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Conventional tillage versus no-tillage: Nitrogen use efficiency component analysis of contrasting durum wheat genotypes grown in a Mediterranean environment

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ABSTRACT

Very little information is available for Mediterranean areas about the soil N dynamics and crop N use efficiency during the transition phase from conventional tillage (CT) to no-tillage (NT). Hence, a 2-yr experiment was conducted under semiarid Mediterranean conditions in three sites to study how soil N dynamics, crop N uptake, grain yield, and N use efficiency vary with N-fertilization rate and crop genotype in the switch year from CT to NT. Treatments consisted of two tillage systems (CT and NT), five N-fertilization rates (0, 40, 80, 120, and 160 kg N ha^{-1}), and two durum wheat (*Triticum durum* Desf.) genotypes (one modern variety and one old landrace). Irrespective of the genotype, NT reduced compared to CT both wheat N uptake and grain yield under low soil N availability. The greater soil N supply under CT was the main reason for this outcome, so much so that the differences between CT and NT for these traits gradually decreased with the increase of N-fertilization rate, practically disappearing at 80 kg N ha^{-1}). The analysis of the N use efficiency components corroborated this hypothesis showing clearly that the yield advantage observed in CT depended mainly on the increase in N supply in soil under CT than NT condition. The two wheat genotypes responded similarly to varying soil tillage system. However, the adverse effects of NT practice were more evident in the modern variety than the old landrace. This study ultimately indicates that in the Mediterranean areas the switch year from CT to NT regime is rather delicate. Given that the lack of soil cultivation considerably reduces the soil N availability, hence, using NT technique alone as a substitute for CT is not agronomically feasible. Instead, an optimal application of NT is achievable by acting simultaneously on other factors of the cropping management, particularly the N-fertilization strategy, to maximize the crop N use efficiency and increase crop yield, which are essential requirements for a more sustainable agriculture.

Data availability: Data will be made available under agreement.

1. Introduction

One of the options proposed to mitigate the detrimental impact of tillage on the soil and the environment is the adoption of soil conservation management techniques (Lal, 2015), among which of particular interest is the no-tillage (NT) technique (Six et al., 2004), which lies in direct drilling in an untilled soil. Many studies have shown the great potential of using NT as an alternative to conventional tillage (CT) (which is usually based on mouldboard ploughing) in providing various environmentally friendly benefits, including: greater soil protection from erosion (Scopel et al., 2005; Montgomery, 2007); improved soil aggregation and aggregate stability (Blanco-Canqui and Ruis, 2018); increased soil organic matter content (Alvarez, 2005; Badagliacca et al., 2018a and 2018b); greater protection of the soil macro- and microfauna

Abbreviations: NT, no-tillage; CT, conventional tillage; N0, N40, N80, N120, and N160, 0, 40, 80, 120, and 160 kg N ha^{-1} applied with fertilizer; $\%^{15}$Nrec, Percentage of ^{15}N-fertilizer recovery; Gw, Grain yield; Ns, N supply; Nf, N applied with fertilizer; Nav, Available soil N; Nt, Plant N uptake; NUE, N Use Efficiency (= Gw/Ns); NUpE, N Uptake Efficiency (= Nt/Ns); NUtE, N Utilization Efficiency (= Gw/Nt); Gw/Nav, Available N Use Efficiency; Nt/Nav, Available N Uptake Efficiency; Nav/Ns, Available N efficiency.

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(Zhang et al., 2015; Melman et al., 2019); enhanced soil microbial activity (Zhang et al., 2015; Badagliacca et al., 2021); and reduced fuel consumption and energy inputs (Khaledian et al., 2014; Pratibha et al., 2019). Furthermore, it is well recognized that NT can increase water storage in the soil compared to CT regime through positive changes in soil hydraulic properties and due to the maintenance of crop residues on the soil surface, which would result in enhanced growth and yield of crops especially in arid and semiarid climates (Bonfil et al., 1999; De Vita et al., 2007; Amato et al., 2013). This latter aspect would be of particular relevance for the Mediterranean environments, where water scarcity during the grain filling period is frequently the main factor limiting crop growth and yield (Lampurlanés et al., 2002 and 2016; Amato et al., 2013).

The multiple benefits achievable by applying the NT technique suggest that it may represent an optimal solution for many Mediterranean areas. However, despite the scientific evidence, NT technique is not yet widespread in this region, currently being practiced an area of only 2% of the arable land. Several reasons contribute to this low level of use, including the lack of policies that promote and encourage the adoption of NT and the reluctance of farmers, discouraged by the lack of results (or more frequently by an even substantial reduction in crop production) in the first years of application, that is during the transition from CT to NT regime (Peigné et al., 2007). These disappointing results could also depend on an incorrect application by the farmer of the NT technique, which cannot simply be a substitute for the CT, but which must necessarily provide for a complete reorganization of the entire cropping system, also taking into account the different soil and climatic conditions. This in order to effectively face a series of problems that inevitably arise when switching from the CT to the NT regime, such as changes on the soil N dynamics which often lead to a reduction of the soil N available to crops.

Many studies have highlighted that NT considerably impacts soil N dynamics and the fate of applied N fertilizers, with positive or negative effects on soil N availability, N uptake, and N use efficiency by crops when compared to CT (Huggins and Pan, 2003; Licht and Al-Kaisi, 2005; Liu et al., 2015; Ruisi et al., 2016; Omara et al., 2019). The inconsistency of the findings reported in the literature reflects the different experimental conditions across the studies, and can therefore be attributable to various factors, including differences in climatic conditions, soil type, and the agronomic practices applied (crop type and variety, type, amount, and method of N-fertilizer application, etc.). Furthermore, given that the effects of NT on soil N dynamics and N availability to crops change over time (as it usually takes a few years of continuous application of NT before a new equilibrium is reached in the soil; Pittelkow et al., 2015), one must consider how long NT has been applied when comparing NT systems with CT or with other soil tillage systems. Anyway, the lack of unequivocal findings regarding the effects of NT on soil N dynamics and N use efficiency by crops, and the awareness that these effects depend on a complex interaction of several factors, suggest that this subject remains an area that deserves further research. Acquiring more knowledge on these aspects is in fact of paramount importance to optimize the agronomic management under NT in a way that allows to increase the N use efficiency by crops, and ultimately the sustainability of cropping systems. This aspect is of particular importance if considering that the transition from CT to NT very often pose serious issues (e.g., higher rates of N fertilization required, difficulties in weed and disease control) that often lead the farmer to abandon the NT practice and return to CT.

