

Article

Effect of Tillage, Previous Crop, and N Fertilization on Agronomic and Economic Performances of Durum Wheat (*Triticum durum* Desf.) under Rainfed Semi-Arid Environment

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Abstract: The implementation of conservation agriculture (CA) remains crucial for facing interannual variability in climatic conditions that impact durum wheat production and food security. The current work was conducted to assess the effects of the tillage practice, previous crop, and nitrogen (N) fertilization rate on the agronomic and economic performances of rainfed durum wheat in a semi-arid environment in Tunisia. Tillage practices included no-tillage (NT) and conventional tillage (CT). Preceding crops were either a common vetch or a bread wheat. The N rates applied were: 0, 75, 100, 120, and 140 kg N ha⁻¹. Our results show that, based on a 2-year experiment, tillage practices are not affecting grain yield, grain N, and gross margins. However, the N-use efficiency of durum wheat was significantly higher when wheat was grown using NT. Grain yield and N content in grain were 340 kg ha⁻¹ and 0.34%; much higher after vetch than after bread wheat. For both tillage practices, the merit of 75 kg N ha⁻¹ is paramount to maximize yield through a more efficient use of available N. Our results highlight the importance of no-tillage-based CA combined with rotation, including vetch, on enhanced yields, N-use efficiency, and gross margins. These findings provide the evidence of the positive impact of CA for rainfed durum wheat under semi-arid Mediterranean conditions.

Keywords: durum wheat; crop yield; nitrogen-use efficiency; water-use efficiency; gross margins; conservation agriculture; semi-arid environment

1. Introduction

In Tunisia, durum wheat (*Triticum durum* Desf.) is a strategic crop that makes up a large part of the national diet [1]. Durum wheat production represents more than 50% of the whole cereal land surface and meets about 70% of annual national demand [2]. Durum wheat productivity is highly variable from year to year, closely linked to the variability and distribution of annual precipitation

during the growing season [3]. This interannual variability is expected to be accentuated by climate change according to several projections [4].

In order to face this alarming situation, the implementation of a strategy based on the sustainable intensification of wheat-based cropping systems remains crucial for food security. Conservation agriculture (CA) has been proposed as an adapted set of crop management principles that assures a more sustainable agricultural production, reduces soil degradation, and also contributes to making agricultural systems more resilient to climate change [5]. Three complementary principles are considered by CA: (1) no-tillage (NT) or minimal mechanical tillage, (2) permanent soil surface cover with mulch of crop residues, and (3) crop diversification through rotations or associations of crops that control the main bio-aggressors (diseases, pests, and weeds) [5,6]. In Tunisia, no-tillage-based CA was introduced in 2000. Currently, CA covers an area of 14,000 ha, mainly for cereals, performed by almost 200 farmers and 107 no-till seeders, available in the country [5,7].

Numerous agronomic benefits of no-tillage-based CA have been reported in a wide array of cropping systems [5,6]. CA is effective in improving soil infiltration and thus reducing surface runoff and soil erosion as well as greater soil moisture-holding capacity. In addition, CA improves nutrient cycling, carbon sequestration, and biological soil health [6–8]. So, in dry rainfed areas, wheat yields under CA exceeded those under conventional tillage (CT) due to improved soil water conservation [9]. However, in relatively moist conditions (humid or irrigated areas), consistent yield declines under NT were observed [9]. Adopting CA principles can further directly influence nutrient dynamics [10]. Likewise, fertilizer inputs are crucial to the successful implementation of CA [11]. Integrated Nutrient Management was suggested as a fourth CA crop management principle [6]. Nitrogen (N) is the most limiting nutrient for cereal production. Its availability and efficiency are often lower in CA than in conventional tillage (CT) practices. This is due to slower decomposition of crop residues and higher N immobilization with residue surface retention [12]. Adjusting N management, according to the changes in soil properties and processes in CA, is necessary at the transition phase of CA-adoption for improving yield and N-use efficiency [12]. It is further important to mention that farmers' adoption of CA practices is also related to expectations in terms of increase in gross margin. In this vein, CA is prone to reduce production costs and increase profitability, often attributed to decreases in labor and energy consumption compared to conventional agriculture [13]. Economic benefits associated with reduced soil erosion are considered as the main reasons to adopt CA [14].

The objective of this paper is to contribute to the debate about the scope and usefulness of CA in Tunisia. We particularly aim to compare the effects of no-tillage and conventional tillage agriculture, under two previous crops and five levels of N fertilizer rates, on the agronomic and economic performances of rainfed durum wheat in the semi-arid conditions of Tunisia.

2. Materials and Methods

2.1. Experimental Site Description

The experiment was carried out during two growing seasons (2013–2014 and 2014–2015) at Bourabia experimental station of the National Institute of Agricultural Research of Tunisia, which is located 25 km south of Tunis (36°36'5.69" N; 10°7'23.49" E, 59 m). The Bourabia site is characterised by an upper semi-arid climate with an average annual rainfall of 470 mm and an annual mean temperature of 19 °C. The soil type for the field trial was a brown rendoll, according to the USDA soil taxonomy [15], with a clayey texture. The main soil characteristics in the first 40 cm are presented in Table 1.

Table 1. Physicochemical properties of topsoil (0–40 cm) in Bourabia experimental station.

