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

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ABSTRACT

Long term investigations on the combined effects of tillage systems and other agronomic practices such as mineral N fertilization under Mediterranean conditions on durum wheat are very scanty and findings are often contradictory. Moreover, no studies are available on the long term effect of the 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 = no tillage) 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 × 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 modelling.

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

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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 (López-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 semi-arid Mediterranean conditions, Amato et al. (2013) and Ruisi et al. (2014) showed that durum wheat yield was higher under no tillage than conventional tillage only when water stress was high and that N fertilizer requirements increase with no tillage compared with conventional tillage, because of changes in N cycling that lead to a reduction in plant-available soil N. Sunflower, together with other oilseed crops, is recently drawing a renewed commercial and scientific attention because of its role as energy crop in the cereal-based cropping systems (Barontini et al., 2015 and references therein). Under Mediterranean rainfed conditions, sunflower production is heavily constrained by summer water stress, hence it is practiced as a rainfed crop only in the clayey soil of the northern areas, where the spring-summer rainfall regime is favorable and soil water holding capacity can buffer crop water availability. Under Mediterranean rainfed conditions in southern Spain, CA did not exert a beneficial influence on sunflower grain yields (López-Bellido et al., 2003; Murillo et al., 1998), although a high interannual variability was observed, mainly influenced by soil water conditions throughout the crop cycle.

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

To our knowledge, no studies are available on the long term effect of conservation tillage on the productivity of rainfed maize and sunflower under Mediterranean conditions. The duration of such studies on sunflower ranged from one (Lopez-Garrido et al., 2014) to four years (López-Bellido et al., 2003). In the case of grain maize, the available long term studies on the role of tillage systems on yields are referred to a range of climate conditions, from a typical Northern-Central USA climate (Karlen et al., 2013), to the subhumid temperate climate in the Pampas of Argentina (Diaz-Zorita et al., 2002), to the semi-arid, subtropical climate of highlands of Central Mexico (Verhulst et al., 2011) and to the cold semi-arid and humid subtropical climate of Northern China (Wang et al., 2012), none of which comparable to the Mediterranean climate type.

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

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

In the context of rainfed cereal cropping systems of the clayey hills of central Italy, in approximately 300,000 ha of arable hillslope land, the rotation of wheat and a spring-summer crop such as sunflower or maize implies about 8–9 months of intercropping period between the wheat harvest (early July) and the seeding of sunflower (March) or maize (April). Because of the high soil clay content (up to 50%) and the seasonal ranfall/evapotranspiration regime, the main tillage under the conventional practice (i.e., 30–40 cm deep ploughing) is made in the summer, in order to exploit the structuring effect of thermal and water regimes in the soil during autumn–winter. Moreover, tillage practices during autumn may be difficult due to the high plasticity of the clayey soils when autumn is wet. Further harrowing is practiced during intercropping to prepare the maize or sunflower seedbed. Therefore, the conventional practice exposes the bare soil to soil erosion (Roggero and Toderi, 2002) and nitrate leaching (De Sanctis et al., 2009) during the wet and cool season. CA techniques including no tillage and reduced N fertilization rates can provide options to mitigate such undesirable processes, but are considered by farmers as not reliable enough to ensure yield targets and stability, particularly in the case of the spring–summer crops.

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

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

2. Materials and methods

2.1. Experimental site

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

The climate of the experimental site is Mediterranean (Fig. 1), with a mean annual rainfall of 820 mm, mostly distributed in the autumn and winter (54%) and in the spring (24%). The mean air

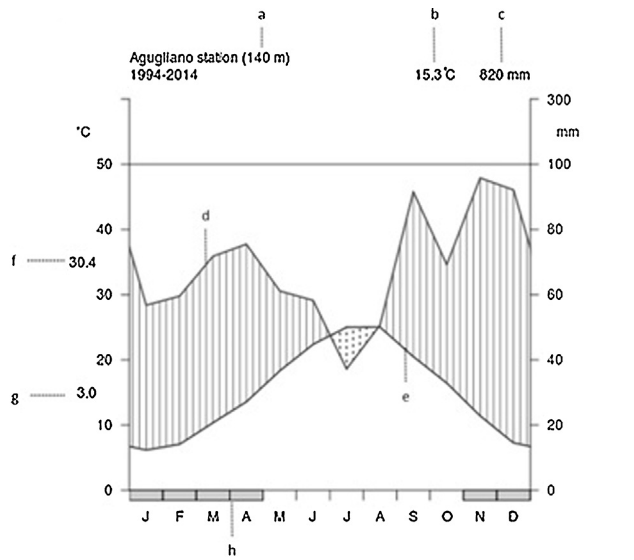

Fig. 1. Walter and Lieth climate diagram of Agugliano weather station. Period of observation: 1994–2014. (a) Elevation, (b) annual average of temperature, (c) annual average of precipitation, (d) monthly mean temperatures, (e) monthly mean precipitations, (f) mean daily maximum temperature of the warmest month, (g) mean daily minimum temperature of the coldest month, (h) indication of potential frost periods (months with absolute monthly minimum temperature below 0 °C). Vertical lines: humid period, dotted area: dry period.

