kazmi et al., 2012). When N was not a limiting factor, the water availability in April, which
407 depends on rainfall and evapotranspiration, was a key driver for grain yields. The earing and
408 anthesis occurred mainly in April and these are the most critical phases in wheat for yield (Ozturk et

409 al., 2004; Wheeler et al., 2006; Albrizio et al., 2010). A water stress in this period could have
410 reduced the number of kernels per spike, leading to a significant reduction of grain yield. A
411 significant sensitivity of durum wheat to high air temperature and water stress in April and May was
412 also observed by Campiglia et al. (2015) who carried out a 6-years trial under similar soil and
413 climate conditions to our study. They highlighted a different level of sensitivity to rainfall in spring
414 depending also on the soil N availability associated to the compared cropping systems. This finding
415 is consistent to the results of the decisional tree analysis that revealed a key role of April rainfall in
416 constraining grain yield under sufficient N fertilizer application. In spring, the N availability is a
417 main driver of the aerial biomass production and leaf area, hence under no limiting soil N, wheat
418 may become more vulnerable to water stress and, at the same time, more able to exploit the benefits
419 of water availability (Sadras et al., 2012) than an unfertilized crop. When N was not supplied, only
420 air temperature in May, together with air temperature in January, were the main grain yield
421 constraints. The grain filling period started during May. High temperatures throughout this stage,
422 affecting kernel weight and accelerating grain maturity (Monpara, 2011), may lower grain yield.
423 Overall, temperature in the early growth stages, soil moisture during flowering and anthesis and
424 their interaction with N nutrition explained most of the inter-annual durum wheat yield variability.

425 426 *4.2. Effects of tillage and fertilization systems on sunflower yield traits*

427 The most important yield-limiting factor for sunflower in the specific environmental conditions,
428 characterized by clayey soils that are not Vertisols, was the application of NT practices. The
429 substantial failure of NT was strongly related to poor crop establishment under unsuitable soil
430 moisture conditions at sowing time, as already highlighted by Farina et al. (2011) in the same LTE.
431 In clayey soils, NT is constrained by the mechanical impedance of the seed-slot walls in compacted
432 and wet soil conditions for plants emergence, as reported by some authors (e.g., Bayhan et al.,
433 2002). This sunflower sensitivity to NT systems was also observed with less problematic soil
434 texture as in loamy sand soils (Ruhlemann and Schmidtke, 2015) and in sandy clay loam soils

(Lopez-Garrido et al., 2014). In these latter conditions, the number of plants m^{-2} at the emergence and, in turn, the plant density at harvest were -97% less under NT than under CT. In our experiment, plant density with NT was on average 60% lower with NT than under CT. Plant density was independent of tillage systems (on average, 5.4 plants m^{-2}) only in 1997, when no yield differences were observed between CT and NT. This confirms the negative role of worsened physical soil conditions, such as high penetration resistance and low macroporosity (Pastorelli et al., 2013), under NT for seedling emergence. The low soil porosity may also restrict gaseous exchange creating unfavorable conditions for germination and seedlings establishment (Gantzer and Blake, 1978). In contrast to our findings, Halvorson et al. (1999) reported a beneficial effect of NT on sunflower yields, although under more suitable soil texture conditions (silt-loamy soil) and no limiting soil N availability.

Overall, the sunflower productivity measured in our long term experiment was rather low (1.4 t ha^{-1}) with high interannual variability associated to weather patterns. Under rainfed Mediterranean conditions, other scholars found higher yields by about $+1 \text{ t ha}^{-1}$ (Lopez-Bellido et al., 2003; Murillo et al., 1998), although with similar variations among years mainly related to soil water availability. When sunflower had received less than 100 mm of rainfall during the growing season, yields were dramatically lowered under soil inversion tillage (0.5 t ha^{-1}) while reduced tillage was able to keep reasonable growth and yields (1.5 t ha^{-1}). In the Northern Great Plains (USA), characterized by severe drought during the sunflower growing season (less than 250 mm of rainfall from April to September), this crop produced extremely low yields (always lower than 0.5 t ha^{-1}) (Lenssen et al., 2007). Under water-limiting conditions, i.e. some 400 mm of rainfall from May to August, Krupinsky et al. (2006) observed around 1.4 t ha^{-1} of achene yield for sunflower grown in rotation with spring wheat. In our experimental conditions, rainfall from April to September ranged between 280 to 520 mm during the seven years of the trial and the least productive year corresponded to the least rainfall amount in the period June-July when flowering occurred.

460 The main weather driver influencing sunflower yield identified through the recursive partition
461 analysis was the mean temperature of July, followed by evapotranspiration in June and rainfall
462 amount in August. Mean temperatures of July in the range 25-30 °C determined higher grain yields.
463 In fact, the optimum temperatures for sunflower seed filling range from 23 to 28 °C. Above this
464 range grain filling is constrained (Chimenti et al., 2010). Moreover, sunflower sensitivity to heat
465 stress decreases as grain filling proceeds (Rondanini et al., 2003). Regarding soil water deficit, the
466 most critical period occurs soon before and after flowering (Rao et al., 1977). According to this, we
467 found that lower evapotranspiration values in June when flowering initiates, are among the main
468 weather factors influencing yield in particular under NT. Rainfall amount in August was negatively
469 correlated with grain yield. In fact, sunflower in August is usually at the end of the grain filling
470 phase and adverse conditions during this period could affect the achene viability. In particular, the
471 heavy rains that occurred in August 1996 could have lead to the detachment of the achenes from the
472 flower head and likely to the occurrence of diseases and other biotic stresses, resulting in severe
473 production losses.

