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Impact of No Tillage and Low Emission N Fertilization on Durum Wheat Sustainability, Profitability and Quality

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Abstract: Mitigation practices for cereal systems, including conservation agriculture and low emission fertilization, are required to face global challenges of food security and climate change. The combination of these climate-smart approaches was investigated for durum wheat in a dry region of the Mediterranean basin in two crop seasons. The experimental design consisted in two different genotypes, Marco Aurelio (high protein content) and Saragolla (higher adaptability), subjected to no tillage (NT) vs. conventional tillage (CT) and to two fertilization strategies (standard vs. low emission plus an unfertilized control). Different environmental and economic sustainability parameters as well as two different technological and nutritional quality traits were evaluated. Saragolla showed a better environmental adaptability and a higher nitrogen use efficiency, evaluated as partial nutrient balance (+27%), and was associated with a lower protein content (14.5% vs. 15.6%). NT was associated with an improvement in yield (+15%) and quality, i.e., micronutrients (Fe, Zn) and antioxidant capacity (+15%), in the drier crop year. Low emission fertilization did not reduce crop performance and its combination with NT showed a higher economic net return. The combination of the two mitigation practices improved not only environmental and economic sustainability but also the health quality of durum wheat under water limited conditions.

Keywords: conservative agriculture; climate-smart crop production; micronutrients; AOX; gluten; durum wheat quality; slow-release fertilizers

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1. Introduction

Agriculture faces the dual challenges of increasing productivity to meet global food demands while minimizing environmental impacts. This is particularly relevant in regions vulnerable to climate change, such as the Mediterranean basin, where water scarcity and soil degradation are significant concerns. Durum wheat (*Triticum turgidum* L. *durum*) is a staple crop with high importance in Mediterranean area, with Italy representing the second largest producer after Canada [1]; durum wheat is mainly used for the production of pasta and semolina bread, and its productivity and quality is generally influenced by environmental conditions, including terminal abiotic stresses that can cause severe yield loss [2–5]). The major stresses typically occurring in Mediterranean area are heat and drought, especially during the grain filling period, and their severity and duration determine the extent of the yield loss, which can be higher than 50% [6,7]. To address these challenges, the implementation of climate-smart agricultural practices, aimed to improve mitigation both by increasing carbon sequestration and reducing greenhouse gases emissions due to tillage and fertilization [8–10], is essential to ensure the sustainability, profitability, and quality of durum wheat production.

Conservation agriculture (CA), particularly no-tillage (NT) systems, has emerged as a viable approach for improving soil structure, water retention, and carbon sequestration, thereby enhancing the resilience of cropping systems under climate stress [11–13]. No-tillage practices contribute to the preservation of soil organic matter, reduce soil erosion, and promote biodiversity, factors that collectively support more sustainable agricultural ecosystems [14–16]. No till practices are generally reported to reduce crop yield by about 5%; however, in drier environments, wheat yields match those achieved under conventional tillage [17]. Complementing NT, low-emission nitrogen (N) fertilization strategies, including the use of slow-release fertilizers with urease and nitrification inhibitors, have been shown to reduce greenhouse gas emissions without having a negative influence on nitrogen use efficiency (NUE), which is crucial for lowering the environmental footprint of crop production [18–20]. The EU N expert Panel indicated that the recommended NUE values, in terms of N output/input balance, should be comprised within 50 to 90%, with a great influence of farm type, management and environmental conditions [21,22].

While the environmental benefits of these practices are well-documented, their effects on quality, particularly in durum wheat, require further investigation. Durum wheat quality is categorized by several traits that are essential for its market value, particularly in the pasta-making industry. Among these traits, protein content and composition are critical for determining the technological performance of the grain, influencing dough strength and elasticity [23]. Beyond protein quality, the micronutrient content of durum wheat, particularly iron (Fe) and zinc (Zn), is gaining attention due to its importance in human nutrition. Micronutrient deficiencies, also known as hidden hunger, remain a global health issue, and enhancing Fe and Zn content in staple crops like wheat can significantly contribute to addressing this problem [24]. Furthermore, the antioxidant capacity of durum wheat, linked to its content of phenolic compounds and flavonoids, adds a nutritional dimension to its value, as antioxidants are known to reduce oxidative stress and contribute to human health [25,26]. However, few investigations report the effects of no tillage on durum wheat quality and its influence requires further clarification. For instance, in a study conducted in the Mediterranean area [27], the authors reported that variations in protein content and high and low molecular weight glutenin subunits expression in no tillage systems depend on field growing conditions, highlighting the complexity of storage protein regulation. Furthermore, no tillage has been found to enhance the activity of antioxidant enzymes during grain filling, but the correlation with grain antioxidant activity was not explored [28].

This study aims to evaluate the hypothesis that the combination of no-tillage and low-emission nitrogen fertilizers might improve the sustainability of durum wheat production in the context of climate-smart agriculture in South Italy. Specifically, the effects of these practices were investigated in relation to (i) sustainability, in terms of nitrogen use efficiency, (ii) economic profitability for farmers, and (iii) grain quality traits, including protein content and composition, technological quality, micronutrient content (Fe, Zn), and antioxidant activity (AOX). By integrating agronomic, economic, and environmental assessments, this study seeks to contribute to the knowledge on sustainable cereal production in Mediterranean environments.

2. Materials and Methods

2.1. Description of the Study Site

Field experiments were carried out in the province of Foggia, at farm level in Bovino (Foggia, Italy, 41°17′22.8″ N 15°26′40.7″ E, at about 243 m a.s.l.) during 2019–2022 in two crop seasons (2021 and 2022, respectively). Weather data were recorded from a proximal weather station, with monthly temperatures and precipitations (P) reported in Figure 1; in addition, 10-day trends of growing degree days (GDD), cumulative P, and potential evapotranspiration (PET) calculated according to Hargreaves method [29] are reported in Appendix A (Table A1).