temperature is 15.3 °C, with monthly means ranging from 6.2 °C in January to 25 °C in August. The mean annual evapotranspiration (ET0), estimated at daily basis over the 20-years period with the FAO Penman–Monteith formula by using the computer tool ET0Calculator (Annandale et al., 2002), was 1068 mm (standard deviation (SD) = 75 mm), producing an average aridity index (Rain/ETo) of 0.76 (SD = 0.16).

2.2. Experimental design and crop management

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

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

2.3. Measurements

At crop maturity, grain yield for all the studied crops was measured in each plot through combine harvesters and it was expressed on a dry matter content basis. Twenty (1995–2014), seven (1995–2001) and thirteen (2002–2014) years of grain yield data were collected respectively for durum 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.

2.4. Data analyses

All data were submitted to the PROC MIXED procedure in SAS (SAS Institute, 1999), suitable for analyzing mixed effects and repeated measures with non-constant variance and any covariance structure models. The independence assumption on the error terms required for the ANOVA of a factorial model (Montgomery, 1997) was in fact likely not met. The appropriate mixed model was built following Onofri et al., 2016 and considering “year” as a repeated factor and for each year, tillage (T) and N fertilisation (N) as randomised treatment factors. The appropriate variance–covariance structure for this particular model was selected fitting all possible models and making an ‘a posteriori’ selection, based on those statistics which put a penalty on ‘complexity’, such as the Akaike Information Criterion (AIC: Akaike, 1974). For assessing the yield stability over the experimental years, the Shukla’s (1972) stability variance was calculated by applying the R code reported by Onofri et al., 2016. The closer to zero is the Shukla’s stability variance the more stable is the yield. We tested the null hypothesis of any grain yield trend over time associated to the repeated T and N fertilization treatments by fitting a simple linear regression of yield vs. years as suggested by Piepho et al. (2014) The treatment (T × N) effect was regarded as fixed as well as the treatment-dependent slopes, while the year effect and the year × treatment interactions as random. The robustness of this analysis increases with the duration of the experiment (Onofri et al., 2016), hence is higher for the durum wheat experiment than for maize (13-years trial). For this reason, this analysis was not performed for sunflower.

For all the studied crops, three agro-meteorological variables were calculated and analysed on monthly basis starting from sowing until crop harvest: mean temperature (Tmean), rainfall amount (Rain) and cumulated reference evapotranspiration (ET0). Linear correlation coefficients (Pearson *r*) were then used to determine the effect of each meteorological variable on yields considering both yields of all treatments and yields related to each singular management factor (CT, MT, NT and N0, N1, N2). Only the meteorological variables that were statistically significant in at least one treatment, together with the categorical factors T and N, were submitted as

Table 1
Number of days from the first of January (median, minimum and maximum) of the 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_2O_5 ha^{-1})	319 (296–345)	69 (43–89)	92 (58–138)
Sowing[a]	327 (293–339)	90 (81–100)	103 (91–139)
Glyphosate application [NTb]	90 (70–122)	89 (91–101)	134 (99–172)
1st N fertilization[c]	67 (35–94)	115 (105–151)	126 (98–169)
2nd N fertilization[c]	101 (76–116)	–	–
Harvest	188 (178–197)	251 (235–276)	274 (255–283)

CT: Conventional tillage; MT: Minimum tillage; NT: No-tillage.
Row spacing: 0.17 m for durum wheat; 0.50 m for both sunflower and maize.
[a] Seed rate: 220 kg ha^{-1} for durum wheat; 75,000 seeds ha^{-1} for both sunflower and maize.
[b] At a rate of 2.25 kg ha^{-1} of active ingredient.
[c] For durum wheat 50% of N distribution for each date. N Source: urea.

Table 2
Annual variability of the monthly statistically significant meteorological variables selected by ctree tool for the three studied crops. Period of observation: 1994–2014.

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

Tmean = mean monthly temperature (°C), Rain = monthly precipitation (mm), ET0 = cumulated monthly reference evapotranspiration (mm), M = Month from 1 (January) to 8 (August).

inputs in a recursive partitioning analysis. The inter-annual variability of these variables is shown in Table 2. The recursive partition explores the structure of a dataset, developing decision rules for predicting a categorical (classification tree) or continuous (regression tree) variable (Rokach and Maimon, 2008; Strobl et al., 2009). In our study, we used the regression tree function *ctree* available in the *party* R package (Hothorn et al., 2006) to explore the variation of yield as influenced by several explanatory (meteorological and management) variables. Regression trees are constructed by recursively splitting the response variable (i.e., grain yield) into two groups on the basis of the explanatory variables (Tmean, Rain, ET0) so as to minimize variability within a group and maximizing variability between groups. At the end, the terminal node (leaves) is characterized by the mean values of the response variable. *Ctree* function bases its node splitting on statistical tests providing a *P* value for the significance of its splitting. Although *ctree* was used in this study just to explore the interactions among explanatory variables and not as a predictive tool, we estimated anyway the performance of the regression using the root-mean-square error (RMSE) and the mean absolute error (MAE).