Soil Properties	Unit	Mean Value
Clay (0.02–0.002 mm) [16]	g kg ⁻¹	490
Silt (0.2–0.02 mm) [16]	g kg ⁻¹	330
Sand (2.0–0.2 mm) [16]	g kg ⁻¹	180
pH [17]		7.1
Total CaCO ₃ [18]	g kg ⁻¹	412
Active CaCO ₃ [17]	g kg ⁻¹	200
Electrical conductivity (EC) [17]	dS.m ⁻¹	0.2
Organic C [19]	g kg ⁻¹	7.3
Available P [17]	mg kg ⁻¹	73
Available K [17]	mg kg ⁻¹	174

2.2. Experimental Design and Treatments

Two tillage practices were evaluated: no-tillage with 1500 kg ha⁻¹ of crop residues on soil surface as mulch (NT) and conventional tillage (CT). The CT practice included autumn mouldboard ploughing and disk harrowing for seedbed preparation. The two tillage practices were combined with two previous crops (Pre-crop): a common vetch (*Vicia sativa* L.) and a bread wheat (*Triticum aestivum* L.). In addition, five nitrogen rates [N4: 140 kg N ha⁻¹; N3: 120 kg N ha⁻¹; N2: 100 kg N ha⁻¹; N1: 75 kg N ha⁻¹; N0: 0 kg N ha⁻¹] were combined with tillage practices and previous crops. The N fertilizer was broadcast as ammonium nitrate (NH₄NO₃; 33.5% N) at three phenological stages of durum wheat: 30% at 3-leaf stage (GS21 of Zadoks scale, [20]), 40% at ear-1-cm (GS30 of Zadoks scale), and 30% at the stem elongation stage (GS37 of Zadoks scale).

A Tunisian durum wheat, cv. Maali, was sown on 31 December 2013 and 4 December 2014 using no-till seeder (SEMEATO SHM-15/17) and conventional seeder for NT and CT, respectively, with a sowing density of 350 plants per square meter. The treatments were arranged in a split-split-plot experimental design with tillage practices (Tillage) as main-plot, the previous crop (Pre-crop) as subplot and the nitrogen rate (N rate) as sub-subplot factors, with three replications, making a total of 60 sub-subplots for each growing season. Each sub-subplot was 10 m by 5 m (50 m²). Standard agronomic practices after sowing (herbicide and fungicide treatments) were performed in the same way and at the same time for all sub-subplots. In the NT system, weeds were controlled before sowing by spraying glyphosate [N-(phosphonomethyl)-glycine] (3 L ha⁻¹).

2.3. Weather Conditions Monitoring

Weather data were recorded daily by an automatic agrometeorological station near the experimental site. Daily minimum and maximum air temperatures (Tmin and Tmax in °C) and daily rainfall (Prec in mm) were collected throughout the study period (2013–2014 and 2014–2015).

The 20-year average annual rainfall, from 1996 to 2015, for the Bourabia site was 333 mm (Figure 1). Overall, the 2013–2014 growing season was considered as a wet period (457 mm) since its annual rainfall was over this long-term average. On the contrary, annual rainfall at this site for the 2014–2015 growing season (269 mm) was below this long-term average. Then, the 2014–2015 growing season was relatively dry.

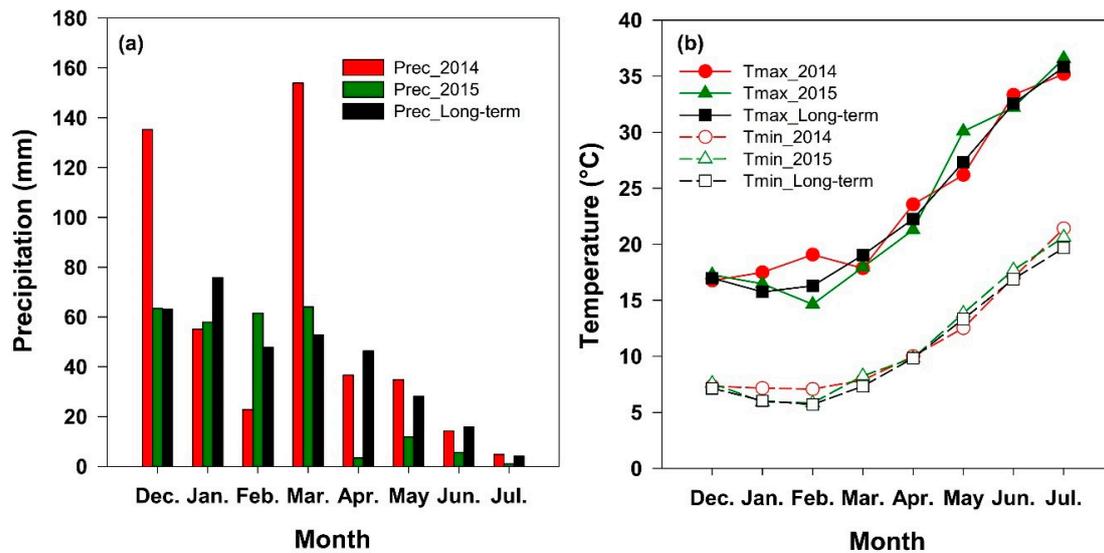


Figure 1. (a) Monthly precipitation (Prec), (b) minimum air temperature (Tmin), maximum air temperature (Tmax) during two growing seasons (2013–2014 and 2014–2015) and their long-term averages (1996–2015) at Bourabia station.

2.4. Grain Yield and Straw Yield Measurements

Samples of grains and straws of durum wheat were collected at physiological maturity, which corresponds to 168 and 189 days after sowing in the first- and second-year experiment, respectively. The samples were collected using a square meter sampler with three replicates. Grains were separated from straw using a laboratory thresher (Wintersteiger LD 350). Grain yield and straw yield were measured using a high capacity precision balance.