474 The effect of N fertilization was not significant and independent of the tillage system, although the
475 high error variance is likely to conceal a type II error in the F test as the grain yield of the
476 unfertilized crop was on average -18% than that of the fertilized ones. On the contrary, Halvorson et
477 al. (1999) and De Vuyst and Halvorson (2004) reported a significant tillage x N interaction under
478 CT combined with 100 kg N ha⁻¹ which led to the highest 12-year average grain yields. The lack of
479 significant effect of the N input in our experimental conditions may support the empirical
480 considerations of many farmers growing rainfed sunflower in rotation with wheat in Mediterranean
481 basin areas who do not apply N fertilizers directly to sunflower but to durum wheat, since they
482 experienced a lack of significant response of sunflower to N (Lopez-Bellido et al., 2003).

483 Considering the sunflower productivity, the highest N fertilizer rate under MT and CT reached
484 higher yields (on average, 1.8 t ha⁻¹) and were characterized by high stability. Yield stability results

485 indicate however a relatively good performance of sunflower cropped under MT and intermediate N
486 fertilizer rates, as it was shown for durum wheat.

487

488 *4.3. Effects of tillage and fertilization systems on maize yield traits*

489 Similarly to what discussed for sunflower, the most relevant yield-limiting factor for maize grain
490 yields was the NT application. Similarly to what discussed for sunflower, this was mainly
491 associated to unsuitable soil conditions for direct seed drilling operations, that constrained seed
492 germination, as revealed by the lower mean plant density (-50%) under NT vs. CT. The retention of
493 previous crop residues in the surface soil with NT might also have delayed seedling emergence
494 because of a longer duration of low temperatures as compared to tillage practices with residue
495 incorporation. This interpretation is supported by the findings of Cai and Wang (2002) and Wang et
496 al. (2012) who found a lower surface soil temperature of -2 to -6°C under NT with residue retention
497 systems with respect to residue removal or incorporation, leading to lower emergence and grain
498 yield in maize. Soil texture is another important factor influencing the outcomes of NT practices
499 with the worst results or nihil benefits usually obtained with fine-textured soils (Tabaglio and
500 Gavazzi, 2009; Verhulst et al., 2011) as it was for our clayish soil. In these soil types long term NT
501 result in increased soil bulk density (Pastorelli et al., 2013) that, in turn, constrains root growth in
502 the subsoil contributing to limited water and nutrient uptake capability of maize, particularly after
503 the tasseling stage (Wang et al., 2015).

504 The lower productivity of rainfed maize under NT was constantly observed along the 13-years
505 experiment with very few exceptions, although we observed very high interannual variations, as
506 also demonstrated by the lower yield stability of NT as compared to CT or MT systems. However, a
507 significant upward trend was found over time in terms of maize grain yield for MT and NT with
508 both N2 and N1 rates. These results need to be confirmed when the duration of the maize trial will
509 reach an appropriate length for the fertility trend analysis to be sufficiently reliable (at least 20
510 years). Other authors observed an increasing trend of yields after at least two to four years since the

511 start of NT adoption that were considered a minimum time period for creating better soil structure
512 and, hence, better soil and plant water status (Karunatilake et al., 2000; Diaz-Zorita et al., 2002).
513 Also Colvin et al. (2001) raised several concerns regarding consistently lower maize yields under
514 NT than under CT or MT systems in the first period after conversion to NT, while in the same
515 environment but in the long term, Karlen et al. (2013) found similar yields among tillage systems.
516 Even though NT maize, in our experimental conditions, followed seven years of continuous NT in
517 the context of the wheat-sunflower rotation and showed a slight increasing trend over the thirteen
518 years of the trial, the level of productivity remained quite low. This suggests that, although soil
519 available water might have been higher in the top soil (Wang et al., 2015), yield was likely
520 constrained by a combination of unsuitable soil conditions for sowing, reduced water uptake ability
521 or soil nutrient deficit. Tabaglio and Gavazzi (2006, 2009) in Northern Italy reported opposite yield
522 results with NT depending on soil fertility traits, with better maize performances in the most
523 nutrient-rich soil. On the contrary, we did not find a significant interaction between T and N
524 fertilization systems. However, the highest N rate (180 kg N ha^{-1}) was far lower than the common
525 rate in the maize-based cropping systems in Italy (about 250 kg N ha^{-1}) under irrigation or in wetter
526 climates and this could have flattened the maize performance particularly in more humid years. In
527 terms of yield stability and yield outcomes over the thirteen years of the experiment, the best
528 performance was achieved with the intermediate N rate and MT. Nevertheless, the overall mean
529 productivity (2.1 t ha^{-1}) was rather low if compared to what reported by other scholars for rainfed
530 maize grown under more suitable rainfall patterns (9 t ha^{-1} in Northern Italy by Tabaglio and
531 Gavazzi, 2009; 8 t ha^{-1} in Northern-Central USA by Karlen et al., 2013; 5 t ha^{-1} in Central Mexico
532 by Verhulst et al., 2011; 5 t ha^{-1} in Northern China by Wang et al., 2012).
533 In our experimental conditions, weather factors affected negatively maize yields, particularly high
534 mean temperatures in June ($>23.2^{\circ}\text{C}$) and drought conditions in July. This latter factor is
535 particularly important when N was less limiting. In these periods, maize sensitivity to high
536 temperatures was associated to high evapotranspiration and low soil moisture during anthesis

537 (Sánchez et al., 2014) when potential total number of kernels per plant is defined. Two of the most
538 vulnerable developmental stages of maize to water stress, i.e. the end of the flowering and the
539 beginning of the grain filling, occurred in July. In rainfed systems, water stresses are recognized to
540 be responsible of maize yield losses particularly if they occur after tassel initiation, at anthesis and
541 during the grain filling (Tollenaar and Bruulsema, 1988).