Therefore, an experiment was performed in a typical Mediterranean environment to address the following questions: i) How much does the transition from CT to NT system alter the soil N dynamics, and impact crop N uptake and N use efficiency? ii) How much do these effects vary with agronomic practices such as N-fertilization rates and crop genotype? The experiment was conducted during the first year of transition from CT to NT (which, as already said, is a crucial phase) and was replicated over two growing seasons. Durum wheat (*Triticum durum* Desf.) was used as focal plant because of its importance as a crop in the arid and semiarid Mediterranean areas. Two durum wheat genotypes (one modern variety and one ancient Sicilian landrace) were included in the experiment to verify whether genotypes that differ in their morpho-physiological and agronomic traits respond differently to NT application with respect to crop yield and quality, and especially to the efficiency in the use of N. The insights obtained from this study are expected to contribute to more successful application of NT within the cropping systems of the Mediterranean areas in a way that satisfies farmer expectations while benefiting the soil and the environment, which is an ongoing objective to improve the sustainability of agriculture.

2. Materials and methods

2.1. Site characteristics

The research was conducted over two seasons (2011–2012 and 2012–2013) in three sites representative of the arable land in the Sicilian inland, all located within the experimental farm Pietranera (Agrigento, Sicily, Italy, 37°30′ N, 13°31′ E; 160–440 m a.s.l.). The farm covers about 700 ha and includes a wide variety of soils, differentiated by chemical-physical characteristics, morphology and orography. The first soil where the experiment was conducted is classified as Typic Calcixerept (Soil Survey Staff, 2006): it is deep with a predominantly clayey texture, a sub-angular structure, sub-alkaline reaction and with a low to moderate organic matter content (Table A1). The second soil is a Vertic Haploxerept evolved on a recent alluvial deposit; the soil is deep with a sandy-clay texture, a granular structure, good drainage, a sub-alkaline reaction, and a very low organic matter content. The third soil, classified as Chromic Haploxerert, is a fine-clayey, calcareous, mixed, xeric Vertisol that developed on Mio-Pliocenic clayey substrata; it is rich in montmorillonite clay, which favours crevassing and promotes the mixing of the soil, it is very productive given its high natural fertility.

The climate is Mediterranean with an annual rainfall of 580 mm, concentrated in autumn/winter (about 75%) and in spring (18%); the mean annual potential evapotranspiration is approximately 1100 mm (according to Penman-Monteith method). The dry season extends from May to September. The average air temperature is 15.9 °C in autumn, 9.8 °C in winter and 16.5 °C in spring; the average minimum and maximum annual temperatures are equal to 10.0 °C and 23.3 °C, respectively.

2.2. Experimental design and crop management

The three soils were managed using conventional tillage techniques in the 20 years prior to the experiment set up (mouldboard ploughing followed by shallow harrowing or reduced tillage, depending on crop type — wheat or forage legumes). In both growing seasons and at all sites, berseem clover (*Trifolium alexandrinum* L.) was the previous crop. The soil was always prepared for berseem clover sowing by shallow harrowing before sowing. Berseem clover plants were cut in early April to a stubble height of ~ 8 cm, which allowed for regrowth and seed production. Standing straws were always left in the soil, and loose residues (about 3–4 Mg dry matter ha^{-1}) were distributed evenly.

The experiments were set up as a split-split-plot design with four replications. The main plots (180 m^2 each) were the soil tillage techniques: conventional tillage (CT) and no tillage (NT); subplots were the durum wheat genotypes: cv. Vertola and landrace Russello; subsubplots were the N-fertilization rates: 0, 40, 80, 120, and 160 kg N ha^{-1}; hereafter referred as N0, N40, N80, N120, and N160, respectively. The size of each subsubplot was 18 m^2 (16 rows, each 6 m long, spaced 0.1875 m). In 2012–2013, the experiments were performed in the same three sites in surfaces adjacent to those used in 2011–2012, to maintain the "first year switch conditions".

Conventional tillage consisted of one mouldboard ploughing to a depth of 0.30 m in the summer, followed by one or two shallow harrowing (0–0.15 m) operations before planting. No-tillage consisted of sowing by direct drilling; here the weeds were controlled before planting with glyphosate at a dose of 720–1440 g acid equivalent ha^{-1}, depending on the development of weeds.

In CT the residues of the previous crop were incorporated into the soil, while in NT they were left on the soil surface in order to ensure its coverage of more than 30%. All the cultivations and tillage were realized using commercial farming equipment. Phosphate fertilization was carried out by distributing triple superphosphate at a rate of 69 kg P_2O_5 ha^{-1} before sowing; the N fertilization was done manually by distributing in each plot the expected quantity of N, as ammonium sulphate ($[NH_4]_2SO_4$), according to the experimental design. The total amount of N fertilizer was always split-applied: 50% at crop emergence and 50% at the end of tillering. For both genotypes and in all treatments, 350 viable seeds m^{-2} were sown. The sowing was always carried out in the second decade of December. In all cases, weeds were controlled at an early growth stage with application of thifensulfuron-methyl (25 g active ingredient ha^{-1}) and tribenuron-methyl (12.5 g active ingredient ha^{-1}).

The cv. Vertola (released in 2003) is characterized by short plant height, very early heading and maturity, high yield potential, and good pasta-making quality. Russello is a landrace that was widely grown in Sicily (Italy) in the first half of the last century and is particularly appreciated for the sensorial properties of its products (bread in particular). It is characterized by tall plant stature, high tillering capacity, medium-late heading and maturity, moderate productivity, and good adaptability to environments characterized by scarce water and nutrient resources.

Every year and in each site, following the emergence of the crop, two test areas, each 2.25 m^2 wide (8 rows 1.5 m long), were identified within each subsubplot in order to carry out the subsequent surveys. Limited to the N80 treatment, N fertilizer enriched with the ^{15}N isotope, with an enrichment of 1.33 atom% was distributed in the test areas (50% at the emergence and 50% at the end of the bunching) following the application procedure described by Høgh-Jensen and Schjoerring (1994); the remaining part of the subsubplots, outside the ^{15}N labeled areas, received a similar amount of unlabled N fertilizer.

Soil samples (0–0.40 m layer) were collected from each subplot soon after wheat harvest and analyzed for 2 M KCl-extractable NH_4–N and NO_3–N using a Bran & Luebbe AutoAnalyzer 3 (Norderstedt, Germany).