RMSE was calculated as:

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

and MAE was given by:

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

where y_{obs} is the observed crop yield, y_{model} is the modelled yield at year$_i$ and n is the number of observations.

3. Results

3.1. Durum wheat yield, yield components and yield stability

Significant year × T and year × N interactions were observed, while no significant T × N interaction was observed (Table 3). Grain yields ranged from 1.3 (CT 2004) to 5.0 t ha^{-1} (CT 2013) and from 0.6 (N0 2007) to 5.9 t ha^{-1} (N2 2004). Grain yield under NT was significantly higher than CT in one out of twenty years, while CT and NT were not significantly different in ten out of twenty years (Table 4). MT differed significantly from CT in eight out of twenty

Table 3
Results of the repeated measures mixed model for durum wheat traits. Bold numbers in 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 × N	4	0.09	4	0.88	0.26	0.16
T × Y	38	**<0.01**	24	0.34	**0.05**	**0.02**
N × Y	38	**<0.01**	24	0.06	**<0.01**	**<0.01**
T × N × Y	76	0.76	48	0.59	0.11	0.16
CV (%)		12		11	9	2

Table 4
Durum wheat grain yield (kg ha^{-1}) as influenced by tillage and N fertilization systems over 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

Means within a row for tillage and N fertilization factors separately that are followed by the same letter are not significantly different at $P \leq 0.05$. N2, N1, N0 = 180, 90, 0 kg N ha^{-1}; CT = conventional tillage; MT = minimum tillage; NT = no tillage.

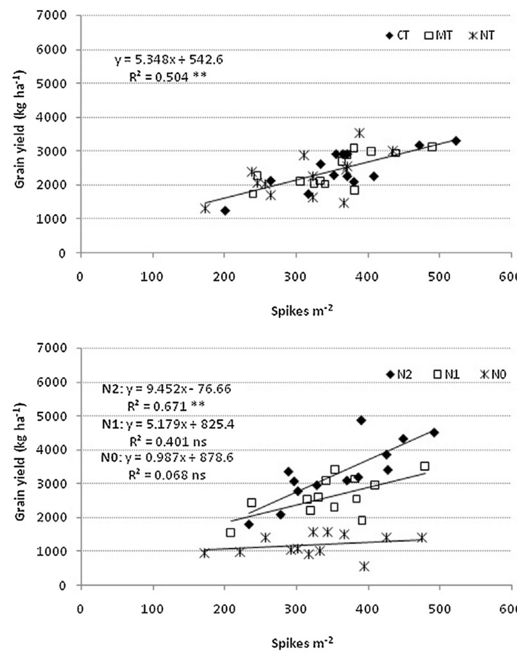

Fig. 2. Relationships between mean grain yield and spikes m^{-2} for durum wheat as influenced by tillage techniques (top) or by N fertilization rates (bottom). Data on spikes m^{-2} are referred to thirteen years from 1995 to 2001, from 2007 to 2008 and from 2011 to 2014.

years being significantly higher and lower in three and five years respectively. Wheat grain yields were higher under MT than NT in seven out of twenty years throughout the experiment. N2 showed higher grain yields than N1 in sixteen out of twenty years. Among the four years with no significant differences between N2 and N1, two years were the least productive ones.

On average, NT resulted in lower spikes m^{-2} than MT and CT by about −13% (313 vs. 359). A significant relationship was found between spikes m^{-2} and grain yield independently of the tillage treatment averaged for all N levels, while the same relationship was significant only for N2 (Fig. 2).

The number of kernels per spike and the 100 kernels weight were significantly influenced by the tillage × year and nitrogen × year interactions (Table 3). The number of kernels per spike ranged between 21 and 42 with NT showing a slight higher value than CT and MT (33 vs. 29). In 70% of the years when the number of kernels per spike was determined, N2 had about 6 kernels per spike more (+20%) than N1.

In about half of the years, 100 kernels weight showed significant higher values under NT than CT.

The stability analysis (Fig. 3) showed that the most productive treatment (CT_N2) was the least stable in terms of grain yield, while CT_N1 and, even more, MT_N1 characterized by intermediate yields were the most stable. Also NT_N0 had very stable grain yields that were however associated to low yields. No significant time trend was found for grain yield for any of the T × N fertilization combinations.