542

543 **5. Conclusions**

544 In this study we investigated how long term tillage management and N fertilization strategies and
545 their interaction with some meteorological factors, especially temperature and precipitation, can
546 explain the interannual yield variability of durum wheat, sunflower or maize in a rainfed
547 Mediterranean 2-year crop rotation. The identification of the key drivers that influence wheat,
548 sunflower and maize yields will be useful to target further research and to support adaptive crop
549 management responses to climate variability and to design policy interventions for these important
550 rainfed cropping systems in the Mediterranean hill-slopes. Moreover, this long term evaluation can
551 represent an important and robust source of data and information for cropping system modeling
552 approaches.

553 Long term NT systems did not provide any additional advantage or disadvantage to durum wheat
554 productivity and no tillage x N fertilization interaction was observed. Consequently, the decision to
555 adopt conservation tillage methods will depend rather than just on productivity objectives, on the
556 specific farming system context and related potential benefits in terms workload or production
557 costs. The interannual wheat grain yield variability was constrained by the temperatures in the early
558 growth stages, in relation to the tillering enhancement effect, and by the water stress during the
559 reproduction phase in spring.

560 The long term experimental results clearly indicate that in the non-Vertisols clayish soils of the
561 study area the adoption of continuous NT under rainfed conditions is not a viable options for
562 sunflower and maize. In particular for sunflower, N fertilization seemed to be not sufficient to

563 compensate for the yield penalty associated to NT practices. This finding is strongly associated to
564 the site-specific characteristics of the study area that constrained the success of the direct seed
565 drilling. MT proved instead to be a viable option for both maize and sunflower crops particularly to
566 enhance grain yield stability. However, the overall productivity of both sunflower and maize,
567 independently of the tillage and N fertilization systems, was found to be rather low in absolute
568 terms, even if it was consistent to yields observed for sunflower grown under rainfed conditions in
569 semi-arid environments. Maize yields were instead absolutely not satisfactory, considering the high
570 productivity potential of this crop. This indicates that in the study area, the severe water stress
571 during the reproductive phases heavily constrains maize productivity under rainfed conditions.
572 However, our findings on rainfed maize productivity under conservation tillage represent, to our
573 knowledge, a unique attempt to assess the role of these tillage systems in the Mediterranean
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575

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588

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776 Fig. 1. Walter and Lieth climate diagram of Agugliano weather station. Period of observation:
777 1994-2014. a) Elevation, b) Annual average of temperature, c) Annual average of precipitation, d)
778 Monthly mean temperatures, e) Monthly mean precipitations, f) Mean daily maximum temperature
779 of the warmest month, g) Mean daily minimum temperature of the coldest month, h) Indication of
780 potential frost periods (months with absolute monthly minimum temperature below 0°C). Vertical
781 lines: humid period, Dotted area: dry period.

782
783 Fig. 2. Relationships between mean grain yield and spikes m^{-2} for durum wheat as influenced by
784 tillage techniques (top) or by N fertilization rates (bottom). Data on spikes m^{-2} are referred to
785 thirteen years from 1995 to 2001, from 2007 to 2008 and from 2011 to 2014.

786
787 Fig. 3. Relation between yield and yield stability (Shukla SD) for durum wheat (top), sunflower
788 (middle) and maize (bottom).

789
790 Fig. 4. Regression tree showing the emerging drivers of the durum wheat grain yield interannual
791 variation: meteorological variables (Tmean= mean monthly temperature, RAIN = monthly
792 precipitation, ET0 = cumulate monthly reference evapotranspiration; M = month from 1 - January
793 to 5 -May) and N fertilization rate (0, 90, 180 N kg ha^{-1}). n = number of observations and y = mean
794 yield (kg ha^{-1}) in each terminal node.

795
796 Fig. 5. Regression tree showing the emerging drivers of the sunflower grain yield interannual
797 variation: meteorological variables (Tmean= mean monthly temperature, RAIN = monthly
798 precipitation; M = month from 6 -June to 8 -August) and management factors (T – Tillage: CT=
799 conventional tillage, MT = minimum tillage; NT = no tillage). n = number of observations and y =
800 mean yield (kg ha^{-1}) in each terminal node.

801
802 Fig. 6. Linear regression between grain yield and plants m^{-2} for maize as influenced by tillage
803 techniques. Data on plants m^{-2} are referred to nine years from 2002 to 2003, from 2006 to 2008 and
804 from 2011 to 2014.

805
806 Fig. 7. Regression tree showing the effect of emerging drivers of the maize grain yield interannual
807 variation: meteorological variables (Tmean= mean monthly temperature, RAIN = monthly
808 precipitation; M = month from 6 -June to 7 -July) and management factors (N - nitrogen
809 fertilization rate: 0, 90, 180 N kg ha^{-1} ; T – Tillage: CT= conventional tillage, MT = minimum

810 tillage; NT = no tillage). n = number of observations and y = mean yield (kg ha^{-1}) in each terminal
811 node.
812

813 Table 1. Number of days from the first of January (median, minimum and maximum) of the
814 agronomic management practices adopted during the experimental years.