In each growing season, at both heading and ripening, a plant sample was taken from a segment (0.5 m long) of the two central rows of each test area. The harvested plant biomass was dried at 60 °C for 48 h, weighed and ground to a fine powder (sieved using a 0.1-mm mesh) in a fast-running mill (Retsch ZM 100; F.Kurt Retsch GmbH & Co., Haan, Germany), and analyzed for total N and, limited to N0 and N80, for ^{15}N enrichment. The plant biomass N concentration was determined using the Dumas method (flash combustion with automatic N analyzer DuMaster D-480; Büchi Labortechnik AG, Flawil, Switzerland), and ^{15}N concentrations were determined using a Roboprep-CN and 20–20 isotope ratio mass spectrometer (Europa Scientific Ltd, Crewe, UK). In the remaining area of each test area, the overall production of biomass was determined and, limited to the collection, the grain production.

At heading and maturity, all the plant biomass present was cut on a segment (0.5 m long) of the two central rows of each test area. Plants and tillers were counted and separated into leaves, stems, and ears; the fresh weight of each sample was determined, and the leaf area of the leaves was immediately measured using a leaf area meter (LI-COR LI-3100 C Area Meter; Li-Cor Inc., Lincoln, NE, USA). All samples, collected both at heading and maturity, were dried in a forced air oven at 60 °C for 36 h and weighed. At maturity, grain yield was recorded after hand-cutting plants from a sampling area of 2.25 m^2; yield components (number of ears per m^2, number of seeds per ear, and 1000-seed weight), N grain content (determined according to the Dumas method by means of the automatic N-analyzer DuMaster D-480; Buchi Labortechnik, Flawil, Switzerland), and test weight (determined by means of the humidimeter TM NG; Tripette and Renaud – Chopin, Villeneuve-la-Garenne, France) were also recorded.

2.3. Calculations and statistical analysis

Data on ^{15}N enrichment of biomass, taken both at heading and maturity, were used to trace the fate of the N-fertilizer applied (Smith and Chalk, 2020). The labeled-fertilizer N recovery (^{15}Nrec) was calculated on an area basis (kg N ha^{-1}) and percentage basis according to Hauck and Bremner (1976):

$$^{15}\mathrm{Nrec} = \mathrm{Nt} \times \frac{^{15}\mathrm{Nfp} - {}^{15}\mathrm{Nnfp}}{^{15}\mathrm{Nfert} - {}^{15}\mathrm{Nnfp}} \quad (1)$$

and

$$\%^{15}\mathrm{Nrec} = \frac{^{15}\mathrm{Nrec}}{\mathrm{f}} \times 100 \quad (2)$$

where Nt is the plant N uptake (kg N ha^{-1}), ^{15}Nfp is the atom% ^{15}N in the N-fertilized plants (N80 treatments), ^{15}Nnfp is the atom% ^{15}N in the nonfertilized plants (N0 plots), ^{15}Nfert is the atom% ^{15}N in the fertilizer, and f is the N-fertilizer rate (kg N ha^{-1}).

Moreover, the following parameter was calculated according to Cox et al. (1986) and Arduini et al. (2006):

$$\mathrm{N_{remobilization\ efficiency}}(\%) = \frac{\mathrm{Nth} - (\mathrm{Ntm} - \mathrm{Ng})}{\mathrm{Nth}} \times 100 \quad (3)$$

where Nth is the plant N uptake (kg N ha^{-1}) in the aboveground biomass at heading, Ntm is the plant N uptake (kg N ha^{-1}) in the aboveground biomass at maturity, and Ng is the grain N yield (kg N ha at maturity.

Nitrogen efficiency parameters were calculated according to Moll et al. (1982) and Huggins and Pan (1993). Nitrogen use efficiency was defined as the ratio of grain produced (Gw, kg ha^{-1}) to N supply (Ns, kg N ha^{-1}), where Ns was estimated as the amount of applied N (Nf) plus the available soil N (Nav), the latter calculated as the plant N uptake in the aboveground biomass and the grain N yield at maturity (Nt, kg N ha^{-1}) plus the residual postharvest N in the soil (kg N ha, both determined from control plots (N0 plots). Nitrogen uptake efficiency (NUpE) was calculated as Nt/Ns; N utilization efficiency (NUtE) was determined as Gw/Nt.

Stepwise regression analyses, separately for each genotype, of Gw vs. tillage system, and either Nf, Ns, Nav or Nt, were performed to determine significant model parameters. According to Huggins and Pan (1993), if tillage regime was a significant variable ($p < 0.10$) with either Ns, Nav or Nt in a regression model predicting Gw, then regression models were developed separately for each tillage regime. If tillage regime was not a significant variable ($p > 0.10$) in the regression model, then the same regression model was used for both tillage regimes. The predictive equations determined by regression analyses were used in the N efficiency component analysis to partition differences in yield and grain N between the two tillage systems into N efficiency components according to Huggins and Pan (1993).

Data were analysed using a linear model for split-plot design (Montgomery, 1997), with tillage system as the main plot, N-fertilization rate as the subplot, and genotype as the sub-subplot replicated four times in three different sites. In the model, the year and the site were considered random factors. In all the tables and figures presented in this paper we reported the "*p* values instead of asterisks or parenthetical inequalities based on arbitrary demarcations, so that readers can judge for themselves whether chance is a viable explanation of the results" (Sen et al., 2022). All the analyses were carried out using R software (R Core Team, 2020).

3. Results

3.1. Climatic conditions

In 2011–2012, total rainfall was 596 mm (very close to the long-term average), with rains well distributed throughout the growing season (Fig. A1). The mean temperature during the first growing season was a little bit lower than the normal for the area, especially in the winter period. In 2012–2013, total rainfall was 866 mm, that is about 50% higher than the long-term average. Rains mainly occurred in October (180 mm) and between January and March (430 mm), with a peak in January (185 mm). The mean temperature was similar to the normal for the area.

3.2. Biomass production, grain yield and yield components

The tillage technique influenced biomass yield at heading and maturity, LAI at heading, and grain yield, with the extent of such variations being determined by the amount of N fertilizer applied (interaction p values always < 0.01; Table 1). For these characters, the highest values were obtained, for both genotypes, by adopting the CT technique compared to NT. However, the differences gradually decreased with the increase in the N-fertilizer rate, so much so that already at N80 no difference emerged between the two tillage techniques. As expected, the biomass, at both heading and maturity, was always decidedly higher in the landrace than in the modern variety (+44% and +13% at heading and maturity, respectively). On the contrary, the differences in LAI values between the genotypes appeared generally modest.

Also for the number of ears per unit area, the tillage technique induced diversified effects as the rate of N fertilizer varied (interaction p value < 0.001; Table 2). In fact, for both genotypes, no difference was observed in the number of ears per m^2 at N0 and N40, whereas, at higher rates, higher values were recorded in NT compared to those of CT. As expected, the number of ears per unit area increased as the rate of N fertilizer increased. On average, the number of ears was higher in the landrace than the modern variety ($p < 0.001$), but the differences observed were large at the lowest N-fertilizer rate (+17%) and were reduced at the highest rates (+ 4%; interaction p value = 0.042).