The correlation analysis between the meteorological variables and grain yield selected the following significant variables (Table 5): mean temperature of January (M1_Tmean), mean temperature (M3_Tmean) and rainfall (M3_RAIN) of March, mean temperature (M4_Tmean), rainfall (M4_RAIN) and reference evapotranspiration (M4_ET0) of April and mean temperature of May (M5_Tmean).

The decision tree obtained considering these significant meteorological variables, together with T and N factors, is reported in Fig. 4. The first important factor was N fertilization, with N0 associated to the lowest yields. M1_Tmean was the second most important factor independently of the N fertilization rate, and 6.5 °C represented the partitioning threshold. The group identified by N2 and N1 and M1_Tmean ≤ 6.5 °C was further split according to the N fertilization rate and both subgroups obtained were divided by a M4_ET0 value of 91 mm. Other important meteorological factors were M4_Rain for the group firstly identified by N2 and N1 and M1_Tmean > 6.5 °C, and the M5_Tmean for the group identified by N0 and M1_Tmean ≤ 6.5 °C. The lowest wheat grain yield was associated to N0 and M1_Tmean > 6.5 °C, while the highest yield to M1_Tmean ≤ 6.5 °C, N2 and M4_ET0 ≤ 91 mm. The two indicators of the model performance RMSE and MAE were respectively 694 kg ha^{-1} and 525 kg ha^{-1}. Similarly to what found with the mixed model analysis, the effect of tillage on wheat grain yield was not significant also for the decisional tree approach.

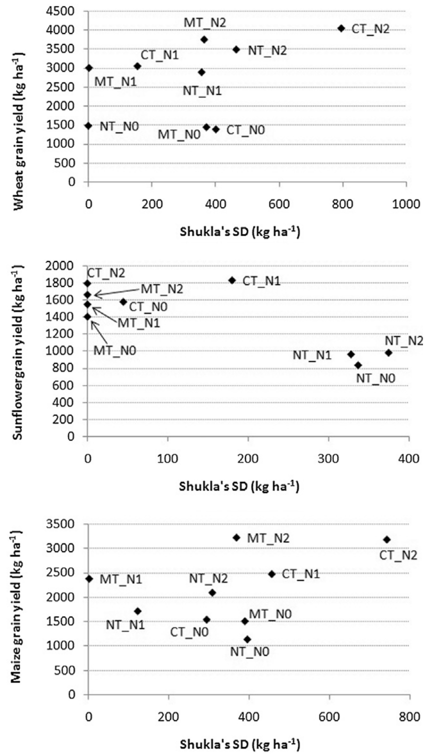

Fig. 3. Relation between yield and yield stability (Shukla SD) for durum wheat (top), sunflower (middle) and maize (bottom).

Table 5
Correlation coefficients among durum wheat grain yields and selected monthly meteorological 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	

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 $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.

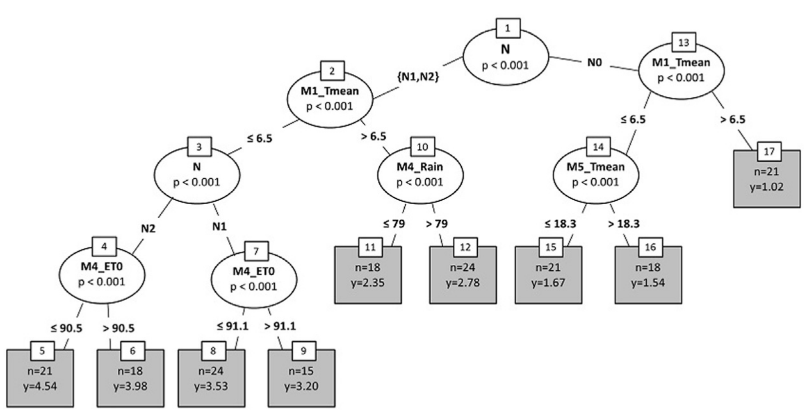

Fig. 4. Regression tree showing the emerging drivers of the durum wheat grain yield interannual variation: meteorological variables (Tmean = mean monthly temperature, RAIN = monthly precipitation, ET0 = cumulate monthly reference evapotranspiration; M = month from 1-January to 5-May) and N fertilization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

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

Factors	df	Grain yield	Plants m^{-2}	Achenes weight per flower head	1000 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 × N	4	0.61	0.91	0.33	0.42
T × Y	12	**<0.01**	**<0.01**	**<0.01**	**<0.01**
N × Y	12	0.66	0.74	0.88	0.10
T × N × Y	24	0.97	0.93	0.77	0.03
CV (%)		17	14	17	7

Table 7
Sunflower grain yield (kg ha^{-1}) as influenced by tillage and N fertilization systems over seven 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

Means within a row for the tillage factor that are followed by the same letter are not significantly different at $P \leq 0.05$. N2, N1, N0 = 180, 90, 0 kg N ha^{-1}; CT = conventional tillage; MT = minimum tillage; NT = no tillage.