Agro-technique	Durum wheat	Sunflower	Maize
Ploughing (40 cm) ^{CT}	285 (223-304)	250 (233-297)	249 (235-260)
Chisel (25 cm) ^{MT}	272 (228-291)	258 (242-306)	245 (231-312)
Harrowing and seed bed preparation ^{CT, MT}	303 (261-330)	73 (58-92)	94 (36-138)
P fertilization (70 kg P ₂ O ₅ ha ⁻¹)	319 (296-345)	69 (43-89)	92 (58-138)
Sowing *	327 (293-339)	90 (81-100)	103 (91-139)
Glyphosate application ^{NT} **	90 (70-122)	89 (91-101)	134 (99-172)
1 st N fertilization ***	67 (35-94)	115 (105-151)	126 (98-169)
2 nd N fertilization ***	101 (76-116)	-	-
Harvest	188 (178-197)	251 (235-276)	274 (255-283)

815 CT: Conventional tillage; MT: Minimum tillage; NT: No-tillage

816 * Seed rate: 220 kg ha⁻¹ for durum wheat; 75,000 seeds ha⁻¹ for both sunflower and maize.

817 Row spacing: 0.17 for durum wheat; 0.50 m for both sunflower and maize.

818 ** at a rate of 2.25 kg ha⁻¹ of active ingredient

819 *** for durum wheat 50 % of N distribution for each date. N source: urea

820

821

822 Table 2. Annual variability of the monthly statistically significant meteorological variables selected
 823 by ctrees tool for the three studied crops. Period of observation: 1994-2014. Tmean= mean monthly
 824 temperature (°C), Rain = monthly precipitation (mm), ET0 = cumulated monthly reference
 825 evapotranspiration (mm), M = Month from 1 (January) to 8 (August).

Year	M1_Tmean	M5_Tmean	M6_Tmean	M7_Tmean	M4_Rain	M7_Rain	M8_Rain	M4_ET0	M6_ET0
1994	7.0	17.2	20.8	24.3	77.6	68.6	4.4	91.6	147.2
1995	5.8	16.9	19.4	24.5	93.4	40.8	97.6	93.0	152.5
1996	6.0	17.5	22.2	23.3	82.0	28.2	181.2	95.0	165.5
1997	6.0	18.4	22.4	23.6	103.6	27.8	67.8	92.4	158.1
1998	5.7	17.1	23.2	26.0	95.0	14.8	24.0	91.1	157.5
1999	7.0	19.7	22.5	24.3	87.6	54.4	39.2	86.5	143.8
2000	4.7	19.7	22.9	23.5	51.2	53.8	15.2	87.5	162.5
2001	7.4	18.8	21.8	25.1	82.6	4.4	67.8	91.1	156.7
2002	4.5	18.4	23.3	23.9	67.8	94.4	78.8	83.4	164.9
2003	6.2	19.5	26.2	26.9	29.0	14.2	43.4	89.8	166.9
2004	5.3	15.9	21.7	25.1	75.6	12.8	18.0	75.6	139.4
2005	4.8	18.8	22.0	25.0	73.6	45.0	77.6	92.6	147.7
2006	4.1	18.4	22.4	25.0	109.8	51.4	95.0	89.8	147.5
2007	9.5	20.0	23.8	27.1	30.0	1.0	89.2	111.1	152.7
2008	7.5	18.9	23.2	26.0	95.4	38.0	1.4	102.8	155.0
2009	5.7	21.2	22.4	25.8	70.8	26.6	24.4	90.5	143.3
2010	4.4	18.2	22.0	25.6	90.2	17.2	79.4	89.3	151.0
2011	5.1	18.4	22.8	24.4	48.6	50.2	0.2	108.2	152.1
2012	6.5	16.8	21.3	28.1	114.0	6.8	35.8	95.2	152.3
2013	7.0	17.6	21.6	24.6	28.6	23.2	19.4	90.3	135.2
2014	9.2	17.7	22.5	23.4	79.0	108.4	4.4	79.2	138.7
Mean	6.2	18.3	22.4	25.0	75.5	37.2	50.7	91.7	151.9
SD	1.5	1.3	1.3	1.3	25.4	28.4	44.7	8.2	9.0

826

827

828 Table 3. Results of the repeated measures mixed model for durum wheat traits. Bold numbers in
829 columns indicate significant P values (≤ 0.05) of the F tests.

Factors	df	Grain yield	df	Spikes m ⁻²	nr. kernels per spike	100 kernels weight
Tillage (T)	2	0.11	2	0.05	0.05	0.17
N rate (N)	2	<0.01	2	0.11	<0.01	0.02
Year (Y)	19	<0.01	12	<0.01	<0.01	<0.01
T x N	4	0.09	4	0.88	0.26	0.16
T x Y	38	<0.01	24	0.34	0.05	0.02
N x Y	38	<0.01	24	0.06	<0.01	<0.01
T x N x Y	76	0.76	48	0.59	0.11	0.16
CV (%)		12		11	9	2

830

831

832 Table 4. Durum wheat grain yield (kg ha⁻¹) as influenced by tillage and N fertilization systems over
833 twenty years.