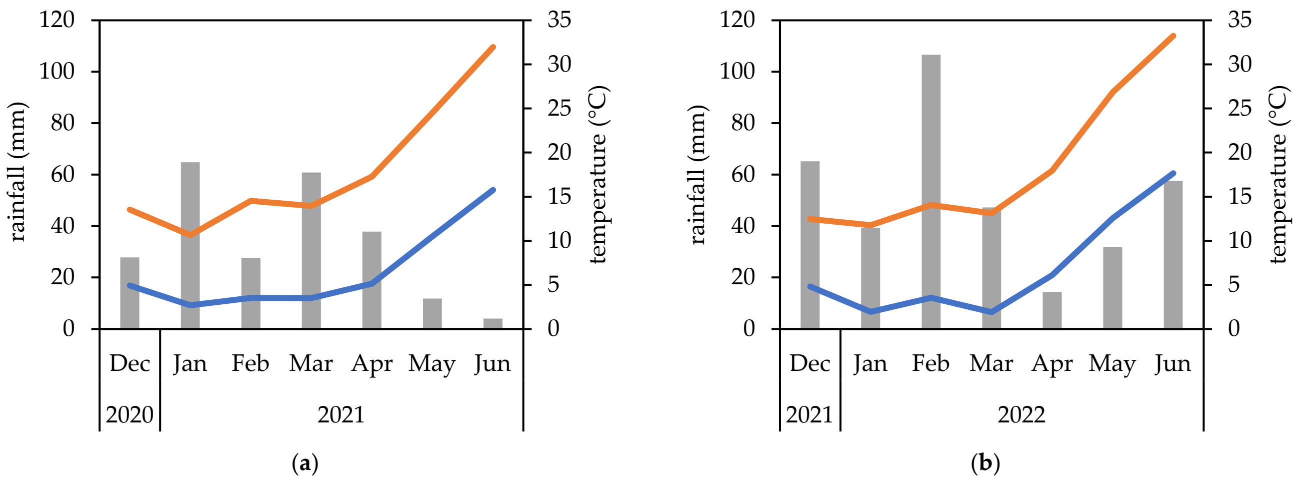


Figure 1. Weather conditions during experimental field trials, described in terms of monthly precipitation (grey histograms) and maximum (orange line) and minimum (blue line) temperatures during (**a**) 2021 and (**b**) 2022 crop years.

2.2. Experimental Design, Soil Sampling

Each plot was 18 m^2 (3 m × 6 m) in a split-split plot design with tillage as main plot, genotype as sub-plot, and fertilization as sub-sub plot, each with three replications, for a total of 36 plots in each experimental crop year. The soil for the experiments was a silty loam Vertisol, according to USDA classification, with 26.4% sand, 52.8% silt, and 15.1% clay, respectively, with 8.2 pH, 323 $\mu s\ cm^{-1}$ of conductivity, low total nitrogen (N, 0.66 g/kg, by CHNS elemental analyzer), and good available P_2O_5 (43.1 ppm, determined by Olsen method) and soil organic carbon (SOC, 1.71%, by Walkley–Black method) as starting conditions and at the end of the experiment. Mean SOC stock variations (t/ha of C) between NT and CT were evaluated as following: soil C stock = (final SOC − initial SOC) × bulk density × soil depth (0.3 m).

2.3. Land Preparation, Fertilization, Sowing, Weeding, and Disease Control

Wheat was the preceding crop. Two soil tillage practices were compared within the field experiments, conventional tillage (CT) and no tillage (NT), as detailed in Supplementary Table S1. CT did not include straw incorporation. Two durum wheat genotypes largely cultivated in Italy were adopted, with Marco Aurelio, characterized by a higher protein content suitable for good technological performance, and Saragolla, characterized by a higher environmental adaptability, as detailed in Supplementary Material (Table S1).

Sowing occurred on 16 December 2020 and 20 December 2021 at a rate of 450 seeds per m^2. Herbicides and fungicides were adopted according to the local practices. A standard nitrogen fertilization, according to the local practice (T1), was compared to a low-emission strategy with the use of stabilized fertilizers with inhibitors of urease and nitrification (T2); an unfertilized control (T0) was included in the experiment to evaluate N use efficiency. Details of N rate, source, and timing are reported in Table 1. The N rates were defined on the basis of the indications for durum wheat in Italy for good quality targets [30]. Before sowing, 50 kg/ha of phosphorus was supplied as a single superphosphate. Before harvest, for each plot, plants from a square meter were collected for the determination of plant height (PH) and harvest index (HI). At maturity (197 and 194 days after sowing), grains were harvested by plot combine and grain yield (GY, t/ha) was determined and normalized at 12% moisture. An aliquot of 1 kg was collected for analyses, including grain weight (GW, mg), test weight (TW), and grain protein content (GPC, Foss Tecator 1241). Grain number per m^2 (GN) was calculated as the ratio between GY and GW.

Table 1. Details of nitrogen and sulfur fertilization strategies in terms of N source and timing.

Code		GS 23		GS 31	
		N (kg/ha)	N Source	N (kg/ha)	N Source
T0	unfertilized	0	-	0	-
T1	standard	90	U	50	AN
T2	low emission	80	UAS + NBPT	40	ASN + DMPP

N = nitrogen; S = sulfur; GS 23 = tillering; GS 31 = stem elongation; U = urea; AN = ammonium nitrate; UAS = urea ammonium sulfate; NBPT = N-(n-Butyl)thiophosphoric triamide, inhibitor of urease; ASN = ammonium sulfate nitrate; DMPP = 3,4-Dimethylpyrazole phosphate, inhibitor of nitrification.

2.4. Crop Physiological Measurements

Data on crop development were recorded and expressed as days after sowing (DAS) and GDD. At heading (GS 55, 137, and 141 days for 2021 and 2022), measurements of canopy spectral reflectance were carried using a field spectroradiometer (Apogee SS-110). Normalized difference vegetation index (NDVI) was calculated [31] according to the following formula:

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{RED}})/(\rho_{\text{NIR}} + \rho_{\text{RED}}) \quad (1)$$

with ρ_{NIR} as the crop reflectance at 800 nm and ρ_{RED} as the crop reflectance at 680 nm. At maturity, plant height (PH) was also measured. N uptake in grain was determined by multiplying grain yield (d.m.) to N concentration in grain. N use efficiency traits were calculated according to the formula:

$$\text{NAE} = (\text{GY}_x - \text{GY}_0)/\text{N rate} \quad (2)$$

$$\text{ARE} = (\text{N uptake}_x - \text{N uptake}_0)/\text{N rate} \quad (3)$$

$$\text{PNB} = \text{N uptake}/\text{N rate} \quad (4)$$

with NAE as N agronomic efficiency, ARE as apparent N recovery efficiency, and PNB as partial nutrient balance [32,33]; $_x$ and $_0$ referred to the N fertilization rates and unfertilized control, respectively.

2.5. Analysis of Durum Wheat Storage Protein Composition

Grains were milled by laboratory milling with a sieve of less than 1 mm (Bona 4RB, Monza, Italy) and flour was used for chemical analysis. Analysis of protein composition was carried out in order to evaluate differences in gliadin and glutenin content [34,35].