2.5. Nitrogen Content in Grain

The grains were ground through a 1 mm screen in a laboratory mill (Culatti, Steinen, Switzerland, DFH 48). The milled grains were analysed for total N content using the Kjeldahl method [21].

2.6. Nitrogen Use Efficiency

Nitrogen use efficiency for grains (NUE), expressed in kg kg⁻¹ N, was calculated according to Equation (1) [22]:

$$NUE = \frac{GY}{N \text{ rate}} \tag{1}$$

where N rate: the amount of applied N fertilizer (kg N ha⁻¹); GY: grain yield (kg ha⁻¹).

2.7. Real Evapotranspiration and Water-Use Efficiency

The real evapotranspiration (ETR) of the crop was calculated based on the water balance method, considering drainage and runoff as zero, according to Equation (2) [23]:

$$ETR \text{ (mm)} = W_i - W_f + P \tag{2}$$

where ETR (mm) is the water consumption during the growing season; P (mm) is the precipitation amount during the durum wheat growth cycle; W_i and W_f (mm) are the gravimetric soil water content at 0–40 cm depth at sowing and harvest of durum wheat, respectively.

Water-use efficiency for grains (WUE) was calculated as the ratio of grain yield (GY in kg ha⁻¹) to real evapotranspiration (ETR in mm), according to Equation (3) [24]:

$$\text{WUE (kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{GY}}{\text{ETR}} \quad (3)$$

2.8. Gross Margin Analysis

Unitary Gross Margin (GM) of durum wheat cultivation is calculated by subtracting variable costs from the total production value per ha (Equation (4) [25]). Grain and straw yield prices and cost of inputs expressed in Tunisian dinar (TND) were recorded yearly. The mean exchange rate over the trial period was 1.00 TND to 0.546 USD.

$$\text{GM} = \text{Total production value} - \text{variable costs} \quad (4)$$

where: Total production value = (grain yield × price) + (straw yield × price).

Variable costs included seed, agro-chemicals (i.e., pre-seeding use of glyphosate for NT, post-seeding use of herbicide for both systems), machinery operations (it is assumed to have less machinery operations and thus lower costs under NT), salary/supervision, land rent, costs of nitrogen fertilizer and straw press operation costs.

The cost of nitrogen fertilizer was variable according to the N rates tested: N4:228 TND ha⁻¹; N3:198 TND ha⁻¹; N2:168 TND ha⁻¹; N1:131 TND ha⁻¹; N0:0 TND ha⁻¹.

$$\text{If NT then Variable costs (TND ha}^{-1}) = 1052 + \text{N fertilizer cost} + \text{straw pressing cost} \quad (5)$$

$$\text{If CT then Variable costs (TND ha}^{-1}) = 1040 + \text{N fertilizer cost} + \text{straw pressing cost} \quad (6)$$

where “1052” and “1040” are the total of charges of variable costs (TND ha⁻¹) under NT and CT, respectively (See Table S1 for detail).

2.9. Statistical Analysis

The agronomic and economic variables were analysed using the MIXED procedure of SAS 9.0 [26]. Least significant differences (LSDs) for letter mean separation were assigned using the pdmix800 macro [27] with a significance level of 0.05. All effects are fixed. The linear mathematical model of the split-split-plot experiment is given by:

$$Y = \text{Season}|\text{Tillage} + \text{Tillage}|\text{Pre-crop}|\text{N rate} \quad (7)$$

where: Y: dependent variable (output variable); Season: growing season; Tillage: tillage system; Pre-crop: Previous crop; N rate: Nitrogen rate.

Simple linear regressions relating nitrogen use efficiency (NUE) to water use efficiency (WUE) were estimated for the various N rates individually, and for the pooled data using R3.4.2 (R Foundation for Statistical Computing, Vienna, Austria) [28]. Slopes and intercepts obtained with the four N rates individually were evaluated through an analysis of covariance (ANCOVA) using JMP[®]11.0 statistical software (SAS Institute: Cary, NC, USA) [29].

3. Results

3.1. Agronomic Performance

3.1.1. Durum Wheat Yield and Grain Quality

When considering the two tested growing seasons (2013–2014 and 2014–2015), tillage did not significantly affect grain yield, straw yield, and grain N; their average being 2520 kg ha⁻¹, 3517 kg ha⁻¹,

and 2.6%, respectively (Table 2). However, Tillage \times Season interaction is significant due mainly to the positive effect of NT compared to CT on the tested parameters during the 2014–2015 growing season where climatic conditions were less favourable. Under NT, grain yield varied similarly over the two growing seasons with an average of about 2642 and 2444 kg ha⁻¹ in the first and second growing season, respectively. However, under CT, grain yield considerably decreased by about 921 kg ha⁻¹ in the second growing season compared to that in the first growing season (2957 kg ha⁻¹). Under NT, the second-year experiment recorded a higher straw yield (4220 kg ha⁻¹) compared to the first-year experiment (2929 kg ha⁻¹). While under CT, the second-year experiment presented lower straw yield (3231 kg ha⁻¹) compared to the first-year experiment (3684 kg ha⁻¹). On the other hand, grain N considerably increased in the second-year experiment (2.89% and 3.05%) compared to that in the first-year experiment (2.36% and 2.12%), respectively, for NT and CT.