Year	Tillage			N fertilization		
	CT	MT	NT	N0	N1	N2
1995	2907 a	2674 a	2253 b	1585 b	3069 a	3181 a
1996	2613 a	2033 b	2073 b	1078 c	2585 b	3057 a
1997	3299 a	3106 ab	3015 b	1417 c	3505 b	4497 a
1998	2904 a	2878 a	2890 a	1422 c	3404 b	3846 a
1999	2294 a	2081 a	1688 b	1088 c	2206 b	2769 a
2000	2244 a	2132 a	2028 a	930 c	2529 b	2943 a
2001	1748 ab	2017 a	1638 b	1036 b	2291 a	2077 a
2002	3778 a	3219 b	2371 c	2168 c	3315 b	3885 a
2003	2793 ab	2679 b	3154 a	1379 c	3331 b	3917 a
2004	5003 a	3932 b	4435 ab	2536 b	4910 b	5924 a
2005	3285 a	3440 a	3217 a	2103 b	3717 a	4122 a
2006	3852 a	3205 b	3420 b	1779 c	3585 b	5113 a
2007	2265 a	1822 b	1478 c	570 c	1912 b	3082 a
2008	3181 a	2954 ab	2546 b	1414 c	2951 b	4316 a
2009	2812 b	3354 a	3700 a	1493 c	3831 b	4543 a
2010	3573 a	3504 a	2752 b	1029 c	3360 b	5439 a
2011	2103 b	2968 a	2449 ab	1582 c	2541 b	3397 a
2012	2906 a	3073 a	3513 a	1511 c	3122 b	4860 a
2013	1252 b	1742 a	1306 b	972 b	1540 a	1788 a
2014	2123 a	2259 a	2379 a	986 c	2430 b	3345 a
Mean	2847	2754	2615	1404	3007	3805

834 Means within a row for tillage and N fertilization factors separately that are followed by the same letter
835 are not significantly different at $P \leq 0.05$.

836

837 Table 5. Correlation coefficients among wheat grain yields and selected monthly meteorological
838 variables.

	ALL	N2	N1	N0	CT	MT	NT
M1_Tmean	-0.30 ***	-0.43 ***	-0.52 ***	-0.52 ***	-0.29 *	-0.32 *	-0.30 *
M3_Tmean	-0.20 **	-0.30 *	-0.34 **	-0.34 **	-0.23	-0.15	-0.23
M3_RAIN	-0.16 *	-0.14	-0.37 **	-0.31 *	-0.18	-0.11	-0.20
M4_Tmean	-0.20 **	-0.23	-0.43 ***	-0.35 **	-0.25	-0.16	-0.19
M4_RAIN	0.23 **	0.43 ***	0.36 **	0.24	0.24	0.20	0.24
M4_ET0	-0.18 *	-0.20	-0.37 **	-0.32 *	-0.20	-0.12	-0.21
M5_Tmean	-0.15 *	-0.20	-0.22	-0.33 *	-0.18	-0.11	-0.15

839 where ALL = yields of all treatments; N2, N1, N0 = yields for 180, 90, 0 kg N ha⁻¹; CT= yields for
840 conventional tillage; MT = yields for minimum tillage; NT = yields for no tillage; M = Month from 1
841 (January) to 5 (May).

842 *: significant at $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.

843

844 Table 6. Results of the repeated measures mixed model for sunflower traits. Bold numbers in columns
 845 indicate significant P values (≤ 0.05) of the F tests.

Factors	df	Grain yield	Plants m ⁻²	Achenes weight per flower head	1,000 achenes weight
Tillage (T)	2	0.01	<0.01	0.14	0.06
N rate (N)	2	0.10	0.69	0.04	0.05
Year (Y)	6	<0.01	<0.01	<0.01	0.01
T x N	4	0.61	0.91	0.33	0.42
T x Y	12	<0.01	<0.01	<0.01	<0.01
N x Y	12	0.66	0.74	0.88	0.10
T x N x Y	24	0.97	0.93	0.77	0.03
CV (%)		17	14	17	7

846

847

848

849 Table 7. Sunflower grain yield (kg ha⁻¹) as influenced by tillage and N fertilization systems over seven
850 years.

Year	Tillage			N fertilization		
	CT	MT	NT	N0	N1	N2
1995	1366 a	564 b	415 b	653	804	887
1996	883 a	640 b	266 c	593	599	597
1997	1419 a	1138 b	1374 ab	1179	1390	1362
1998	3270 a	3106 a	1982 b	2415	3037	2906
1999	2350 a	2113 a	1327 b	1641	1931	2218
2000	1888 a	1789 a	457 b	1219	1401	1514
2001	1271 a	1339 a	498 b	860	1040	1207
Mean	1778	1527	903	1223	1457	1527

851 Means within a row for the tillage factor that are followed by the same letter are not significantly
852 different at $P \leq 0.05$.

853

854 Table 8. Correlation coefficients among sunflower grain yields and selected monthly meteorological
855 variables.

	ALL	N2	N1	N0	CT	MT	NT
M4_Tmean	0.29 *	0.32	0.28	0.29	0.45 *	0.50 *	-0.07
M4_Rain	0.11	0.09	0.13	0.10	0.05	-0.06	0.46 *
M5_ET0	-0.38 **	-0.40	-0.40	-0.36	-0.52 *	-0.47 *	-0.25
M6_Tmean	0.47 ***	0.46 *	0.47 *	0.50 *	0.44 *	0.65 **	0.45 *
M6_ET0	-0.30 *	-0.37	-0.28	-0.26	-0.38	-0.26	-0.39
M7_Tmean	0.54 ***	0.55 **	0.58 **	0.52 *	0.64 **	0.62 **	0.54 *
M8_Tmean	0.43 ***	0.47 *	0.42	0.42	0.46 *	0.68 ***	0.23
M8_Rain	-0.46 ***	-0.51 *	-0.45 *	-0.44 *	-0.53 *	-0.63 **	-0.35
M8_ET0	0.20	0.15	0.24	0.22	0.16	0.03	0.57 **

856 where ALL = yields of all treatments; N2, N1, N0 = yields for 180, 90, 0 kg N ha⁻¹; CT= yields for
857 conventional tillage; MT = yields for minimum tillage; NT = yields for no tillage; M = Month from 1
858 (January) to 5 (May).