Briefly, 100 mg of flour was suspended in a 0.4 mL solution of KCl buffer (pH 7.8) and centrifuged at 4 °C at 10,000× *g* for 15 min to remove soluble proteins (albumins and globulins). The KCl-insoluble fraction was then suspended in 1-propanol solution (50% *v*/*v*) and centrifuged for 10 min at 4500× *g* (repeated twice) and gliadins were collected. Glutenins were extracted from the pellet by extraction solution (1-propanol 50% *v*/*v*, 1% DTT) after centrifugation at 10,000× *g* for 10 min (room temperature). Extracted glutenins and gliadins were quantified, and their subunits were separated by using a BioRad Mini Protean II system (Bio-Rad, Hercules, CA, USA) with precast acrylamide gels. Gels were stained with Coomassie Brilliant Blue G250 and digitally acquired (Epson Perfection V750pro). Molecular weight markers, from 10 to 250 kDa, were used (Bio-Rad Co., Hercules, CA, USA). Image analysis of gels was performed using ImageLab software (V6.1, Bio-Rad Co., Hercules, CA, USA).

Protein composition was reported in terms of gliadin to glutenin ratio (glia/glut) and HMW-GS to LMW-GS ratio (H/L).

2.6. Antioxidant Capacity

The antioxidant capacity (AOX) was evaluated using the Direct QUENCHER$_{\text{ABTS}}$ Assay (QUick, Easy, New, CHEap, and Reproducible ABTS-2,2′-azinobis-3-ethylbenzothiazoline-6-sulfonic acid) [26]. This method is based on the direct reduction of ABTS radical cation

($ABTS^{\bullet+}$) by the antioxidants present in the fine solid particles of the food sample, resulting in a decrease in absorbance at 734 nm (A_{734}). Measurements were carried out by reacting 10 mL of $ABTS^{\bullet+}$ solution with whole flour sample, ranging from 1 to 2 mg of dry weight, for 60 min. The (%) decrease of A_{734} measured after sample incubation, compared to the A_{734} of $ABTS^{\bullet+}$ solution, was calculated. A linear relationship of the (%) decrease of A_{734} on sample amount was verified by linear regression analysis of the data. AOX was obtained by comparing the slope derived by linear regression analysis with that of the Trolox-derived calibration curve. Data are expressed as mmol Trolox equivalent per kg of dry weight.

2.7. Mineral Analysis

Grain micronutrients, i.e., iron (Fe) and zinc (Zn) content, were analyzed with an induced coupled plasma optical emission spectrometer (ICP-OES). Before the analytical process, samples (0.5 g d.w.) were dissolved in 10 mL HNO_3/H_2O_2 (3:1 v/v) by microwave assisted mineralization (CEM-Mars6). Digested samples were then diluted with Milli-Q water to 50 mL (US-EPA 1989, method 3050 B) and analyzed by ICP-OES. The data were expressed as ppm [35].

2.8. Economic Analysis

Economic analysis was carried out calculating economic net return (ENR, EUR/ha) as following:

$$\text{ENR} = \text{gross return} - \text{cost of cultivation} \quad (5)$$

with gross return as GY (t/ha, 12% moisture) multiplied per durum wheat market price (EUR/t) and cost of cultivation was determined based on the data reported in the Supplementary Materials. To this end, reference durum wheat prices were taken from the historical records of the weekly prices from the Chamber of Commerce of Foggia (https://www.fg.camcom.it, accessed on 10 July 2024), and three market price scenarios were considered due to the variability recorded in the last five years: 300 EUR/t, 400 EUR/t, and 500 EUR/t. According to the supply chain agreements largely present in Italy, a premium bonus on market price of 10 EUR/t is applied when GPC is higher than 13.5%, with a further bonus of 10 EUR/t with GPC of 14.5% or higher [36]. Supplementary EU, national, or regional conditions were not considered for the economic profitability.

2.9. Statistical Analysis

For each crop year, a standard least square regression model was conducted and means were separated by least significant difference according to Tukey's test as post hoc, with a level of significance of $p < 0.05$. Two separated Pearson's multiple regression analyses between the investigated parameters were carried out for samples from conventional tillage and no tillage. Statistical analysis was carried out by JMP (SAS Institute Inc., Cary, NC, USA, 2009).

3. Results

3.1. Effect of Weather Conditions and Agronomic Management on Crop Performances

The first crop year (2021) was characterized by higher rainfall during winter and vegetative growth stages with respect to the second year (2022). On the contrary, in 2022, warmer and wetter conditions were observed during spring, thus influencing grain filling duration, with 31 days in 2022 vs. 26 days in 2021. Thermal trend was comparable between the two years; in fact, anthesis was achieved at 137 and 141 days after sowing in the two years, respectively (about 1–2 days earlier for Saragolla, at about 1200 °C d).

Results of agronomic traits in the two crop years, as subjected to analysis of variance, are reported in Table 2. Spectral measurements carried out at heading (GS 55) only showed lower NDVI values under no tillage (NT) in 2021, which was characterized by a higher spring rainfall deficit, while no differences were observed due to genotype. In both years, significantly higher values due to fertilization were observed with respect to the unfertilized control (T0). The same response to N supply was observed in terms of plant height (PH).

Also, a lower PH was observed under NT only in 2022 (−14%), while a genotypic difference was found in 2021, with higher PH in Saragolla (+9%).

Table 2. Effect of soil tillage, genotype, and N fertilization strategy and their interactions on durum wheat agronomic traits.

Year	Source of Variation	NDVI GS 55	PH cm	HI %	GW mg	GY t/ha	PNB kg/kg	NAE kg/kg	ARE kg/kg
2021	CT	0.70 a	69.1 a	27.7 b	32.9 b	2.0 b	0.49 a	6.0 a	25.2 a
	NT	0.65 b	71.2 a	29.7 a	36.1 a	2.3 a	0.55 a	5.9 a	23.5 a
	Marco Aurelio	0.67 a	67.1 b	25.8 b	33.8 a	1.6 b	0.39 b	3.6 b	17.4 b
	Saragolla	0.68 a	73.2 a	31.6 a	36.1 a	2.7 a	0.55 a	8.3 a	31.3 a
	T0	0.47 b	58.7 b	28.3 a	35.8 a	1.4 b	-	-	-
	T1	0.77 a	75.1 a	29.1 a	33.8 a	2.4 a	0.46 b	5.3 a	20.7 b
	T2	0.79 a	76.7 a	28.7 a	33.8 a	2.6 a	0.55 a	6.6 a	28.0 a
	TxG	ns	ns	ns	ns	ns	ns	*	*
	TxN	ns	ns	ns	ns	ns	ns	ns	ns
	GxN	ns	ns	*	ns	*	ns	ns	ns
	TxGxN	ns	ns	*	*	*	*	ns	*
2022	CT	0.72 a	67.0 a	31.6 a	44.0 a	2.1 a	0.51 a	3.6 a	20.2 a
	NT	0.69 a	58.7 b	31.7 a	42.9 a	2.2 a	0.51 a	4.5 a	16.9 a
	Marco Aurelio	0.70 a	61.6 a	29.4 b	43.7 a	1.9 b	0.48 a	3.2 a	17.5 a
	Saragolla	0.72 a	64.1 a	34.0 a	43.2 a	2.4 a	0.54 a	4.9 a	19.6 a
	T0	0.60 b	58.1 b	33.5 a	44.4 a	1.6 b	-	-	-
	T1	0.75 a	66.8 a	30.8 a	43.4 a	2.3 a	0.49 a	3.7 a	19.2 a
	T2	0.78 a	63.6 a	30.6 a	42.7 a	2.4 a	0.53 a	4.4 a	17.9 a
	TxG	ns	ns	ns	*	*	ns	*	ns
	TxN	ns	ns	ns	*	ns	ns	ns	ns
	GxN	ns	ns	ns	*	ns	ns	ns	ns
	TxGxN	ns	ns	ns	ns	ns	ns	ns	ns