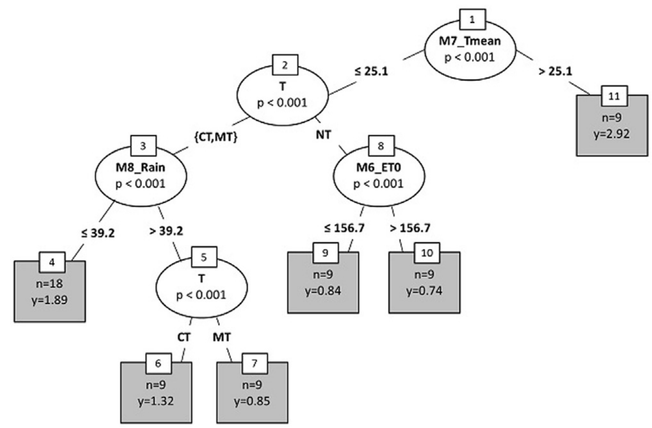

Fig. 5. Regression tree showing the emerging drivers of the sunflower grain yield interannual variation: meteorological variables (Tmean = mean monthly temperature, RAIN = monthly precipitation; M = month from 6-June to 8-August) and management factors (T—Tillage: CT = conventional tillage, MT = minimum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

3.2. Yield, yield components and yield stability in sunflower

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

Plants m^{-2}, achenes weight per flower head and the 1000 achenes weight showed a significant T × year interaction (Table 6). On average (data not shown), under NT the number of plants per m^{-2} were lower by 54% than CT (2.6 vs 5.6). In two out of seven years (1996 and 1998), the number of plants per m^{-2} under NT was more than 80% lower than under CT. Under MT, plant density was significantly lower than under CT in six out of seven years, on average −12% (from −3 to −18%), while it was slightly higher only in 1998.

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

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

The correlation analysis between sunflower grain yields and the meteorological variables selected the following significant variables (Table 8): mean temperature (M4_Tmean) and precipitation (M4_Rain) of April, the reference evapotranspiration of May (M5_ET0), the mean temperature (M6_Tmean) and reference evapotranspiration of June (M6_ET0), mean temperature of July (M7_Tmean), mean temperature (M8_Tmean), precipitation (M8_Rain) and reference evapotranspiration (M8_ET0) of August.

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

3.3. Yield, yield components and yield stability in maize

Maize grain yield showed an irregular pattern over the thirteen years period ranging from very low values (2003 and 2007 for NT) up to 5.0 t ha^{-1} (2012 for MT). The interactions between both year × T and year × N were significant (Table 9). In 2003 and 2007, grain yields under NT were almost zero, due to the very low plant density that did not allow mechanical harvest (Table 10). In more than half of the years, NT showed a lower yield than CT (−40%). MT differed significantly from CT in eight out of thirteen years being significantly higher and lower in four years respectively.

N2 showed comparable grain yields to N1 in 30% of years. N1 in none of the years showed significantly higher yield than N2.

In terms of plants m^{-2}, NT showed always lower values (3.4 plants m^{-2}) by about −45% (from −20% to −96%) compared to CT and MT (data not shown). Plant density was positively correlated with grain yield (Fig. 6) with data grouped by T treatments. By considering the relationship with data grouped by N treatments, a weaker correlation was found (r = 0.54, P = 0.003).

The 100 grains weight was significantly influenced by T × year interaction (Table 9) and ranged from 7.7 g (MT 2014) to 24.1 g (NT 2008) with a mean of 18.5 g. No significant differences were found

Table 8
Correlation coefficients among sunflower grain yields and selected monthly meteorological 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	**

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 4 (April) to 8 (August).
*: significant at $P \le 0.05$; **: $P \le 0.01$; ***: $P \le 0.001$.

among T treatments along the experimental period with the exception of 2008 when 100 grains weight was +11% higher in NT than in CT and MT.

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

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

The significant meteorological variables and the management factors (T and N) were used for obtaining the conditional regression tree for maize yield reported in Fig. 7. The meteorological variables explaining most the yield performances in maize were M6_Tmean (threshold values ranging from 22.0 to 23.3 °C) and M7_Rain (50.2 mm). Both management factors were found to be significant. The lowest maize grain yield was associated to M6_Tmean > 23.2 °C and MT and NT practices, while the highest values to M6_Tmean ≤ 23.2 °C, N2 or N1 and M7_Rain > 50.2 mm. RMSE and MAE obtained with the regression tree for maize were respectively 936 kg ha^{-1} and 785 kg ha^{-1}. According to the mixed model analysis, also this decisional tree found that both T management and N fertilization rates were significant for maize yield.