859 *: significant at $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.

860

861 Table 9. Results of the repeated measures mixed model for maize traits. Bold numbers in columns
862 indicate significant P values (≤ 0.05) of the F tests.

Factors	df	Grain yield	df	Plants m ⁻²	100 grains weight
Tillage (T)	2	0.05	2	<0.01	0.09
N rate (N)	2	<0.01	2	0.26	0.67
Year (Y)	12	<0.01	8	<0.01	<0.01
T x N	4	0.26	4	0.64	0.44
T x Y	22	<0.01	16	<0.01	<0.01
N x Y	24	0.02	16	0.02	0.41
T x N x Y	44	0.99	32	0.07	0.51
CV%		24		7	3

863

864

Table 10. Maize grain yield (kg ha⁻¹) as influenced by tillage and N fertilization systems over thirteen years

Year	CT	MT	NT	N0	N1	N2
2002	1612 a	881 b	1159 ab	715 b	1322 a	1614 a
2003	637 a	497 a	25 b	544 a	508 a	649 a
2004	1565 a	1757 a	854 b	1097 b	1428 ab	1651 a
2005	4453 a	2836 b	1791 c	2072 c	3073 b	3935 a
2006	2165 b	2798 a	1520 c	1330 b	1828 b	3325 a
2007	1256 a	792 b	28 c	545 c	1047 b	1479 a
2008	2064 a	2268 a	1918 a	1208 c	2250 b	2793 a
2009	3430 a	2903 b	2249 c	1883 c	2824 b	3876 a
2010	2032 b	2859 a	2358 ab	1523 c	2453 b	3273 a
2011	2320 a	2219 ab	1642 b	1222 c	2110 b	2849 a
2012	3778 b	4956 a	4919 a	3509 c	4556 b	5588 a
2013	1480 a	1549 a	661 b	611 b	1334 a	1745 a
2014	3810 b	4514 a	3667 b	2333 c	4379 b	5279 a
Mean	2354	2371	1489	1430	2307	2927

Means within a row for tillage and N fertilization factors separately that are followed by the same letter are not significantly different at $P \leq 0.05$.

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Table 11. Correlation coefficients among maize grain yields and selected monthly meteorological variables.

	ALL	N2	N1	N0	CT	MT	NT
M4_Tmean	-0.22 *	-0.21	-0.30	-0.25	-0.17	-0.26	-0.25
M4_ET0	-0.41 ***	-0.43 **	-0.50 **	-0.44 **	-0.25	-0.50 **	-0.48 **
M6_Tmean	-0.49 ***	-0.56 ***	-0.55 ***	-0.53 ***	-0.46 **	-0.53 ***	-0.51 ***
M6_Rain	0.22 *	0.32 *	0.22	0.17	0.24	0.28	0.17
M6_ET0	-0.28 **	-0.34 *	-0.33 *	-0.24	-0.30	-0.36 *	-0.20
M7_Rain	0.21 *	0.27	0.28	0.10	0.25	0.17	0.21
M8_ET0	-0.20	-0.24	-0.20	-0.10	-0.30 *	-0.10	-0.07

where ALL = yields of all treatments; N2, N1, N0 = yields for 180, 90, 0 kg N ha⁻¹; CT= yields for conventional tillage; MT = yields for minimum tillage; NT = yields for no tillage; M = Month from 1 (January) to 5 (May).
*: significant at $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.

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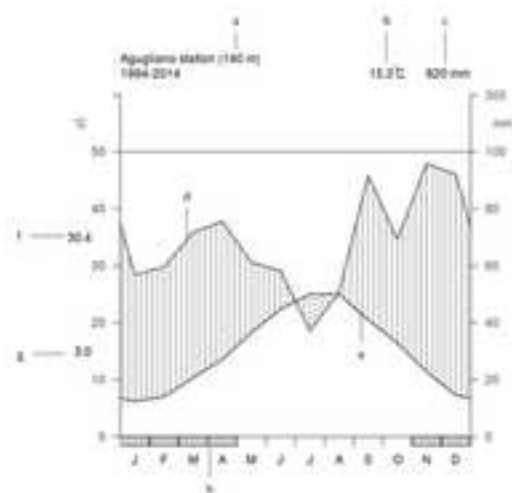


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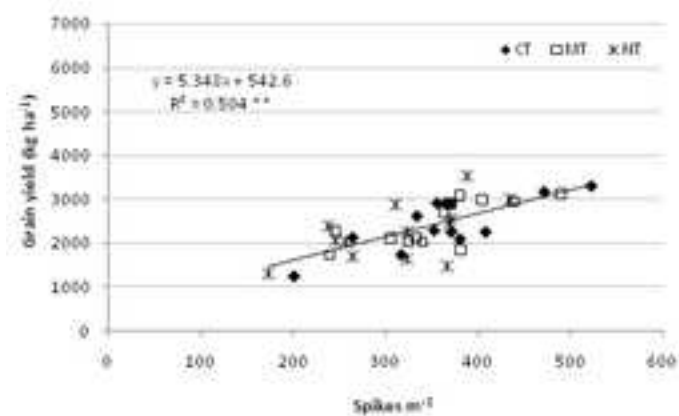