On the other hand, grain yield and grain N were significantly affected by pre-crop; being higher after vetch (2690 kg ha⁻¹ and 2.77%, respectively) than after bread wheat (2350 kg ha⁻¹ and 2.43%, respectively) (Table 3). However, the two-way interaction between Tillage and Pre-crop was statistically significant on grain yield and grain N. NT-Vetch recorded the highest grain yield (2865 kg ha⁻¹). No differences were observed for other combinations with an average of 2221, 2515, and 2479 kg ha⁻¹ for NT-Wheat, CT-Vetch, and NT-Vetch, respectively. Vetch pre-crop increased grain N in CT (2.92%) but decreased that in NT (2.62%). Nevertheless, Tillage \times Pre-crop had no significant effect on straw yield (Figure 2). Grain yield, straw yield, and grain N increased significantly with N rate application (Tables 2 and 3). Grain yield increased with increasing rates of nitrogen from 2013 kg ha⁻¹ (N0) to 2920 kg ha⁻¹ (N4) (Table 3). Likewise, straw yield increased with increasing nitrogen rates from 2996 kg ha⁻¹ (N0) to 3892 kg ha⁻¹ (N4). No difference was observed between N2, N3, and N4 on straw yield. The same trend was observed for grain N, with the highest grain N obtained with N4 (2.82%). However, grain N was similar among other N rates, with an average of 2.49, 2.60, 2.62, 2.48% for N0, N1, N2, and N3, respectively (Table 3). The three-way interaction (Tillage \times Pre-crop \times N rate) had no significant effect on grain yield, straw yield, and grain N (Table 2).

Table 2. Significance from ANOVA testing effect of growing season (2013–2014 and 2014–2015), tillage practice (conventional and no-till), previous crop (bread wheat and vetch), and fertiliser N rate (N0, N1, N2, N3, and N4) and their interactions on grain yield, straw yield, N content in grains (Grain N), N use efficiency (NUE), and water use efficiency in grains (WUE) measured at physiological maturity of durum wheat. [†] Season, growing season; Tillage, tillage practice; Pre-crop, previous crop; N rate, nitrogen rate.

Source of Variation [†]	Grain Yield	Straw Yield	Grain N	NUE	WUE
Season	***	**	***	***	NS
Tillage	NS	NS	NS	*	NS
Tillage \times Season	***	***	***	***	**
Pre-crop	**	NS	***	***	***
Tillage \times Pre-crop	**	NS	***	***	**
N rate	***	**	***	***	***
Tillage \times N rate	*	*	*	NS	*
Pre-crop \times N rate	NS	NS	***	NS	NS
Tillage \times Pre-crop \times N rate	NS	NS	NS	NS	NS

*** < 0.001; ** < 0.01; * < 0.05; NS \geq 0.05.

On the other hand, Tillage and N rate showed a significant interaction on grain yield, straw yield, and grain N (Table 2, Figure 2). CT-N4 treatment recorded the highest grain yield (3041 kg ha⁻¹) and NT-N0 recorded the lowest grain yield (1770 kg ha⁻¹). Likewise, NT-N1, NT-N2, NT-N3, NT-N4, and CT-N4 treatments recorded the highest straw yield (3944, 3675, 3746, 3863, and 3921 kg ha⁻¹, respectively) while NT-N0 recorded the lowest straw yield (2647 kg ha⁻¹). NT-N4 recorded the highest grain N (2.96%), while NT-N0 treatments recorded the lowest grain N with 2.45%. However,

a significant interaction effect of Pre-crop \times N rate was observed on grain N, with the highest grain N recorded after vetch combined with N4 (3.11%).

3.1.2. Nitrogen and Water-Use Efficiencies

The statistical analysis indicated that growing season had a significant influence on NUE but not on WUE (Table 2). Similar to grain yield, tillage had no significant effect on WUE with a WUE average of $7.9 \text{ kg ha}^{-1} \text{ mm}^{-1}$. However, NUE varied significantly among tillage practices. NUE was $2 \text{ kg kg}^{-1} \text{ N}$; much higher in NT than in CT ($24.4 \text{ kg kg}^{-1} \text{ N}$). Likewise, NUE and WUE varied significantly with previous crops (Table 3). Treatments after vetch were more efficient for water- and nitrogen-use ($27.2 \text{ kg kg}^{-1} \text{ N}$ and $8.6 \text{ kg ha}^{-1} \text{ mm}^{-1}$) compared to those after bread wheat ($23.6 \text{ kg kg}^{-1} \text{ N}$ and $7.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$), respectively, for NUE and WUE.

Increasing nitrogen rates induced a decrease in NUE, from $34 \text{ kg kg}^{-1} \text{ N}$ with N1 to 21.8 and $20.9 \text{ kg kg}^{-1} \text{ N}$ with N3 and N4, respectively (Table 3). However, increasing nitrogen rates significantly improved WUE, from $6.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for N0 to $9.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for N4. Even so, no significant differences were observed between N1, N2, N3, and N4 on WUE (Table 3).

Tillage and season had significant interaction effects on NUE and WUE (Table 3). Under NT, NUE varied similarly over the two growing seasons with an average of about 27.6 and $25.3 \text{ kg kg}^{-1} \text{ N}$ in the first and second growing season, respectively. However under CT, NUE significantly decreased by about $10.5 \text{ kg kg}^{-1} \text{ N}$ in the second growing season compared to that in the first growing season ($29.7 \text{ kg kg}^{-1} \text{ N}$). Under NT, WUE significantly increased by about $1.6 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in the second growing season compared to that in the first growing season ($7.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$). In contrast, WUE significantly decreased under CT by about $0.6 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in the second growing season compared to that in the first growing season ($8 \text{ kg ha}^{-1} \text{ mm}^{-1}$).