Abbreviations: CT = conventional tillage; NT = no tillage; T0 = unfertilized control; T1 = standard fertilization; T2 = low emission fertilization; T = tillage; G = genotype; N = fertilization strategy; NDVI = normalized difference vegetation index; PH = plant height; HI = harvest index; GW = grain weight; GY = grain yield; PNB = partial nutrient balance; NAE = agronomic nitrogen use efficiency; ARE = apparent recovery efficiency. Different letters indicate significant differences according to Tukey's test; ns = not significant; * significant difference at $p < 0.05$. Level of significance: ns = not significant.

As regards the yield components, harvest index (HI) showed a higher general mean value in Saragolla; in addition, the TxGxN interaction was significant only in 2021, with no significant differences due to N treatment within each genotype (Figure 2). Grain weight (GW) was generally lower in the first year, which was characterized by a shorter and drier grain filling period. In the same year, NT showed a higher GW than wheat cultivated under CT. Genotype and N fertilization, in general, did not have a significant effect on GW (Figure 2). The observed behavior of the yield components influenced grain yield (GY), which were significantly higher under NT in 2021, characterized by higher water deficit during grain filling. In addition, a significant influence of genotype was found, with Saragolla generally more productive than Marco Aurelio (about +45%). This difference was marked in the N fertilized thesis; the highest GY was observed in Saragolla, under NT, in the T2 strategy (3.9 t ha^{-1}).

Different N use efficiency (NUE) traits were also calculated to assess the level of sustainability of the different agronomic practices. In general, Saragolla showed a significantly higher NUE in 2021 (0.55 vs. 0.39), while in 2022, no difference was found with Marco Aurelio (Table 2). In relation to N fertilization strategies, the low emission T2 showed higher efficiency in terms of PNB and ARE with respect to the standard strategy T1, but only in the first crop year (Table 2). The highest NUE (PNB) value (0.87) was achieved in 2021 with Saragolla fertilized under the T2 strategy in NT tillage (Figure 2).

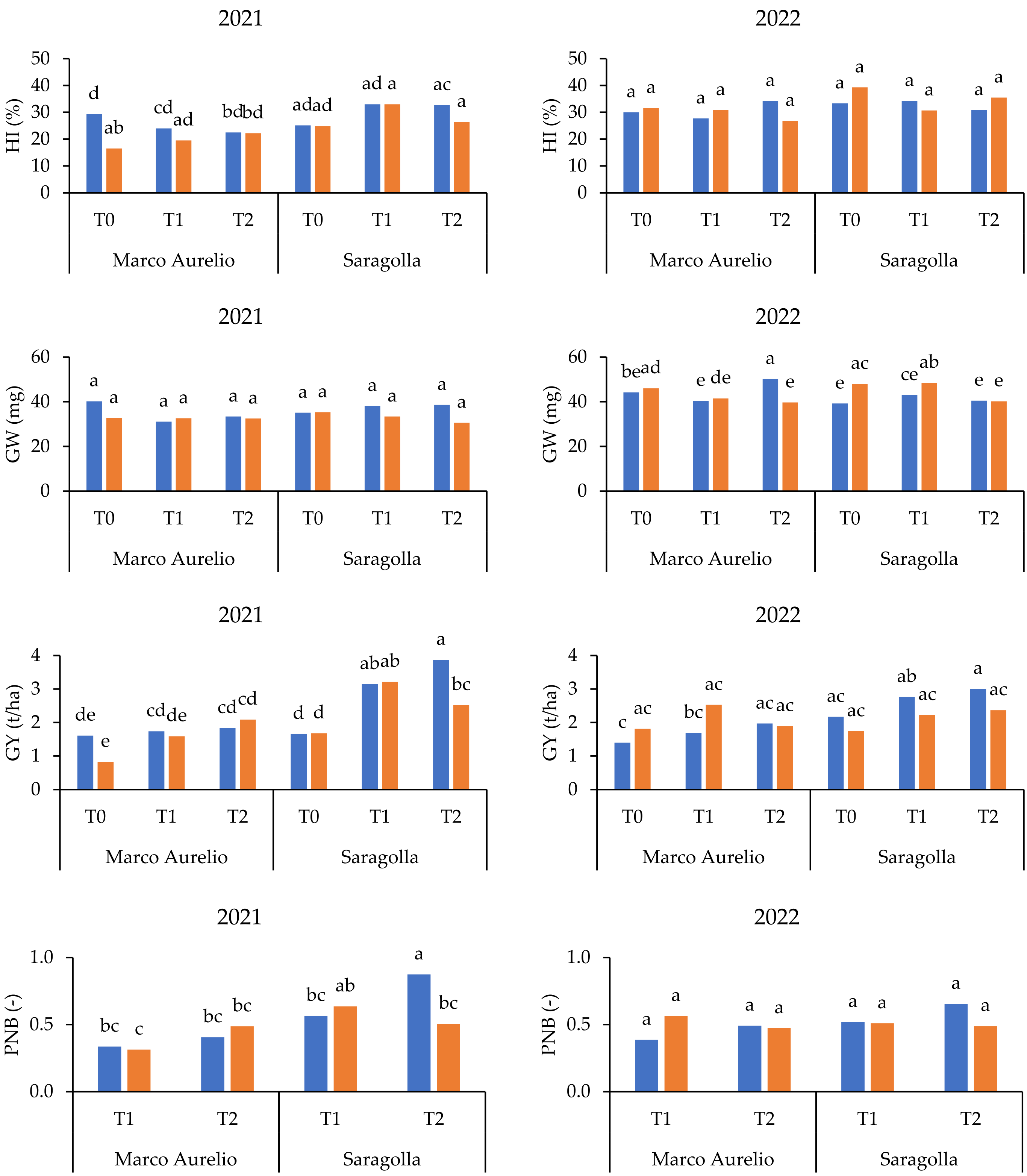


Figure 2. Response of two durum wheat genotypes subjected to two tillage and three N fertilization strategies in two consecutive growing seasons in terms of harvest index (HI), grain weight (GW), grain yield (GY), and partial N balance (PNB). Blue and orange histograms refer, respectively, to no tillage and conventional tillage samples. Different letters indicate significant differences according to Tukey's test.