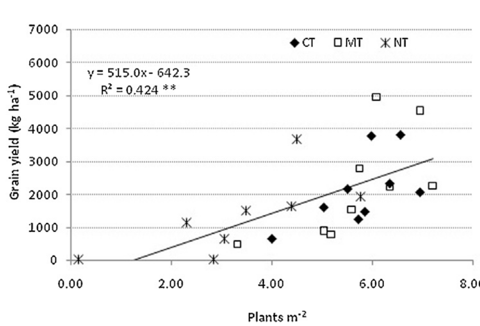

Fig. 6. Linear regression between grain yield and plants m^{-2} for maize as influenced by tillage techniques. Data on plants m^{-2} are referred to nine years from 2002 to 2003, from 2006 to 2008 and from 2011 to 2014.

Table 9
Results of the repeated measures mixed model for maize traits. Bold numbers in columns 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 × N	4	0.26	4	0.64	0.44
T × Y	22	**<0.01**	16	**<0.01**	**<0.01**
N × Y	24	**0.02**	16	**0.02**	0.41
T × N × Y	44	0.99	32	0.07	0.51
CV%		24		7	3

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 $P \le 0.05$. N2, N1, N0 = 180, 90, 0 kg N ha^{-1}; CT = conventional tillage; MT = minimum tillage; NT = no tillage.

4. Discussion

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

Our results show that NT did not provide any substantial advantage or disadvantage to durum wheat grain yield in comparison to CT or MT. This finding is consistent to the evidences reported in the European meta-analysis by Van den Putte et al. (2010), showing an average grain yield of −8.5% for NT compared to CT. Similarly, in a 16-years long term experiment made in Central Italy on poorly drained silt-loam soil, Mazzoncini et al. (2008) reported a mean loss of wheat grain yield of −8.9% under NT vs. CT. Lopez-Bellido et al. (2000, 2001) and De Vita et al. (2007), in the Vertisols of Spain and Italy respectively, found that wheat under CT performed better only in the wet years, while in the dry years, wheat grain yield was higher under NT. Our results do not confirm these findings and our interpretation is that we rarely experienced extremely

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 4 (April) to 8 (August).
*: significant at $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.

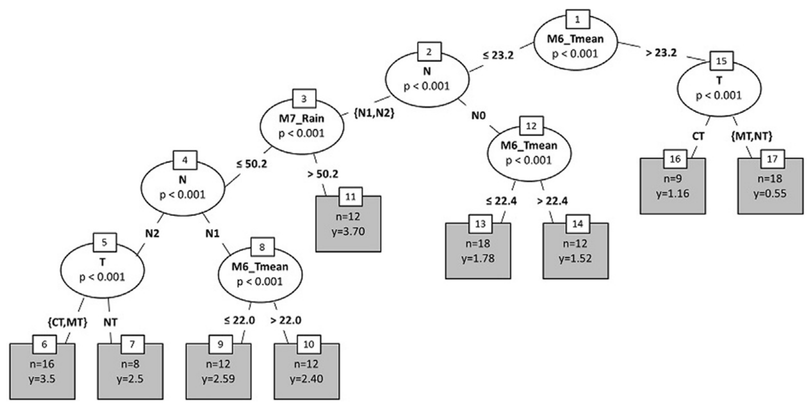

Fig. 7. Regression tree showing the effect of emerging drivers of the maize grain yield interannual variation: meteorological variables (Tmean = mean monthly temperature, RAIN = monthly precipitation; M = month from 6-June to 7-July) and management factors (N—nitrogen fertilization rate: 0, 90, 180 N kg ha^{-1}; T—Tillage: CT = conventional tillage, MT = minimum tillage; NT = no tillage). n = number of observations and y = mean yield (t ha^{-1}) in each terminal node.

dry years (i.e. less than 350 mm of rainfall during the wheat cycle) and because the soil of the experimental field was not a Vertisol, which would have been characterized by self-structuring capacity. In a 20-years experiment carried out on a Vertisol, under semiarid Mediterranean conditions, Ruisi et al. (2014) did not observe significant differences between CT and NT, although they also found a tendency for NT to guarantee superior grain yields under water stress conditions during the crop cycle. However, similarly to our findings, Ruisi et al. (2014) found a great interannual variability in durum wheat productivity, that they interpreted as mainly associated to the interactions between tillage and other agronomic factors, in particular crop sequence. A yield superiority of NT compared to CT was in fact observed only when wheat was grown in a 2-years rotation, while, when grown continuously, it performed better under CT. In our experiment, the 2-years rotation of wheat with a spring crop might have contributed to prevent from the potential progressive increased incidence of pests and diseases, which are often the main drivers causing differences between tillage systems under monocropping. It is interesting to highlight that durum wheat grain yield under NT did not show any significant increasing trend over time, although in the same LTE, De Sanctis et al. (2012) measured an increment of soil organic matter in the top soil in the first twelve experimental years. The possible positive effects on soil quality due to no tillage, as improved water retention (De Vita et al., 2007), aggregation stability (Hernanz et al., 2002), improved biological and biochemical soil processes (Acosta-Martinez and Tabatabai, 2001) did not result into a higher crop productivity.