Tillage and Pre-crop had significant interaction effects on NUE and WUE. NT-Vetch recorded the highest levels of NUE ($30.3 \text{ kg kg}^{-1} \text{ N}$) and WUE ($9.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$) (Figure 2). Even so, no significant differences were observed between other Tillage \times Pre-crop combinations on both NUE and WUE.

Tillage by N rate significantly affected WUE but not NUE (Figure 2). Under NT, WUE was higher with N2, N3, and N4 than with other N rates, although under CT, WUE was higher with N4 compared to the other N rates, which had statistically similar WUE levels. No differences were observed between N1, N2, N3, and N4 under NT and N1, N3, and N4 under CT.

3.1.3. Relationship between NUE and WUE

The individual slopes and y-intercepts were pairwise compared to each other in order to investigate if there was a nexus between NUE and WUE. When WUE and NUE were plotted against each other, a positive relationship was observed ($R^2 = 0.279$ for CT and $R^2 = 0.362$ for NT) between the two agronomic traits for both tillage practices (Figure 3). An ANCOVA test demonstrated that under NT, the slopes of the lines were significantly different. The slope for N1 was twofold higher than for higher N rates (4.0 vs. 1.8). Moreover, the y-intercepts for these four N rates were significantly different only for N2, N3, and N4. On the other hand, the slopes under CT were also significantly different with higher value for N1 (6.1) than for higher N rates (2.3–4.8). The slope under N1 was higher than under higher N rates. However, the slopes of the lines for N3 and N4 were statistically similar. Likewise, the y-intercepts for these four N rates were significantly different only for (N2 vs. N3) and (N2 vs. N4).

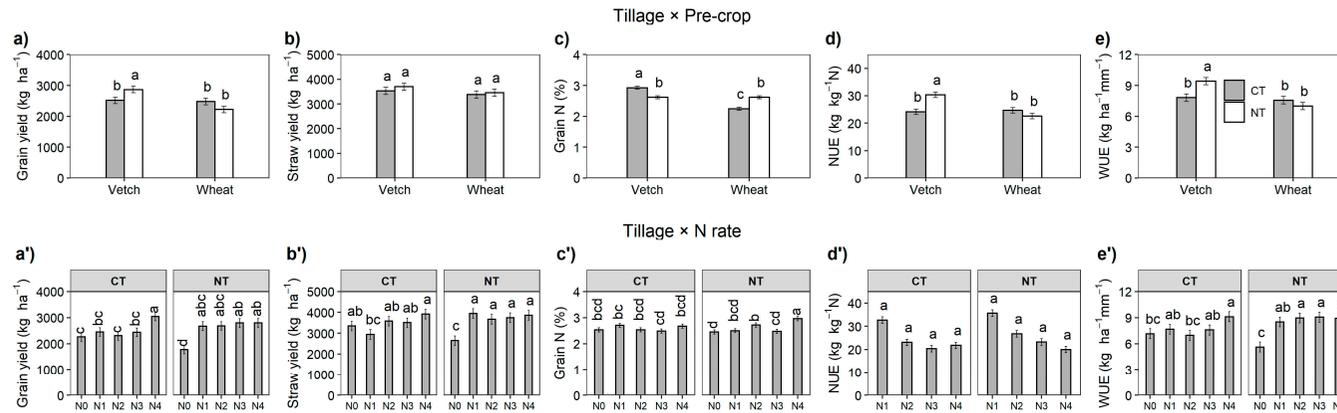


Figure 2. Effect of the two-way interactions of Tillage × Pre-crop (up) and Tillage × N rate (down) on (a) and (a′) grain yield, (b) and (b′) straw yield, (c) and (c′) nitrogen content in grain, (d) and (d′) nitrogen use efficiency (NUE), and (e) and (e′) water-use efficiency in grain (WUE). Data are averages ± standard errors. Different lowercase letters indicate significant differences between all treatments in each item ($p < 0.05$).

Table 3. Grain yield, straw yield, N content in grains (Grain N), N use efficiency (NUE), and water-use efficiency (WUE) as affected by tillage practice (CT and NT), previous crop (bread wheat and vetch), and nitrogen rate (N0, N1, N2, N3, and N4). Data are averages ± standard errors. Different lowercase letters indicate significant differences between all treatments in each item ($p < 0.05$). † Tillage, tillage practice; Pre-crop, previous crop; N rate, nitrogen rate.