3.2. Effects on Durum Wheat Technological and Health Quality

Test weight (TW), like GW, was higher in NT than CT only in 2021. In that year, higher values were observed for Saragolla and with T2 fertilization. As regards quality traits, in both crop years, Marco Aurelio showed a mean higher GPC than Saragolla (Table 3). In 2021, a mean higher GPC was observed (+5%) for NT compared to CT, in particular in the unfertilized control group T0 (Figure 3). N fertilization resulted in the highest source of variation for GPC, with a significant increase due to a higher N rate (140 kg-N/ha T1 > 120 kg-N/ha T2 > 0 kg-N/ha T0). However, both T1 and T2 fertilizations led to GPC values higher than the quality threshold (14.5%), which is satisfactory for the pasta industry, in both years.

Table 3. Effect of soil tillage, genotype, and N fertilization strategy and their interactions on durum wheat quality traits.

Year	Factor	TW kg/hl	GPC %	SSV Ml	glia/glut -	H/L -	AOX mmol/kg	Fe ppm	Zn ppm
2021	CT	74.5 b	14.3 b	33.9 a	1.16 a	0.22 b	47.6 b	53.9 b	35.9 b
	NT	75.6 a	15.0 a	33.4 a	1.12 b	0.30 a	54.9 a	59.0 a	43.4 a
	Marco Aurelio	73.8 b	15.0 a	37.0 a	1.13 a	0.30 a	51.5 a	60.1 a	44.9 a
	Saragolla	76.3 a	14.4 b	30.3 b	1.15 a	0.22 b	50.9 a	52.8 b	34.5 b
	T0	74.1 c	12.8 b	30.2 b	1.07 b	0.21 b	30.4 b	47.6 b	34.7 c
	T1	75.3 b	15.5 a	36.5 a	1.16 a	0.29 a	62.4 a	61.1 a	40.8 b
	T2	75.8 a	15.7 a	34.2 a	1.19 a	0.29 a	61.0 a	60.7 a	43.5 a
	TxG	*	**	*	*	ns	ns	*	*
	TxN	ns	***	ns	ns	ns	ns	*	*
	GxN	*	**	*	***	*	ns	*	*
	TxGxN	ns	*	ns	ns	ns	ns	*	*
2022	CT	76.4 a	15.2 a	38.2 a	1.26 a	0.08 b	33.6 a	31.1 b	25.4 b
	NT	73.8 b	15.5 a	37.9 a	1.19 b	0.12 a	32.5 a	37.1 a	39.8 a
	Marco Aurelio	75.1 a	16.2 a	38.3 a	1.16 b	0.10 a	35.7 a	27.7 b	27.1 b
	Saragolla	75.1 a	14.5 b	37.8 a	1.30 a	0.10 a	30.4 b	40.5 a	38.0 a
	T0	75.2 a	12.7 c	31.9 b	1.05 c	0.15 a	29.2 c	25.1 c	22.9 b
	T1	74.2 a	17.4 a	40.9 a	1.23 b	0.09 b	36.5 a	43.4 a	47.5 a
	T2	75.8 a	16.0 b	41.3 a	1.40 a	0.07 b	33.4 b	33.9 b	27.3 ab
	TxG	ns	*	ns	ns	*	ns	ns	ns
	TxN	ns	***	ns	*	ns	ns	ns	ns
	GxN	ns	ns	ns	*	*	*	*	*
	TxGxN	ns	*	ns	*	*	ns	*	ns

Abbreviations: CT = conventional tillage; NT = no tillage; T0 = unfertilized control; T1 = standard fertilization; T2 = low emission fertilization; T = tillage; G = genotype; N = fertilization strategy; GPC = grain protein content; SSV = sodium-dodecyl-sulfate sedimentation volume; glia/glut = gliadin-to-glutenin ratio; H/L = HMW-to-LMW glutenin subunits ratio; AOX = antioxidant capacity; Fe = iron content in grain; Zn = zinc content in grain. Different letters indicate significant differences according to Tukey's test; ns = not significant; * significant difference at $p < 0.05$. Level of significance: ns = not significant; ** = significant at $p < 0.01$; *** = significant at $p < 0.001$.

Technological quality was evaluated by SDS sedimentation volume (SSV). Of course, this was influenced by both protein content and composition. The higher GPC found in Marco Aurelio resulted in a better technological performance (SSV) only in 2021. Indeed, the same genotype showed a higher HMW-GS to LMW-GS ratio (H/L); this is due to a lower LMW-GS expression, which is generally responsible for good technological quality in durum wheat. No significant differences between the two N fertilization treatments (T1 and T2) were observed.