The ear fertility varied largely as a result of all the treatments applied; overall, the number of kernels per ear was higher in CT compared to NT (+8%; $p < 0.001$), in the modern genotype compared to landrace and increased with increasing the rate of N fertilizer. In addition, it should be noted that the differences due to soil management were greater in the modern variety than in the landrace (Table 2).

The 1000-kernel weight was always higher in Vertola than in Russello, but the two genotypes showed different behaviours as the treatments applied varied. In fact, in the modern variety higher values in CT than in NT have been observed and decreasing values as the rate of N fertilizer increased. On the contrary, in the landrace, no differences emerged for this yield component due to both tillage technique and N-fertilization rate.

The test weight was, on average, higher in NT than in CT ($p = 0.036$), in Russello than in Vertola ($p < 0.001$), and decreased as the rate of N fertilizer increased ($p < 0.001$). However, the observed differences appeared to be modest. For this trait, the p values of the interactions between the applied treatments were always high (Table 2).

3.3. Nitrogen uptake, grain protein content and N-efficiency parameters

As with biomass yield, N uptake at N0, both at heading and maturity, was higher in CT than in NT; the differences between the two tillage techniques were progressively reduced as the rate of N fertilizer increased (Table 3). The amount of N removed at heading was noticeably higher in Russello than in Vertola (on average, 98 and 80 kg N ha^{-1}) whereas at maturity no difference between the two genotypes was observed. As expected, the amount of N accumulated in the biomass, both at heading and at maturity, increased as the N-fertilizer rate increased. The two genotypes showed a similar behaviour when varying both the tillage method (interaction p values = 0.756 and 0.600 for N uptake at heading and maturity, respectively) and the N-fertilizer rate (interaction p values = 0.107 and 0.609 for N uptake at heading and maturity, respectively).

The tillage technique did not affect grain protein content ($p = 0.314$). Both genotypes showed similar protein contents at N0 (on average, 13.7%); however, as N-fertilizer rates increased, increasing differences between the two genotypes were observed with Russello showing always higher contents than Vertola (Table 3).

The amount of N remobilized during the kernel filling phase increased with the increase in the N-fertilizer rate and was greater in Russello than in Vertola (on average 62.1% and 53.2%, respectively). The adoption of NT technique, compared to CT, resulted in a decrease in N remobilization only at the lowest N-fertilizer rates (N0 and N40; Table 3).

At heading, the $\%^{15}$Nrec was not affected by the tillage technique (on average, 22.0%), whereas at maturity, it was higher in NT than CT (28.7% and 25.8%, respectively; Fig. 1). Compared to the modern variety, the landrace has shown a greater ability to intercept the applied N in both at heading and maturity. The two genotypes had a similar

Table 1

Durum wheat plant growth traits (at heading and maturity) and grain yield measured in the two genotypes (*Variety* is the modern variety 'Vertola'; *Landrace* is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions at different N-fertilization rates (N0, N40, N80, N120, and N160 correspond to 0, 40, 80, 120, and 160 kg N ha^{-1}, respectively). Each value is a mean of 24 data (3 sites × 2 growing seasons × 4 replicates). The p values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, N-fertilization rate, and their interactions) on the observed traits is reported in the bottom part of the Table.

	Biomass at heading (kg DM ha^{-1})				**LAI at heading** (cm^2 cm^{-2})				**Biomass at maturity** (kg DM ha^{-1})				**Grain yield** (kg DM ha^{-1})			
	Variety		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
N0	4 707	3 668	6 418	5 453	1.77	1.29	1.84	1.46	7 865	6 428	9 025	7 597	3 089	2 513	2 757	2 354
N40	4 833	4 534	6 891	6 431	1.94	1.66	2.02	1.84	8 502	7 613	9 430	8 974	3 473	3 006	2 951	2 804
N80	5 039	5 079	7 373	7 614	2.06	2.00	2.26	2.11	8 922	8 695	10 229	10 140	3 670	3 423	3 008	3 103
N120	5 406	5 378	7 804	7 796	2.34	2.24	2.57	2.32	9 264	9 582	10 205	10 499	3 835	3 753	2 943	3 063
N160	5 698	6 029	8 238	8 354	2.44	2.60	2.66	2.66	9 760	9 878	10 542	11 061	4 013	4 035	2 945	3 093
Tillage **(T)**	0.229				0.022				0.125				0.095			
Genotype **(G)**	< 0.001				0.002				< 0.001				< 0.001			
Fertilizer **(F)**	< 0.001				< 0.001				< 0.001				< 0.001			
T × G	0.949				0.624				0.419				0.201			
T × F	< 0.001				0.005				< 0.001				< 0.001			
G × F	0.003				0.998				0.449				< 0.001			
T × G × F	0.879				0.781				0.847				0.832			

Table 2
Durum wheat grain yield component traits and test weight measured in the two genotypes (*Variety* is the modern variety 'Vertola'; *Landrace* is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions at different N-fertilization rates (N0, N40, N80, N120, and N160 correspond to 0, 40, 80, 120, and 160 kg N ha^{-1}, respectively). Each value is a mean of 24 data (3 sites × 2 growing seasons × 4 replicates). The *p* values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, N-fertilization rate, and their interactions) on the observed traits is reported in the bottom part of the Table.

	Ears (n m^{-2})				**Kernel per ear** (n)				**1000-kernel weight** (g)				**Test weight** (kg hl^{-1})			
	Variety		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
N0	216	219	251	256	25.0	21.6	23.7	21.1	54.8	52.9	43.7	43.1	83.7	83.7	84.6	84.9
N40	233	233	259	269	26.1	23.5	24.9	23.4	54.4	53.9	43.9	44.1	83.6	84.4	84.6	85.1
N80	238	254	270	283	27.9	25.9	25.0	24.7	53.6	52.0	43.5	44.0	82.9	83.5	84.0	84.8
N120	239	277	267	298	30.0	26.9	25.1	23.7	51.8	50.3	43.4	43.2	83.2	82.9	83.4	83.8
N160	255	295	275	294	30.0	27.5	24.5	24.7	51.1	49.9	43.1	43.2	82.6	82.7	83.3	83.6
Tillage **(T)**	0.029				< 0.001				0.117				0.036			
Genotype **(G)**	< 0.001				< 0.001				< 0.001				< 0.001			
Fertilizer **(F)**	< 0.001				< 0.001				< 0.001				< 0.001			
T × G	0.625				0.099				0.110				0.469			
T × F	< 0.001				0.122				0.669				0.178			
G × F	0.042				< 0.001				< 0.001				0.454			
T × G × F	0.520				0.830				0.898				0.668			

Table 3
Durum wheat N uptake (at heading and maturity), grain protein content, and the percentage contribution of N remobilization to grain N measured in the two genotypes (*Variety* is the modern variety 'Vertola'; *Landrace* is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions at different N-fertilization rates (N0, N40, N80, N120, and N160 correspond to 0, 40, 80, 120, and 160 kg N ha^{-1}, respectively). Each value is a mean of 24 data (3 sites × 2 growing seasons × 4 replicates). The *p* values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, N-fertilization rate, and their interactions) on the observed traits is reported in the bottom part of the Table.