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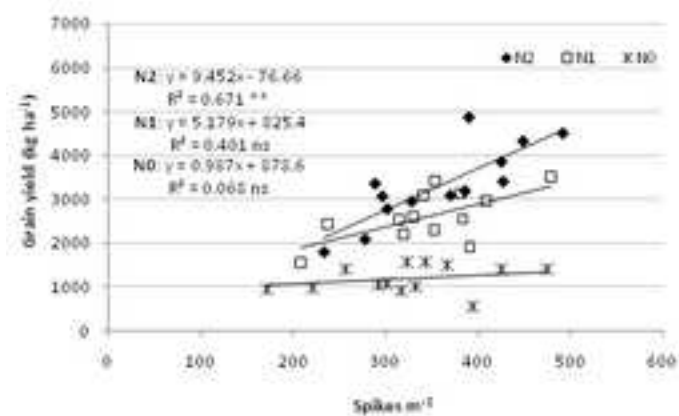


Figure 3

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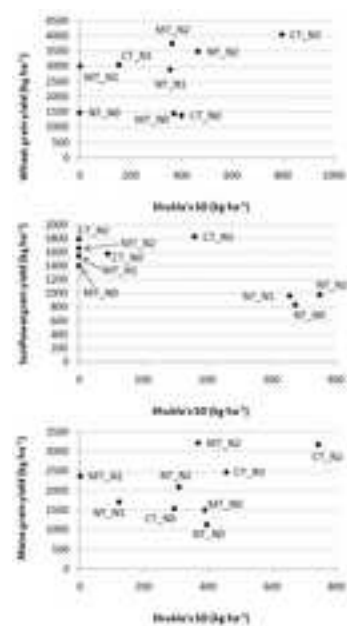


Figure 4

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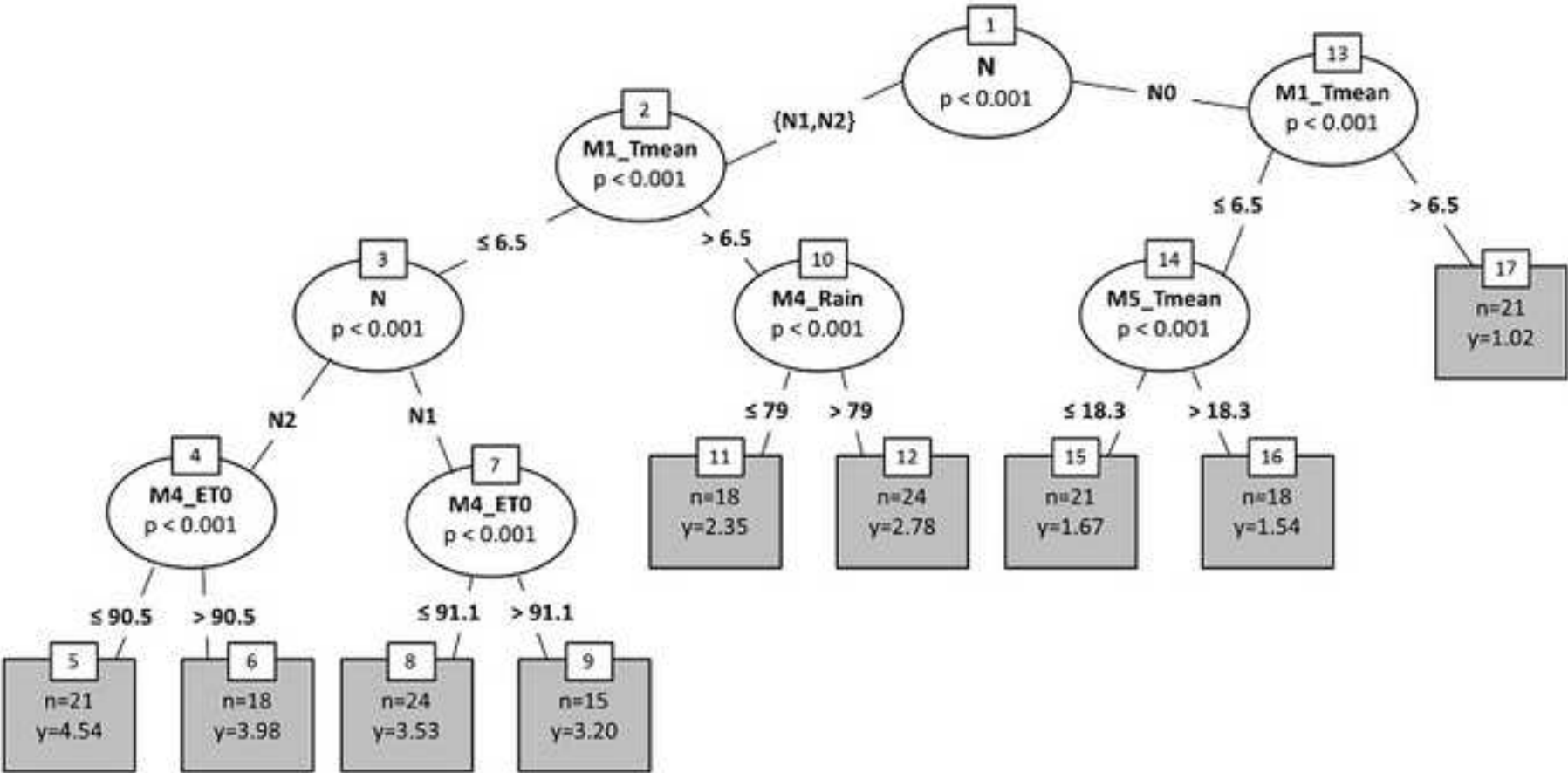