Soil compaction is also an important constraint for wheat grain yield under NT, as documented in the same LTE by Pastorelli et al. (2013). The negative effects of soil compaction on root development and tillering are well documented (e.g., Atwell, 1990) and confirmed by the lower number of spikes m^{-2} under NT in our experiment (−14% with respect to CT). However, this seems in contrast to the findings of other scholars who measured similar soil bulk density and root density values under NT and CT (e.g., Munoz-Romero et al., 2010; Plaza-Bonilla et al., 2014) but on Vertisols, where the self-structuring nature and the better soil water conditions allow sufficient conditions for root growth and tillering also under NT (e.g., López-Bellido et al., 2007).

The most relevant factor influencing wheat yield was N fertilization, which provided an advantage of about +30% in terms of grain yield when doubling the N rate from 90 to 180 kg ha^{-1} N. In southern Spain, also Lopez-Bellido et al. (2001) reported a more significant impact of N fertilization than tillage on grain yield, with no additional response to N fertilizer at rates above 100 kg ha^{-1}. In our study, grain yields were more stable with 90 kg N ha^{-1} than with 180 kg N ha^{-1}. Therefore, the decision about the about the optimal N fertilizer rate to adopt will depend on the specific farming system context and associated trade-offs between productivity and stability targets.

The second important driver influencing the grain yield, as resulted from the decisional tree analysis, was the mean temperature of January. Low temperatures at early developmental stages (as it is in January in the experimental site) and in particular when plants are at the tillering stage, might delay the crop development determining an increase of the tillering duration. A greater number of tillers can lead therefore to a greater potential numbers of spikes m^{-2} and, hence, to a higher yield (Kazmi and Rasul, 2012). When N was not a limiting factor, the water availability in April, which depends on rainfall and evapotranspiration, was a key driver for grain yields. The earing and anthesis occurred mainly in April and these are the most critical phases in wheat for yield (Ozturk and Aydin, 2004; Wheeler et al., 1996; Albrizio et al., 2010). A water stress in this period could have reduced the number of kernels per spike, leading to a significant reduction of grain yield. A significant sensitivity of durum wheat to high air temperature and water stress in April and May was also observed by Campiglia et al. (2015) who carried out a 6-years trial under similar soil and climate conditions to our study. They highlighted a different level of sensitivity to rainfall in spring depending also on the soil N availability associated to the compared cropping systems. This finding is consistent to the results of the decisional tree analysis that revealed a key role of April rainfall in constraining grain yield under sufficient N fertilizer application. In spring, the N availability is a main driver of the aerial biomass production and leaf area, hence under no limiting soil N, wheat may become more vulnerable to water stress and, at the same time, more able to exploit the benefits of water availability (Sadras et al., 2012) than an unfertilized crop. When N was not supplied, only air temperature in May, together with air temperature in January, were the main grain yield constraints. The grain filling period started during May. High temperatures throughout this stage, affecting kernel weight and accelerating grain maturity (Monpara, 2011), may lower grain yield. Overall, temperature in the early growth stages, soil moisture during flowering and anthesis and their interaction with N nutrition explained most of the inter-annual durum wheat yield variability.

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

The most important yield-limiting factor for sunflower in the specific environmental conditions, characterized by clayey soils that are not Vertisols, was the application of NT practices. The substantial failure of NT was strongly related to poor crop establishment under unsuitable soil moisture conditions at sowing time, as already highlighted by Farina et al. (2011) in the same LTE. In clayey soils, NT is constrained by the mechanical impedance of the seed-slot walls in compacted and wet soil conditions for plants emergence, as reported by some authors (e.g., Bayhan et al., 2002). This sunflower sensitivity to NT systems was also observed with less problematic soil texture as in loamy sand soils (Rühlemann 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 t ha^{-1} (López-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 280–520 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.

The main weather driver influencing sunflower yield identified through the recursive partition analysis was the mean temperature of July, followed by evapotranspiration in June and rainfall amount in August. Mean temperatures of July in the range 25–30 °C determined higher grain yields. In fact, the optimum temperatures for sunflower seed filling range from 23 to 28 °C. Above this range grain filling is constrained (Chimenti et al., 2001). Moreover, sunflower sensitivity to heat stress decreases as grain filling proceeds (Rondanini et al., 2003). Regarding soil water deficit, the most critical period occurs soon before and after flowering (Rao et al., 1977). According to this, we found that lower evapotranspiration values in June when flowering initiates, are among the main weather factors influencing yield in particular under NT. Rainfall amount in August was negatively correlated with grain yield. In fact, sunflower in August is usually at the end of the grain filling phase and adverse conditions during this period could affect the achene viability. In particular, the heavy rains that occurred in August 1996 could have lead to the detachment of the achenes from the flower head and likely to the occurrence of diseases and other biotic stresses, resulting in severe production losses.