	N uptake at heading (kg ha^{-1})				**N uptake at maturity** (kg ha^{-1})				**Grain protein** (%)				**N remobilization** (%)			
	Variety		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
N0	66.1	48.7	75.3	63.8	92.2	76.3	88.8	72.1	13.7	14.0	13.6	13.6	48.2	35.4	53.5	48.0
N40	73.5	64.6	88.3	79.8	113.4	98.0	103.5	96.2	14.4	14.3	14.6	14.5	49.5	43.3	61.8	56.0
N80	81.5	78.4	101.3	97.1	121.5	111.8	120.4	114.3	14.7	14.3	15.2	14.9	56.5	54.7	62.6	65.5
N120	90.9	88.7	111.5	110.6	132.0	134.2	128.2	128.4	14.6	14.3	15.3	15.0	59.8	50.5	63.4	64.1
N160	100.8	104.8	124.0	126.1	143.3	143.1	136.4	137.8	15.1	14.6	15.9	15.7	67.0	67.6	71.5	74.5
Tillage **(T)**	0.047				0.019				0.314				0.123			
Genotype **(G)**	< 0.001				0.059				< 0.001				< 0.001			
Fertilizer **(F)**	< 0.001				< 0.001				< 0.001				< 0.001			
T × G	0.756				0.600				0.988				0.162			
T × F	0.001				< 0.001				0.269				0.166			
G × F	0.107				0.609				< 0.001				0.758			
T × G × F	0.918				0.914				0.879				0.887			

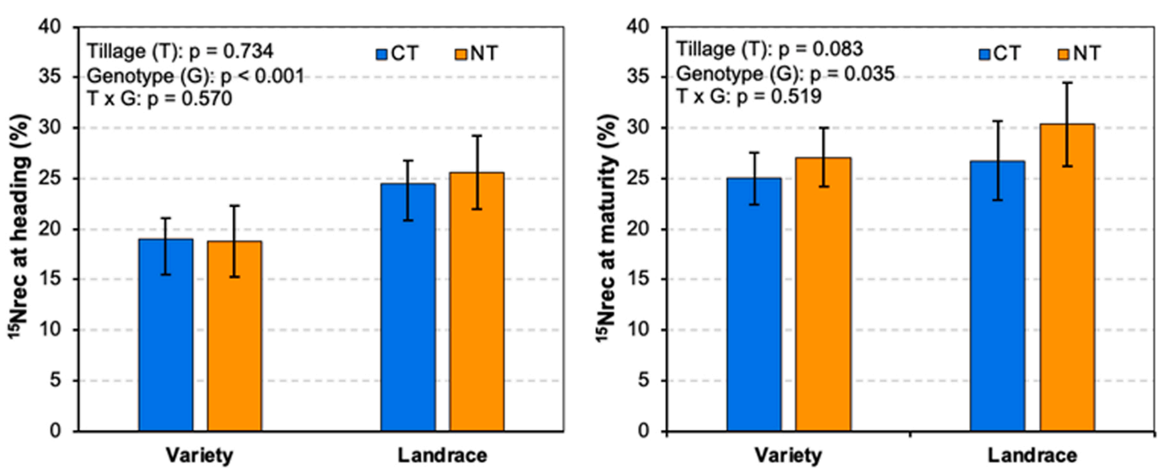

Fig. 1. The percentage of ^{15}N fertilizer nitrogen recovery (% $^{15}Nrec$) measured at heading (left) and maturity (right) in the two genotypes (Variety is the modern variety 'Vertola'; Landrace is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions and supplied with 80 kg N ha^{-1} (N80 treatment). Reported values are means ± SE (n = 24; 3 sites × 2 growing seasons × 4 replicates). The *p* values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, and their interaction) on this trait is reported in the upper left part of the Figure.

response to the variation of the tillage technique.

Nitrogen use efficiency ratios were, on average, greater in NT than in CT, except for available N use efficiency (Gw/Nav), available N uptake efficiency (Nt/Nav), and N utilization efficiency (Gw/Nt), which did not differ between tillage systems (Tables 4 and 5). Nitrogen fertilization markedly decreased all NUE ratios (p values always < 0.001). In Vertola, N use efficiency (Gw/Ns), available N use efficiency (Gw/Nav), and N utilization efficiency (Gw/Nt) were higher than in Russello (p values always < 0.001). However, the two genotypes did not differ for available N efficiency (Nav/Ns), available N uptake efficiency (Nt/Nav), and N uptake efficiency (Nt/Ns) (Tables 4 and 5). Overall, the response of the two genotypes was similar at varying the tillage technique (high p values of the interaction Tillage × Genotype for all NUE ratios). The effects of the tillage technique did not vary with the N-fertilizer rate (high p values of the interaction Tillage × Fertilization) except for available N uptake efficiency (Nt/Nav, $p < 0.001$), and N uptake efficiency (Nt/Ns, $p = 0.033$), which, with the increase of the N-fertilizer rate, underwent less marked reductions in NT compared to CT (Tables 4 and 5).

The regression analysis highlighted that the tillage technique affected markedly the relationships between Gw and Nf, Gw and Ns, Gw and Nav, and Gw and Nt only in the modern variety (p values always lower than 0.10), but not in the landrace (Fig. 2). Thus, only for the modern variety, the regression equations were used in the analysis of the components of NUE to break down the differences in grain yield between the two tillage techniques into different N efficiency components (Table 6). Without N fertilization (N0), the component ΔGw(Ns), which represents the contribution of Ns to the differences between CT and NT with the same Nf, was nearly thrice as large as the ΔGw(Gw/Ns) component. ΔGw(Ns) decreased as N-fertilizer rate increased reaching values < 0 kg ha^{-1} at 160 kg N applied ha^{-1}. The ΔGw(Gw/Ns) component, which indicates the contribution of the NUE to explaining the difference in Gw between CT and NT at equivalent Ns level, was found to be 126 kg ha^{-1} at N0 (Table 6). Also, for this component of NUE, the values have progressively reduced as the rate of N fertilizer applied increased reaching values < 0 at N160.