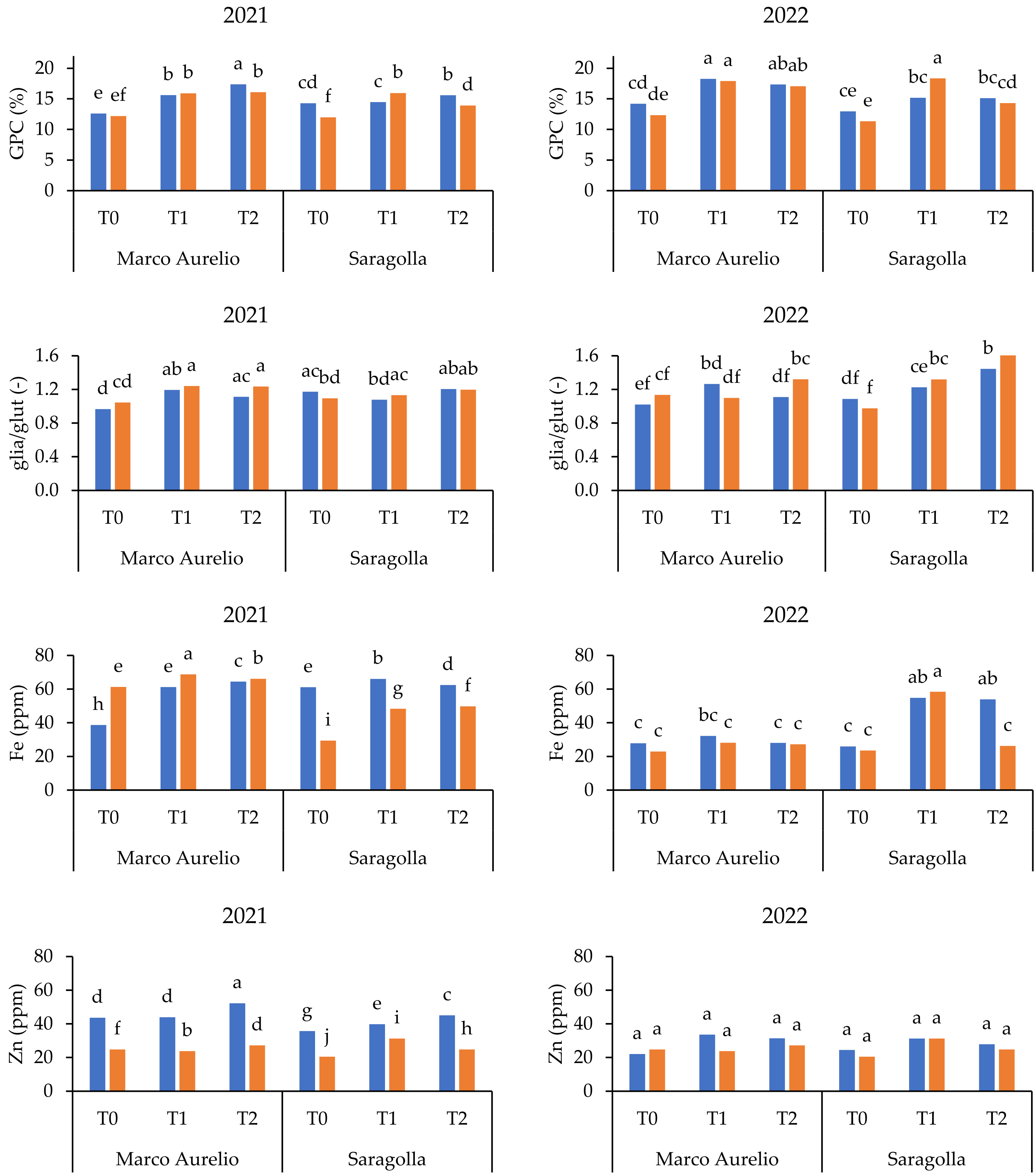
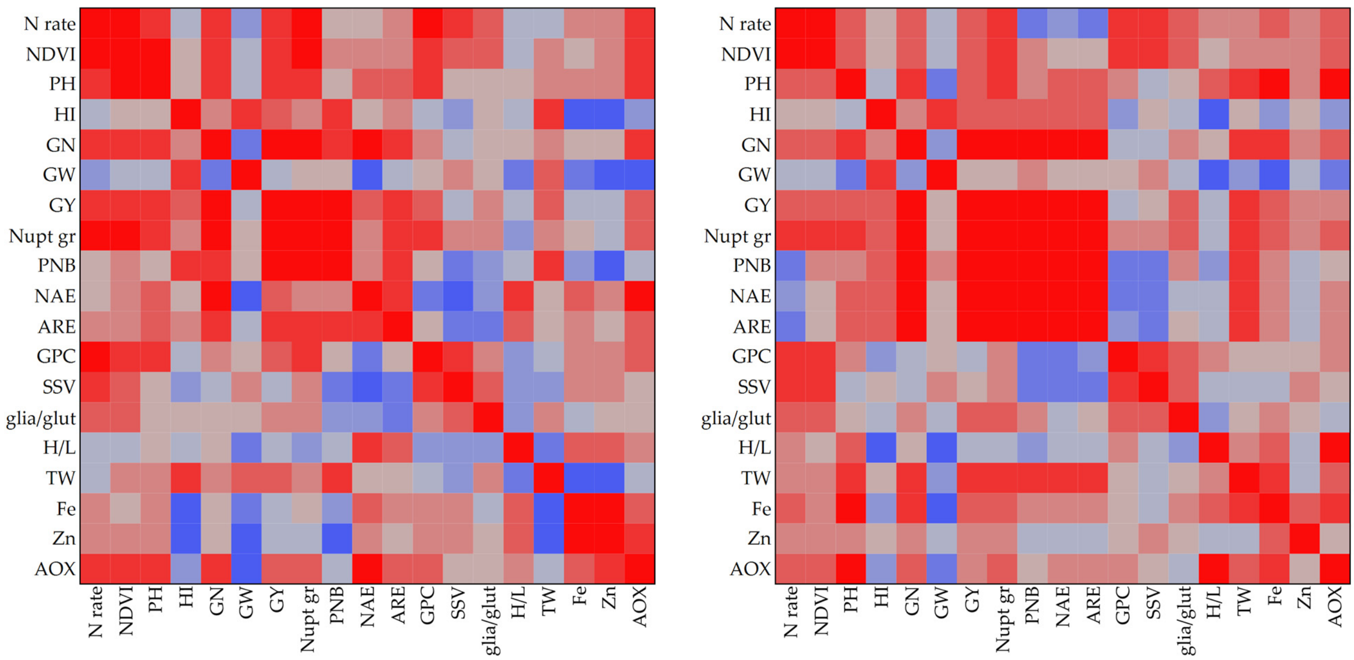


Figure 3. Response of two durum wheat genotypes subjected to two tillage and three N fertilization strategies in two consecutive growing seasons in terms of grain protein content (GPC), gliadin to glutenin ratio (glia/glut), iron (Fe), and zinc (Zn) content. Blue and orange histograms refer, respectively, to no tillage and conventional tillage samples. Different letters indicate significant differences according to Tukey's test.

Interesting results were observed for the investigated health-related quality traits, i.e., antioxidant capacity (AOX) and micronutrients content, showing higher values under NT (on average +15%, Table 3), even if only in 2021 for AOX. This trait was higher in Saragolla than Marco Aurelio only in 2022. Contrasting genotypic response in grain Fe (range within 23 to 64 ppm) and Zn (range within 22 to 52 ppm) content was observed, with higher concentrations in Marco Aurelio than Saragolla in 2021. Finally, higher N rates improved both AOX and micronutrient content, since unfertilized T0 generally showed lower values, except for Marco Aurelio in 2022 for Zn (Figure 3).

3.3. Multiple Regression Analysis

The analysis of the correlations between agronomic and quality traits is shown in Figure 4a (CT) and Figure 4b (NT). The trend of correlations was comparable between the two tillage systems. Also, the N rate showed a strong correlation with NDVI, yield, and quality traits, except H/L. The same NDVI measurements at heading showed a good correlation with both GY and GPC. As regards quality, a negative correlation between H/L and SSV was also found, as well as between GW and AOX and Fe and Zn, in both CT and NT.



(**a**) (**b**)

Figure 4. Heatmap of Spearman's multiple regression analysis between the investigated agronomic and quality traits for durum wheat grown under (**a**) conventional tillage and (**b**) no tillage. R values are indicated in a scale of blue (negative) and red (positive). Abbreviations: NDVI = normalized difference vegetation index; PH = plant height; HI = harvest index; GW = grain weight; GY = grain yield; PNB = partial nutrient balance; NAE = agronomic nitrogen use efficiency; ARE = apparent recovery efficiency; GPC = grain protein content; SSV = sodium-dodecyl-sulfate sedimentation volume; glia/glut = gliadin-to-glutenin ratio; H/L = HMW-to-LMW glutenin subunits ratio; AOX = antioxidant capacity; Fe = iron content in grain; Zn = zinc content in grain.