Source of Variation †		Grain Yield (kg ha ⁻¹)	Straw Yield (kg ha ⁻¹)	Grain N (%)	NUE (kg kg ⁻¹ N)	WUE (kg ha ⁻¹ mm ⁻¹)
Tillage	NT	2543 ± 74 ^a	3575 ± 103 ^a	2.62 ± 0.04 ^a	26.43 ± 0.71 ^a	8.2 ± 0.26 ^a
	CT	2497 ± 74 ^a	3458 ± 103 ^a	2.58 ± 0.04 ^a	24.42 ± 0.71 ^b	7.69 ± 0.26 ^a
Pre-crop	Vetch	2690 ± 74 ^a	3613 ± 103 ^a	2.77 ± 0.04 ^a	27.22 ± 0.71 ^a	8.61 ± 0.26 ^a
	Wheat	2350 ± 74 ^b	3420 ± 103 ^a	2.43 ± 0.04 ^b	23.64 ± 0.71 ^b	7.28 ± 0.26 ^b
N rate	N0	2013 ± 117 ^c	2996 ± 163 ^b	2.49 ± 0.06 ^b		6.38 ± 0.41 ^b
	N1	2562 ± 117 ^b	3442 ± 163 ^{a,b}	2.6 ± 0.06 ^b	34.16 ± 1.01 ^a	8.08 ± 0.41 ^a
	N2	2491 ± 117 ^b	3626 ± 163 ^a	2.62 ± 0.06 ^b	24.91 ± 1.01 ^b	7.95 ± 0.41 ^a
	N3	2614 ± 117 ^{a,b}	3626 ± 163 ^a	2.48 ± 0.06 ^b	21.78 ± 1.01 ^c	8.31 ± 0.41 ^a
	N4	2920 ± 117 ^a	3892 ± 163 ^a	2.82 ± 0.06 ^a	20.86 ± 1.01 ^c	9.01 ± 0.41 ^a

3.2. Gross Margins

Our results show that Tillage had no significant effect on GM, with an average GM of about 996 and 965 TND ha⁻¹ for NT and CT, respectively. However, GM varied significantly across different previous crops (Table 4). For instance, durum wheat after vetch was more profitable (1116 TND ha⁻¹) than after bread wheat (845 TND ha⁻¹).

Similarly to agronomic traits, GM increased significantly with increasing rates of nitrogen from 704 TND ha⁻¹ for N0 to 1228 TND ha⁻¹ for N4 (Table 4). However, no significant differences were observed between N1, N2, and N3 on GM, with an average GM of about 1020, 945, and 1006 TND ha⁻¹, respectively.

Tillage and season had significant interaction effects on GM. Under NT, GM varied similarly over the two growing seasons with an average of about 1019 and 973 TND ha⁻¹ in the first and second growing season, respectively. However, under CT, GM significantly decreased by about 727 TND ha⁻¹ in the second growing season compared to that in the first growing season (1328 TND ha⁻¹).

Tillage and Pre-crop had significant interaction effects on GM. The highest level of GM (1248 TND ha⁻¹) was recorded under NT-Vetch, while the lowest one (745 TND ha⁻¹) was recorded under NT-Wheat (Figure 4). Even so, no significant differences were observed between CT-Vetch and CT-Wheat on GM, with an average of 984 and 945 TND ha⁻¹, respectively.

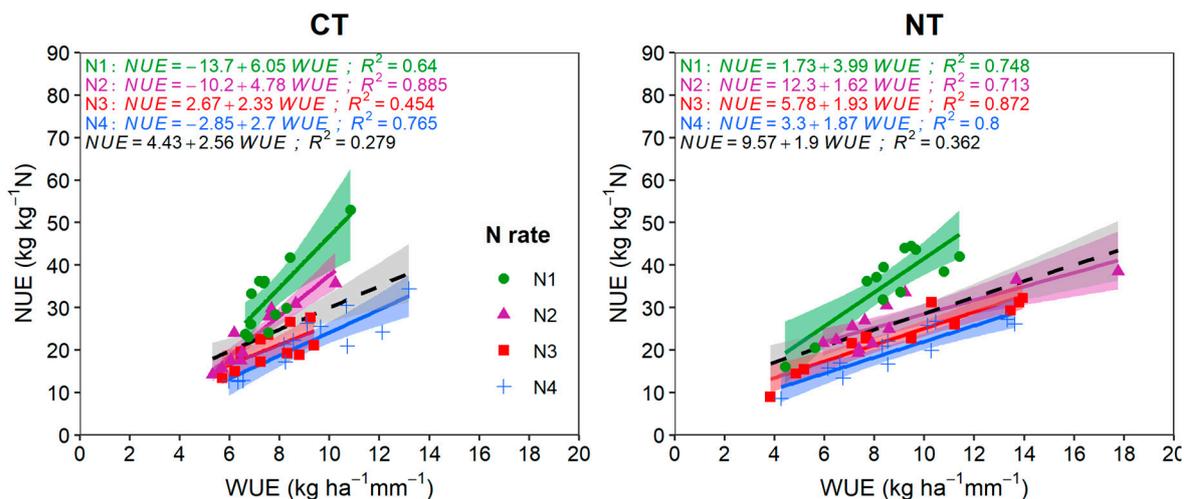


Figure 3. Simple linear regressions relating nitrogen use efficiency (NUE) to water-use efficiency (WUE) used at four N rates individually (solid lines), and for the pooled data (dashed black line) for each tillage practices (CT and NT). Nitrogen rates (N rate) are represented with different symbols (N1: green circle; N2: purple triangle; N3: red square; N4: blue plus).

Tillage and N rate had significant interaction effects on GM. Under NT, GM was higher with N1, N2, N3, and N4 (1139, 1083, 1143, and 1129 TND ha⁻¹, respectively) than with N0 (487 TND ha⁻¹). Furthermore, GM was significantly higher under CT combined with N4 (1327 TND ha⁻¹) compared to other CT - N rates combinations (as they averaged 921, 901, 806, and 870 TND ha⁻¹, respectively for CT-N0, CT-N1, CT-N2, and CT-N3), which have statistically similar GM levels (Figure 4).