The ΔGw(Gw/Ns) component was then partitioned into components of available N efficiency ΔGw(Nav/Ns) and available N use efficiency ΔGw(Gw/Nav). The ΔGw(Gw/Nav) component at N0 was equal to 192 kg Gw ha^{-1} and then gradually decreased as the N-fertilizer rate increased. As regards the ΔGw(Nav/Ns) component, increasing trends were observed as the rate of N fertilizer applied increased. Finally, decomposition of ΔGw(Gw/Nav) revealed that this component was almost entirely derived from the ΔGw(Gw/Nt) component (Table 6).

4. Discussion

The results of this study highlight that the crop yield variation induced by the transition from CT to NT regime are closely related to the effects that the two soil tillage techniques have on the soil N availability and the N use efficiency by the crop. Irrespective of the genotype used, with no N fertilization wheat yields were considerably higher in CT than NT, and the greater availability of N (N supply, Ns) under CT played a fundamental role in this outcome, confirming the results of other research conducted in the Mediterranean environment (Cantero-Martínez et al., 2003; Ruisi et al., 2016; Giambalvo et al., 2018). On average, in CT systems the N supply was 18 kg ha^{-1} higher than in NT systems; this difference certainly played an important role in N0 as it contributed to over 65% of the differences observed between CT and NT for grain yield. This occurred despite wheat was always grown after berseem clover, a legume crop whose N-rich residues are easily decomposed and which has been proved to be an excellent previous crop to no-till wheat in the area (Amato et al., 2013; Ruisi et al., 2014).

In order to explain the higher Ns in CT compared to NT, it is important to remember that soil cultivation increases soil aeration, soil temperatures, and oxygen diffusion rates, which in turn favours the degradation of organic matter resulting in a consequent increase in mineral N. Moreover, by incorporating and mixing the crop residues with the soil, it also increases their accessibility to soil microorganisms, thus speeding up further their mineralization (Dungait et al., 2012; Badagliacca et al., 2021). On the other hand, several experiments have shown that a key factor in determining the decrease of N availability in NT compared to CT is the presence of residues on the soil surface that can increase the immobilization of the element, particularly during the first phases of crop cycle, by reducing its availability for the crops (Erenstein, 2002; Melaj et al., 2003; Dawson et al., 2008; Giller et al., 2009).

In this research, the advantages offered by CT have been realized especially during the vegetative phase of the crop cycle as evidenced by the values of N uptake detected at heading in N0, always higher in CT compared to NT; the differences observed between the two soil management systems then remained almost stable until maturity. Thus, the adoption of CT led to an increase in N availability and, consequently, to more favourable conditions for a more rapid plant early growth (tillering and first phases of stem elongation) compared to NT, increasing the crop N demand.

The advantage in terms of grain yield of CT compared to NT in the absence of N application appeared to depend on greater ear fertility and

Table 4

Durum wheat N Use Efficiency (NUE, calculated as Gw/Ns), available N efficiency (Nav/Ns), and available N-use efficiency (Gw/Nav) in the two genotypes (*Variety* is the modern variety 'Vertola'; *Landrace* is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions at different N-fertilization rates (N0, N40, N80, N120, and N160 correspond to 0, 40, 80, 120, and 160 kg N ha^{-1}, respectively). Each value is a mean of 24 data (3 sites × 2 growing seasons × 4 replicates). The p values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, N-fertilization rate, and their interactions) on the observed traits is reported in the bottom part of the Table.

	NUE ([a]Gw/Ns)				Nav/Ns				Gw/Nav			
	Variety		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
N0	27.2	26.8	25.4	26.0	1.00	1.00	1.00	1.00	27.2	26.8	25.4	26.0
N40	21.9	22.0	19.4	21.3	0.85	0.86	0.81	0.88	25.7	25.9	24.1	24.2
N80	18.4	19.0	15.7	18.0	0.73	0.75	0.74	0.80	25.2	25.7	21.7	22.7
N120	15.9	17.1	12.7	14.5	0.67	0.74	0.67	0.73	23.7	23.3	19.7	20.2
N160	14.2	15.5	10.8	12.3	0.64	0.69	0.62	0.68	22.4	22.7	17.8	18.6
Tillage **(T)**	0.005				< 0.001				0.484			
Genotype **(G)**	< 0.001				0.849				< 0.001			
Fertilizer **(F)**	< 0.001				< 0.001				< 0.001			
T × G	0.117				0.589				0.156			
T × F	0.148				0.100				0.930			
G × F	0.008				0.636				< 0.001			
T × G × F	0.716				0.859				0.991			

[a] Gw is the grain yield; Nav is the available soil N, calculated as the plant N uptake in the aboveground biomass and the grain yield at maturity plus the residual postharvest N in the soil, both determined in N0 plots; Ns is the N supply, calculated as the Nav plus the amount of N applied with the fertilizer.

Table 5
Durum wheat available N uptake efficiency (Nt/Nav), N Uptake Efficiency (NUpE, calculated as Nt/Ns), and N Utilization Efficiency (Gw/Nt) in the two genotypes (*Variety* is the modern variety 'Vertola'; *Landrace* is the old landrace 'Russello') grown under conventional tillage (CT) and no-tillage (NT) conditions at different N-fertilization rates (N0, N40, N80, N120, and N160 correspond to 0, 40, 80, 120, and 160 kg N ha^{-1}, respectively). Each value is a mean of 24 data (3 sites × 2 growing seasons × 4 replicates). The *p* values from the analysis variance for the effects of the applied treatments (tillage system, durum wheat genotype, N-fertilization rate, and their interactions) on the observed traits is reported in the bottom part of the Table.