3.4. Economic Profitability

The economic net return (ENR) of the different experimental combinations of durum wheat genotypes, soil tillage, and fertilization strategies in the current two-year field trial was predominantly influenced by the productive performance and, secondarily, by the achievement of quality targets and the different costs of cultivation. Wheat price, of course, resulted in one of the major factors influencing economic sustainability, falling into the 300 EUR/t scenario, generally with negative ENR (Table 4). Comparable ENR were observed between the two crop years. Conservative agriculture generally showed higher net return because of the lower costs (supplementary) without negatively influencing yield (from +36 to +176 EUR ha^{-1}). On the other hand, genotype was markedly relevant, with genotype Marco Aurelio characterized by a gross return that generally did not compensate for the costs, unless under the best price scenario (500 EUR/t). In general, fertilization benefited economic sustainability; in fact, the unfertilized control generally showed negative ENR values. Also, the low emission T2 strategy, −20 kg/ha with respect to the standard T1, was generally more economically efficient (Table 4) in all price scenarios.

Table 4. Economic analysis of the mean net return (ENR, EUR/ha) of durum wheat genotypes grown under different tillage and fertilization managements, with three different wheat price scenarios: 300 EUR/t, 400 EUR/t and 500 EUR/t.

Source of Variation	Factor	2021			2022		
		300 EUR/t	400 EUR/t	500 EUR/t	300 EUR/t	400 EUR/t	500 EUR/t
tillage	CT	−191	7	206	−159	51	260
	NT	−80	151	382	−123	93	310
genotype	Marco Aurelio	−296	−134	27	−215	−27	161
	Saragolla	24	292	560	−67	171	409
N fertilization	T0	−240	−96	49	−140	38	216
	T1	−102	140	382	−138	92	322
	T2	−65	193	450	−65	85	316

Abbreviations: CT = conventional tillage; NT = no tillage; T0 = unfertilized control; T1 = standard fertilization; T2 = low emission fertilization; T = tillage; G = genotype; N = fertilization strategy.

4. Discussion

The observations reported in the current study are within the framework of agronomic management suggested by the climate-smart crop production strategies (FAO) to promote mitigation and resource use efficiency [9,37]. This approach has been investigated for durum wheat, which represents one of the main species in Mediterranean cropping systems, especially in South Italy [5], by evaluating, at the same time, the effects of conservative agricultural practices (no tillage) under low emission fertilization in relation to both different qualitative durum wheat traits and the environmental and economic sustainability of the management systems.

4.1. The Influence of Agronomic Practices on Yield and Environmental Sustainability

Environmental influence on crop performance is generally significant in the Mediterranean area due to the considerable seasonal variability in temperature and rainfall distribution. In the current study, weather conditions in the two experimental years did not influence final grain yield, but an effect was observed in relation to yield components, with lower grain weight in the crop year characterized by drier and shorter grain filling [38]. In that year, no tillage showed an improvement in yield (grain weight) and protein content [39–41]. It is reported in the literature that the benefits of no tillage in wheat occur more frequently under dry conditions [17] due to the improvement of soil hydraulic properties [13] associated with an increase in soil organic matter [8,31], which reduces evapotranspiration losses [42,43]. Observations from the current study of 1 t/ha of SOC accumulated during the experiment under NT are in accordance with the well-known improvement in soil fertility due to conservation agriculture [12]. The adoption of slow-release fertilizers is reported to show comparable or improved N use efficiency with a lower greenhouse gas emission level [19,44–46]. The low moisture content of agricultural soils in Mediterranean environments favors nitrification activities; for this reason, the use of nitrification inhibitors, such as DMPP, is recommended for mitigation goals [47]. Under our experimental conditions, the combination of no tillage with the use of lower N rates of slow-release fertilizers does not negatively affect yield and quality traits. On the other hand, the contribution of both practices to mitigation resulted marked, in accordance with the indications of climate-smart crop production, with higher grain yield per unit of GWG [10,15,48]. It has been also reported that N fertilization reduces yield gaps between CT and NT, and that durum wheat yield is generally not influenced by tillage [4,5,40]; this trend was generally observed under our experimental conditions, since the interaction between tillage and fertilization was limited. On the other hand, the different response of the two genotypes suggests that varietal choice is a critical aspect for durum wheat cultivation in conservative agriculture, in particular on NUE [49]. Breeding activity for this target is in progress, reporting early vegetative growth as a key trait to improve yield under no tillage [50]. The better adaptation observed in Saragolla may be possibly related to differences in phenology, with good earliness and adaptation to the Mediterranean environment [51]. As regards the impact of fertilization on NUE traits, in general the low emission strategy showed a higher efficiency, with values within the optimal range indicated by the EU Nitrogen Expert Panel [22]. The standard fertilization adopted by farmers, in fact, is proposed for high quality targets; however, under low yield conditions, these could be associated with a low NUE, even if comprised within the EU panel's range, in terms of ratio between N output to N input, i.e., partial N balance [21]. The low emission fertilization strategy achieved higher NUE values, closer to the target (90%) proposed by EU N Expert Panel [22].

4.2. The Influence of Agronomic Practices on Quality and Economic Profitability

Grain filling is generally one of the most sensitive stages to abiotic stresses, especially water deficit, having a significant influence on quality [2,3]. The impact on protein accumulation was more marked in terms of protein composition, rather than content, with a higher gliadin value and its ratio with glutenin in the wetter crop year during grain filling. Few studies report the effect of tillage on wheat storage protein composition. In a study under transition to conservative agriculture, the authors reported differences of response to N fertilization of gliadin accumulation due to rainfall during grain filling [30]. The same group also reported a higher glutenin to gliadin ratio under no tillage [27], thus highlighting the complexity of storage protein regulation as affected by environmental conditions. However, the same trend was observed in the current study under Mediterranean climate conditions. The limited differences due to genotype in terms of gluten composition is possibly explained by the fact that the two modern durum wheat genotypes have been selected for their high technological quality target, and this resulted in a general low gliadin-to-glutenin ratio and a high expression of LMW-GS for good pasta making quality [34,51]. The investigated fertilizations showed, in general, an increase in gliadin-to-glutenin ratio with respect to the unfertilized control. Higher N supply tends, in fact, to increase this ratio due to the source-related dynamics of grain protein fractions accumulation [52].The low emission fertilization showed an increase in gliadin expression. This is possibly explained by the prolonged soil N availability granted by the controlled-release fertilizers during grain filling, which contributed the accumulation of the monomeric alcohol-soluble fractions [46,53]. With regard to the health-related quality traits, the shorter grain filling time, due to lower water availability, led to lower grain weight and was associated with a higher grain mineral concentration (Fe and Zn) and antioxidant capacity in accordance with other observations on durum wheat [3,54–56].