Table 4. Significance from ANOVA testing effect of tillage practices (CT and NT), previous crop (bread wheat and vetch), and nitrogen rate (N0, N1, N2, N3, and N4) on gross margins (GM). Data are averages \pm standard errors. Different lowercase letters indicate significant differences between all treatments each item ($p < 0.05$). [†] Tillage, tillage practices; Pre-crop, previous crop; N rate, nitrogen rate.

Source of Variation [†]	Levels	GM (TND ha ⁻¹)
Tillage	NT	996 \pm 59 ^a
	CT	965 \pm 59 ^a
	Significance	NS
Pre-crop	Vetch	1116 \pm 59 ^a
	Wheat	845 \pm 59 ^b
	Significance	**
N rate	N0	704 \pm 93 ^c
	N1	1020 \pm 93 ^b
	N2	945 \pm 93 ^b
	N3	1006 \pm 93 ^{ab}
	N4	1228 \pm 93 ^a
	Significance	**

** < 0.01; NS \geq 0.05.

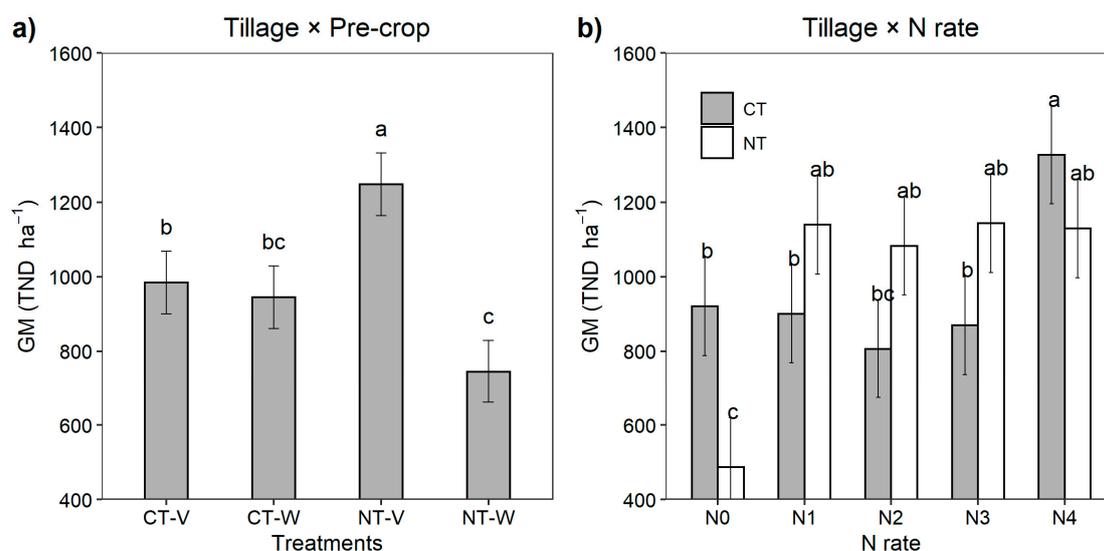


Figure 4. Effect of the two-way interactions of (a) Tillage \times Pre-crop and (b) Tillage \times N rate on GM. Data are averages \pm standard errors. Different lowercase letters indicate significant differences between all treatments in each item ($p < 0.05$). V: Vetch; W: Wheat; CT: conventional tillage; NT: no-tillage.

4. Discussion

The objectives of this study were to examine the effects of tillage practices (NT vs. CT), preceding crops (vetch or bread wheat), and different nitrogen rates (N0, N1, N2, N3, and N4) on the agronomic and economic performances of rainfed durum wheat in a semi-arid Mediterranean environment.

4.1. Agronomic Performance

Overall, grain and straw yields of durum wheat were not affected by tillage practices. This feature is supported by the study of Rieger et al. [30], who did not observe a marked difference in grain yield among tillage practices. Nevertheless, in their global meta-analysis based on 260 studies,

Pittelkow et al. [9] concluded at a best performance of NT in rainfed dry climate conditions, with yields often being equal to or higher than CT practices.

Preceding crop had a remarkable effect on durum wheat grain yield. Overall durum wheat benefits more from a preceding vetch; this is most likely due to the positive contribution of legume to soil N enrichment via symbiotic N-fixing processes. This is in agreement with the findings of Ben Zekri et al. [31], who reported that legumes (including vetch) had higher fertilizing effects than other preceding crops (cereals and vegetables) in Mediterranean conditions.

Tillage and N rate had significant interaction effects on grain yield. With 140 kg N ha⁻¹ mineral fertilizer applied, CT had the highest yield, whereas without N-fertilization, NT had the lowest one. Evidence shows yield advantages of CT compared to NT for all ranges of N rates [9]. However, with more than 80 kg fertilizer N ha⁻¹ applied, CT had few yield advantages over NT. Thus, N fertilization reduced yield declines following NT [9]. This decline is probably due to N tie-up. Nitrogen immobilization, which is generated by cereal residues left on the field, is an issue in NT and is reported to be one of the primary causes for reducing yield and NUE under NT [32].

As discussed elsewhere [11,33], N fertilizer supply is an important practice to be considered with no-till systems, but its role is likely to be more pronounced when water is not the most limiting factor to crop growth. Higher N fertilizer rates at the onset of conversion to NT are required to compensate for the rapidly immobilized N at the beginning of the cropping season [34].