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

Considering the sunflower productivity, the highest N fertilizer rate under MT and CT reached higher yields (on average, 1.8 t ha^{-1}) and were characterized by high stability. Yield stability results indicate however a relatively good performance of sunflower cropped under MT and intermediate N fertilizer rates, as it was shown for durum wheat.

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

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

The lower productivity of rainfed maize under NT was constantly observed along the 13-years experiment with very few exceptions, although we observed very high interannual variations, as also demonstrated by the lower yield stability of NT as compared to CT or MT systems. However, a significant upward trend was found over time in terms of maize grain yield for MT and NT with both N2 and N1 rates. These results need to be confirmed when the duration of the maize trial will reach an appropriate length for the fertility trend analysis to be sufficiently reliable (at least 20 years). Other authors observed an increasing trend of yields after at least two to four years since the start of NT adoption that were considered a minimum time period for creating better soil structure and, hence, better soil and plant water status (Karunatilake et al., 2000; Diaz-Zorita et al., 2002). Also Colvin et al. (2001) raised several concerns regarding consistently lower maize yields under NT than under CT or MT systems in the first period after conversion to NT, while in the same environment but in the long term, Karlen et al. (2013) found similar yields among tillage systems. Even though NT maize, in our experimental conditions, followed seven years of continuous NT in the context of the wheat-sunflower rotation and showed a slight increasing trend over the thirteen years of the trial, the level of productivity remained quite low. This suggests that, although soil available water might had been higher in the top soil (Wang et al., 2015), yield was likely constrained by a combination of unsuitable soil conditions for sowing, reduced water uptake ability or soil nutrient deficit. Tabaglio and Gavazzi (2006, 2009) in Northern Italy reported opposite yield results with NT depending on soil fertility traits, with better maize performances in the most nutrient-rich soil. On the contrary, we did not find a significant interaction between T and N fertilization systems. However, the highest N rate (180 kg N ha^{-1}) was far lower than the common rate in the maize-based cropping systems in Italy (about 250 kg N ha^{-1}) under irrigation or in wetter climates and this could have flattened the maize performance particularly in more humid years. In terms of yield stability and yield outcomes over the thirteen years of the experiment, the best performance was achieved with the intermediate N rate and MT. Nevertheless, the overall mean productivity (2.1 t ha^{-1}) was rather low if compared to what reported by other scholars for rainfed maize grown under more suitable rainfall patterns (9 t ha^{-1} in Northern Italy by Tabaglio and Gavazzi, 2009 8 t ha^{-1} in Northern-Central USA by Karlen et al., 2013; 5 t ha^{-1} in Central Mexico by Verhulst et al., 2011; 5 t ha^{-1} in Northern China by Wang et al., 2012).

In our experimental conditions, weather factors affected negatively maize yields, particularly high mean temperatures in June (>23.2 °C) and drought conditions in July. This latter factor is particularly important when N was less limiting. In these periods, maize sensitivity to high temperatures was associated to high evapotranspiration and low soil moisture during anthesis (Sánchez et al., 2014) when potential total number of kernels per plant is defined. Two of the most vulnerable developmental stages of maize to water stress, i.e., the end of the flowering and the beginning of the grain filling, occurred in July. In rainfed systems, water stresses are recognized to be responsible of maize yield losses particularly if they occur after tassel initiation, at anthesis and during the grain filling (Tollenaar and Bruulsema, 1988).

5. Conclusions

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

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

The long term experimental results clearly indicate that in the non-Vertisols clayish soils of the study area the adoption of continuous NT under rainfed conditions is not a viable options for sunflower and maize. In particular for sunflower, N fertilization seemed to be not sufficient to compensate for the yield penalty associated to NT practices. This finding is strongly associated to the site-specific characteristics of the study area that constrained the success of the direct seed drilling. MT proved instead to be a viable option for both maize and sunflower crops particularly to enhance grain yield stability. However, the overall productivity of both sunflower and maize, independently of the tillage and N fertilization systems, was found to be rather low in absolute terms, even if it was consistent to yields observed for sunflower grown under rainfed conditions in semi-arid environments. Maize yields were instead absolutely not satisfactory, considering the high productivity potential of this crop. This indicates that in the study area, the severe water stress during the reproductive phases heavily constrains maize productivity under rainfed conditions. However, our findings on rainfed maize productivity under conservation tillage represent, to our knowledge, a unique attempt to assess the role of these tillage systems in the Mediterranean environments.

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