Studies on bread wheat reported the benefits of no tillage in terms of grain quality, i.e., protein and Zn [57], which is explained by the contribution of straw incorporation [58]. Indeed, the improvement in soil fertility due to SOC is reported to increase grain nutrient concentration [59,60] by influencing soil nutrient dynamics [61]. The influence of soil tillage on antioxidant capacity is less investigated in durum wheat. Under our conditions, the trend of higher AOX measured with no tillage was observed in the year with the grain filling period characterized by higher evapotranspiration deficit. A comparable response was also observed in the Mediterranean environment, supporting the hypothesis of complexity on the regulation of this health-related trait [62]. It is worth noting that the use of no tillage with straw mulching was recently associated with an improvement in antioxidant enzyme activity under grain filling stage in wheat; the improvement in antioxidant enzyme metabolism reported at leaf level might be responsible for the increase in antioxidant capacity in grain observed in our study [28]. With regard to the effect of N supply, health-related traits were also generally depressed in the unfertilized control, indicating how crop nutrient deficiency could affect not only technological but also health wheat quality, in terms of both micronutrients (Fe and Zn) and antioxidant capacity [30,63]. The combination of no tillage (conservative) and slow-release fertilization showed great benefits in terms of economic profitability, in agreement with other observations drawn from the Mediterranean environment [64,65]. Indeed, the reduction of costs for cultivation is suggested as the major factor in improving economic stability for farmers [66]. This aspect is critical in a market increasingly subjected to price instability and consumer demands in terms of health quality [67].

5. Conclusions

Under our experimental conditions, no tillage showed the best performance for both durum wheat grain yield and quality in the crop year characterized by water deficit during grain filling. Low emission fertilization, also carried out using controlled release fertilizers, did not compromise yield and quality but led to an advantage in terms of sustainability and economic profitability with respect to the standard fertilization. The outcomes of this study indicate that the combination of no tillage and low emission fertilization is the best practice among those investigated to counteract climate changes by reducing nitrogen supply while maintaining yield performance, with benefits for both farmers and consumers. The novel finding that has emerged from this study is the improvement of health-related quality traits, such as micronutrient content and antioxidant activity, which is consistent with GHG emission mitigation and economic benefits. Since this study was carried out in a South Italy environment, further experiments under different growing conditions, and those that also investigate a wider genotypic variability, are necessary to support the outcomes of this study in order to face the goals of food security and mitigation in Mediterranean environment in a climate change scenario.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14122794/s1, Table S1: Details of the investigated durum wheat genotypes; Table S2: Details of agronomic management and economic analysis.

Author Contributions: Conceptualization, M.A.D.S. and Z.F.; methodology, M.A.D.S. and Z.F.; software, M.A.D.S.; formal analysis, M.A.D.S.; investigation, M.A.D.S., L.G., D.T. and M.S.; resources, Z.F.; data curation, M.A.D.S.; writing—original draft preparation, M.A.D.S.; writing—review and editing, Z.F.; visualization, M.A.D.S. and Z.F.; supervision, Z.F.; project administration, Z.F.; funding acquisition, Z.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are available on request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Details of agrometeorological and phenology data of durum wheat grown in south Italy during two consecutive crop years.

Month	10-Day	Phenology	GDD °C d		P mm		PET mm		P-PET mm	
			2021	2022	2021	2022	2021	2022	2021	2022
January	I		175	190	77	37	18	20	59	18
	II		220	259	78	37	26	30	52	7
	III		315	313	93	46	39	43	54	4
February	I	tillering	424	394	101	62	54	57	47	4
	II		485	498	120	63	68	75	52	−12
	III		567	559	120	153	85	87	35	66
March	I		655	606	158	192	104	101	54	90
	II	stem elongation	731	674	181	192	124	124	57	68
	III		837	792	181	200	152	154	29	46
April	I		941	892	181	214	182	180	−1	34
	II		998	1005	202	214	201	214	2	0
	III	heading	1137	1152	215	215	240	253	−25	−38
May	I		1305	1300	217	246	286	292	−68	−46
	II	grain filling	1475	1503	225	246	331	348	−106	−102
	III		1680	1763	227	246	391	416	−165	−170
June	I		1882	2010	231	304	449	483	−218	−179
	II	maturity	2110	2244	231	304	515	545	−284	−241
	III		2396	2527	231	304	587	616	−357	−312

GS = growth stage; GDD = growing degree days; P = precipitation; PET = potential evapotranspiration; P-PET = rainfall deficit.

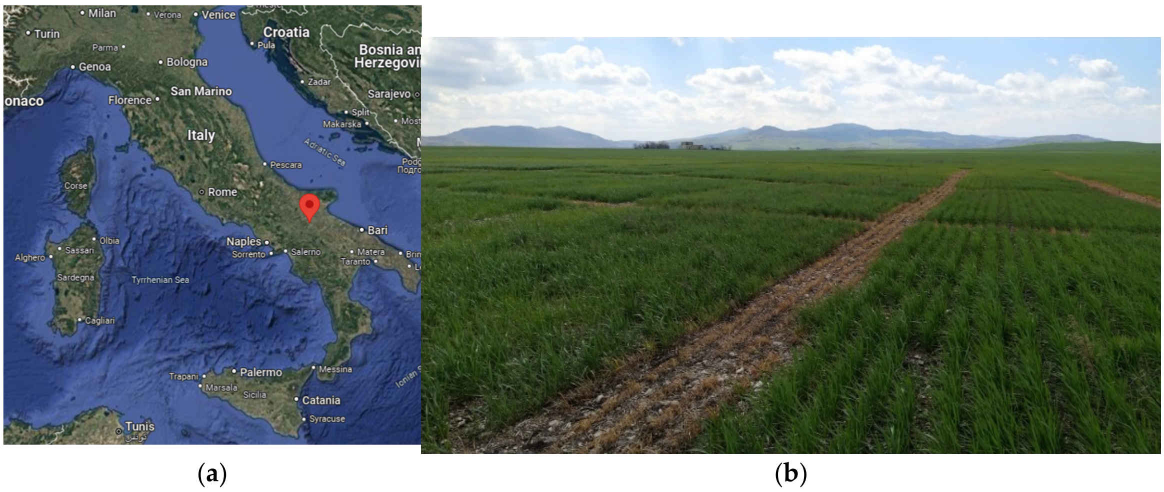

Figure A1. Geographic reference of the experimental site (**a**) and image of the crop plots (**b**).

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