Figure 5
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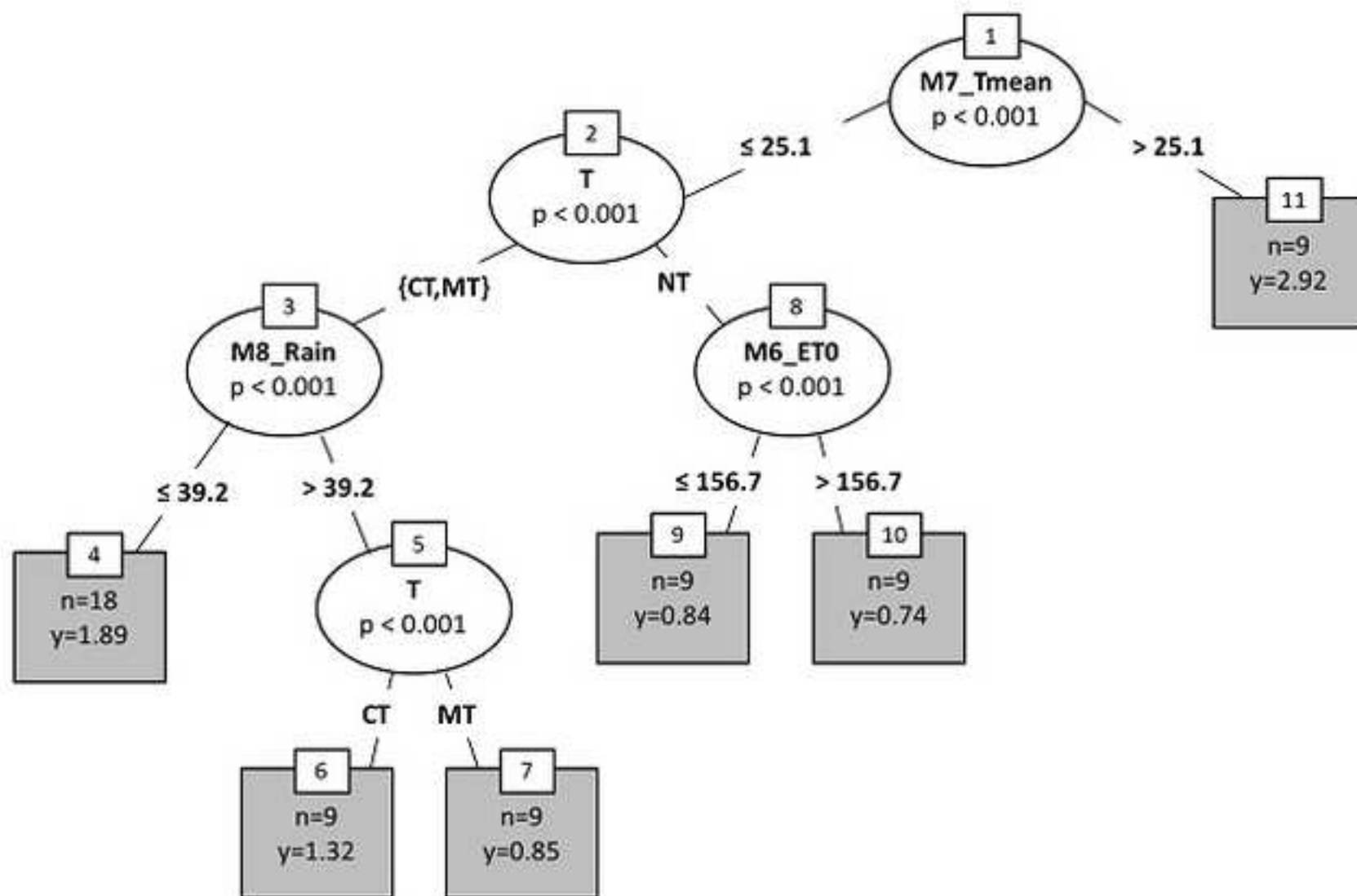


Figure 6

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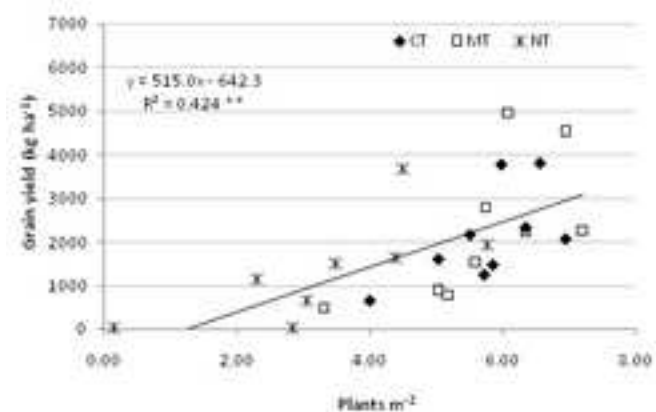


Figure 7
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