	[a]Nt/Nav				NUpE (Nt/Ns)				NUtE (Gw/Nt)			
	Variety		*Landrace*		*Variety*		*Landrace*		*Variety*		*Landrace*	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
N0	0.81	0.78	0.79	0.79	0.79	0.78	0.79	0.78	34.5	34.7	32.6	33.7
N40	0.82	0.80	0.80	0.81	0.70	0.70	0.66	0.72	32.2	32.5	30.7	30.2
N80	0.81	0.80	0.80	0.82	0.60	0.61	0.60	0.65	31.7	32.4	27.7	28.1
N120	0.79	0.80	0.78	0.80	0.54	0.61	0.53	0.59	30.7	29.3	25.9	25.7
N160	0.77	0.78	0.75	0.77	0.50	0.54	0.48	0.54	29.6	29.4	24.3	24.5
Tillage **(T)**	0.484				0.001				0.881			
Genotype **(G)**	0.481				0.871				< 0.001			
Fertilizer **(F)**	< 0.001				< 0.001				< 0.001			
T × G	0.093				0.242				0.713			
T × F	< 0.001				0.033				0.715			
G × F	0.428				0.603				0.004			
T × G × F	0.381				0.615				0.885			

[a] Nt is the plant N uptake in the aboveground biomass and the grain yield at maturity; Nav is the available soil N, calculated as the Nt plus the residual postharvest N in the soil, both determined in N0 plots; Ns is the N supply, calculated as the Nav plus the amount of N applied with the fertilizer; Gw is the grain yield.

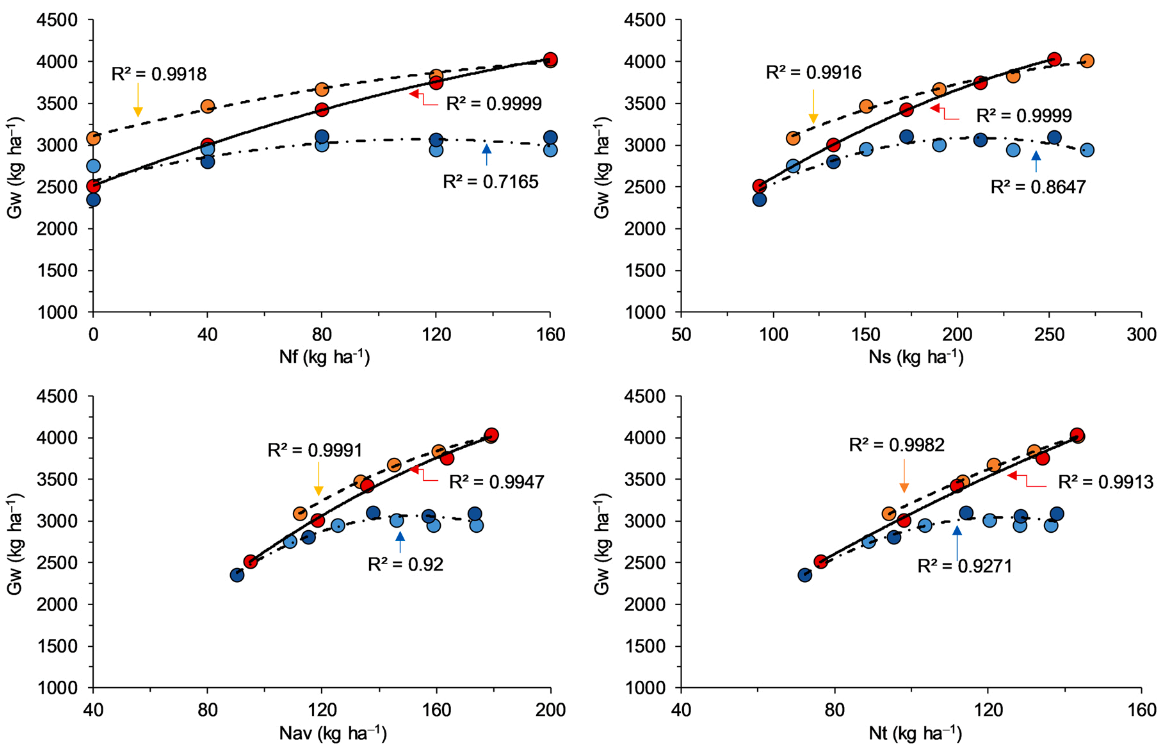

Fig. 2. Relationships of grain yield (Gw) to: applied N (Nf; upper left); N supply (Ns; upper right); available soil N (Nav; bottom left); and plant N uptake in the aboveground biomass and the grain yield at maturity (Nt; bottom right) for conventional tillage (CT) and no-tillage (NT). Results are displayed separately for the two durum wheat genotypes. Red and orange circles refer to the modern variety 'Vertola'; light blue and dark blue circles refer to the old landrace 'Russello'. Since tillage system was a significant variable ($p < 0.10$) with either Ns, Nav and Nt in the regression model predicting Gw for the modern variety 'Vertola', then for this genotype the regression models were developed separately for each tillage regime (in each figure, dashed curve for CT and solide curve for NT). Since tillage system was not a significant variable ($p > 0.10$) in the regression model for the old landrace 'Russello', then for this genotype the same regression model was used for both tillage regimes (in each figure, dashed-dotted curve).

a greater unit weight of the kernels while no difference was observed in the number of ears per unit area. Reasonably we can assume that the more vigorous growth during the vegetative phase, induced by the greater N availability in CT compared to NT and materialized in a greater accumulation of N and a greater leaf surface, has created advantageous conditions also during the reproductive phase, favouring the production of new photosynthates and the N remobilization from shoots to grain.

It has been shown in other research that the adoption of NT over CT can provide the crop with advantages during the reproductive phase of the crop cycle due mainly to the increased water availability. This is generally attributed to the reduction of water loss by evaporation (Blevins and Frye, 1993; Lampurlanés and Cantero-Martínez, 2006; Ruisi et al., 2014 and 2016) and to deeper soil water storage under this tillage

Table 6
Nitrogen efficiency components of yield differences (ΔGw) between the two tillage systems (conventional tillage, CT, minus no-tillage, NT) calculated using the regression equations of the curves shown in Fig. 2. Results are referred only to the modern variety 'Vertola'.

	ΔGw	[a]ΔGw (Ns)	ΔGw (Gw/Ns)	ΔGw (Nav/Ns)	ΔGw (Gw/Nav)	ΔGw (Nt/Nav)	ΔGw (Gw/Nt)
N0	596	470	126	− 66	192	13	179
N40	423	330	94	− 40	133	27	106
N80	260	199	62	− 37	99	20	78
N120	106	77	30	− 22	51	2	49
N160	− 38	− 36	− 2	9	− 12	− 31	20

[a] Ns is the N supply, calculated as the Nav plus the amount of N applied with the fertilizer; Gw is the grain yield; Nav is the available soil N, calculated as the Nt plus the residual postharvest N in the soil, both determined in N0 plots; Nt is the plant N uptake in the aboveground biomass and the grain yield at maturity.

system (Lampurlanés et al., 2016). This advantage, particularly relevant in the Mediterranean environment, characterized by a low and erratic rainfall pattern during the spring, did not materialize in this research, very likely due to the considerable late winter-spring rainfall recorded in the two test years.

In terms of wheat N uptakes from heading to maturity, CT and NT techniques did not differ, but wheat plants grown in the NT regime intercepted more N from the fertilizer during the same interval (values of ^{15}Nrec higher than CT). Evidently, the NT regime resulted in more favourable conditions for the plants during the heading-maturity period, probably due to the greater soil water availability which partially offset the disadvantages observed in the first growth phase. Therefore, it is reasonable to assume that the NT technique, as compared to CT, allowed for a reduction of water used for the transpiration processes in the pre-heading phases of the cycle (as inferred by the lower biomass accumulation and the smaller photosynthesizing area) so allowing more water to be available to the crop during the final phases of its cycle.

The yield advantage of CT compared to NT has progressively reduced as the rate of N fertilizer applied increased. This occurred as yield became less responsive to Ns at greater N rates (Huggins and Pan, 1993) and further corroborates the hypothesis that the lower N supply under NT is the determining factor in reducing grain yield. This is consistent with the findings of Lundy et al. (2015), who, in their meta-analysis, found that, following the adoption of NT, N fertilization reduces yield declines.

On average, the NUE values were higher with NT than CT technique ($p = 0.005$). We observed that the decreases in grain yield with NT compared to CT, especially at higher rates of N fertilizer, were less marked than those for N supply. This is presumably attributable to the fact that the reduction in N supply was counterbalanced by the increase in N uptake efficiency, which was higher in NT than CT ($p = 0.001$). Some factors can contribute to explaining this result: i) the N uptake efficiency is reduced with the increase in N supply (and this is confirmed by analysing the data of this experiment relating to the N-fertilization treatment) and the values of N supply, for the same level of N fertilization, were always lower in NT compared to CT; ii) a better efficiency of use of the N fertilizer applied determined by the best edaphic conditions induced by the NT technique. The latter hypothesis is confirmed by the data relating to N fertilizer recovery (higher in NT compared to CT during the heading-maturity interval) and by the fact that the advantage of NT compared to CT has been achieved when N was applied in adequate amounts (rates higher than N80). It is also important to highlight how the ratio between N available and N supply was higher in NT than in CT, in particular at higher rates of N fertilizer. This allows us to hypothesize that under CT conditions the losses of N were higher than under NT; this aspect deserves further investigation, also considering that the literature on the matter is highly discordant (Oorts et al., 2007; Mkhabela et al., 2008; Constantin et al., 2010; Melero et al., 2011).

The wheat genotypes under study showed, as expected, large differences in phenological, morphological, and agronomic traits. In particular, the old genotype, compared to the modern one, produced more biomass and had lower grain yield and NUE. This is consistent with the findings of a recent study by Xu et al. (2022), who, working on a panel of 437 bread wheat (*Triticum aestivum* L.) cultivars released over 150 years, observed enhanced nutrient grain production efficiency in the modern (short) cultivars with respect to the older ones. The yield differences between the new and the old genotype were found to be low in conditions of low N availability (N0) and were amplified as the rate of N fertilizer increased, highlighting how the productivity gains achieved by breeding are achievable only in conditions of high availability of this nutrient. This has its own logic if we consider that breeding programs has been generally conducted under high-input conditions and this could have led to a failure in improving nutrient use efficiency and increasing grain yield when plants are grown in stressed environments. Nitrogen uptake at heading was markedly higher in the landrace than the modern variety, mainly attributable to the different phenology; in fact, the landrace, reaching the heading later (about 2 weeks) than the modern variety, had more time to intercept the N available in the soil. At maturity, a little difference was found between the two genotypes in terms of total N uptake. The results confirm that breeding played little role in the ability of wheat to absorb N from the soil (Slafer et al., 1990; Calderini et al., 1995; Foulkes et al., 1998). Consequently, the advantage in terms of NUE shown by the modern genotype compared to the old one (advantage, however, increasing as soil N increased) appeared related to its better ability to use the assimilated N to increase grain yield rather than to the improved ability to take up soil N (Brancourt-Hulmel et al., 2003; Barraclough et al., 2010).

Despite the marked differences observed between the genotypes for grain yield and N use efficiency (both for NUE and NUtE), their behaviour when varying the tillage technique was similar (high *p* values of the interaction Tillage × Genotype). However, the regression analysis highlighted that the tillage technique markedly affected the relationships between Gw and Nf, Ns, Nav and Nt in the modern variety but not in the landrace. On the other hand, in the landrace, the ΔGw between CT and NT was modest in all conditions of N availability. On the contrary, in the modern variety the variations in N availability, induced through the N-fertilizer application, have determined different responses in grain yield as the tillage technique varied. In particular, CT yield advantage over NT (up to the rate of 120 kg N ha^{-1}) appears attributable to about 80% to variations in the N supply and about 20% in the N utilization efficiency.

5. Conclusions

In conclusion, the present study shows that, in the Mediterranean areas and under the conditions in which the experiment was conducted, the switching from CT to NT can lead to initial reductions in wheat N uptake and grain yield. The N use efficiency component analysis clearly highlighted that the initial yield advantage of CT over NT observed in the modern variety was attributable for a large part to an increase in the potentially available N in soil, particularly during the vegetative phase of the crop cycle. Results from the present study have also shown that these negative effects can be mitigated by increasing the rate of N fertilizer applied. Obviously, from an agroecological point of view, this could have negative repercussions due to the increased risks of N release in the environment, the higher energy and economic costs, etc., which could partly offset the numerous advantages that NT is able to bring (soil erosion mitigation, carbon sequestration, reduction of energy costs for crop production, etc.). Therefore, the identification of appropriate N-fertilization strategies (rate, type, and timing of N-fertilizer application), capable of minimizing this impact and maximizing the N use efficiency by the crop, is required for an optimal application of the NT technique.

Overall, although the two wheat genotypes used in the experiment differed greatly in productivity and morpho-phenological traits, they responded similarly to the two different soil tillage practices studied. However, the adverse effects induced by the application of NT have become more evident in the modern variety than the landrace. Probably the modern variety, more dependent on the availability of N in soil to fully express its high productive potential, was penalized to a greater extent than the landraces by the reduction in the availability of N induced by the application of NT.

Considering that variations in soil N availability between CT and NT systems appeared to be variable in the different phases of the crop cycle, to further enhance the transition to NT regime, research should aim at identifying genotypes with N needs as much as possible synchronized with the N mineralization rates that this technique determines.

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CRediT authorship contribution statement

Rosolino Ingraffia: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **A. Lo Porto**: Writing – original draft, Writing – review & editing, Visualization. **Paolo Ruisi**: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Gaetano Amato**: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Dario Giambalvo**: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Alfonso S. Frenda**: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.108904.

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