In our study, Tillage did not remarkably affect grain N. This latter is in agreement with the findings of López-Bellido et al. [35] who did not show any effect of tillage practices on grain quality. However, some studies showed lower grain N in NT than in CT [30]. Preceding crop had a significant effect on grain N. Higher grain N was observed after vetch compared to bread wheat. These results are in concordance with those of López-Bellido et al. [35]. Legumes provided a positive contribution to soil N supply [36]. Furthermore, grain N increased with increasing N rates, as observed by López-Bellido et al. [35] who tested three nitrogen rates (50 to 150 kg N ha⁻¹) under contrasted tillage practices (NT vs. CT).

The current study demonstrated that NUE was significantly affected by N fertilizer rate, tillage practices, and previous crop. NUE decreased with increasing N rate, as shown by several studies [37–39]. The negative relationship between N fertilizer rates and NUE is explained by the non-linear pattern of yield response to N that is commonly found in all crops. Nitrogen use efficiency is commonly considered to be antagonistic with grain productivity [40] and is a key environmental indicator to reduce N supply while increasing durum wheat grain yields.

NUE was significantly higher when durum wheat was grown using NT. This result was in agreement with those obtained by Soon et al. [41] and Habbib et al. [42] who showed that for wheat, NUE was higher under NT compared to CT conditions. On the contrary, different results were obtained, when NUE was higher in CT soils due to an increase in yield [37,43] or due to N fertilizer immobilization through crop residues, and by an increase in fertilizer rates with NT [12].

Common vetch is the most known legume forage crop in Northern Africa. Durum wheat after vetch recorded considerably higher NUE than after bread wheat. This feature agrees with the findings of López-Bellido and López-Bellido [43] and Stockdale et al. [44], who reported a higher NUE in wheat rotated with another crop than in continuous wheat. In our results, higher NUE was observed with wheat following vetch in NT than with any other combination. This was due to the more favourable environmental conditions for N uptake being related to better soil water availability when NT was applied [45]. This latter could be also attributed to the enhancement of soil biological health, including the abundance of arbuscular mycorrhizal fungi (AMF) in no-tilled soils [46]. These mycorrhizae strongly enhance plant hydro-mineral nutrition through both higher water and nitrogen-use efficiency. These AMF are most effective in increasing the yield and nutrient uptake of durum wheat, as reported by Schutz et al. [47]. Moreover, N mineralization increased over the conversion period when the soils were switched from CT to conservation agriculture (CA) [48], thus enhancing soil N availability [49]. This observation confirms the importance of crop diversification for the success of conservation

agriculture, mainly through the improvement of soil moisture content, plant water availability, and water-use efficiency [50].

In the same vein, vetch as previous crop positively influenced WUE compared to bread wheat under the NT system, where the WUE increase was of 35%. Evidence shows that legume-based rotation in NT increased water infiltration in semi-arid conditions [51]. This result could be attributed to a more extensive network of root channels for macro- and micro-pores in the soil, which are more developed under no-tillage-based CA when combined with legume rotation, compared to CT [52].

Furthermore, the results of this study demonstrated that WUE was significantly influenced by N rates; the highest WUE was obtained with 140 kg N ha^{-1} , whereas the lowest WUE was recorded in the no-N-fertilization treatments. This result is supported by the study of Mellouli et al. [53]. Nitrogen-nourished durum wheat became more efficient in the use of available water due to the strong interaction between N and water availability and their positive effect on yields, especially in rainfed Mediterranean environments, as reported by Carvalho and Lourenço [54] and Hooper et al. [55].

For both tillage practices, the observed positive correlation between NUE and WUE (Figure 3) is confirmed by Cabrera-Bosquet et al. [56] and Dalal et al. [57] for durum wheat and bread wheat, respectively. As the NUE is negatively correlated to N rate, the high N rates have less available water per N unit. In fact, under these conditions, plants become more efficient in WUE and less efficient in N use. The y-intercept is higher under NT than under CT, which signifies that when WUE is very low, the NUE is higher under NT than under CT. Dalal et al. [57] explained this trend by the improvement of the NUE under NT compared to CT with long-term implementation.

Our results illustrate the opposite effect of N supply on WUE and NUE. Higher N treatments (N2, N3, and N4) have less available water per N unit for both tillage practices; therefore, durum wheat grown under rainfed semi-arid conditions became more efficient in WUE and less efficient in N use. This feature is reported by Cabrera-Bosquet et al. [56]. Under water-limited conditions, the trade-off between WUE and NUE reflects the crop's ability to maximise resource-use efficiency [58]. Therefore, durum wheat growth might lower the utilization of their nitrogen source in order to maximize WUE in semi-arid Mediterranean conditions.

4.2. Economic Performance

Tillage had no significant effects on GM, due mainly to similar grain and straw yields recorded under both tillage practices (NT and CT). This result supports the adoption of CA since it shows that switching CT to NT will not necessarily result in a decrease in GM. However, durum wheat was more profitable when cultivated after vetch, compared to that cultivated after bread wheat. This feature is in agreement with the findings of Schneider et al. [59], Dumans et al. [60], and Jeuffroy et al. [61], who demonstrated that the gross margins of a crop following legume were higher than those following cereals. In the current study, rotation including vetch—known as a major disease- and weed-suppression technique [62]—significantly contributes to an improvement of the gross margins of durum wheat. Having a common vetch as previous crop instead of bread wheat provides considerable gains in term of monetary profit and environmental benefits.

As for grain yield and N-use efficiency, Tillage and Pre-crop had a significant interaction effect on gross margins. NT-Vetch recorded the highest gross margins in durum wheat. The simultaneous increase in both yield, N-use efficiency, and gross margins is at the core of “dual economic-efficient” agriculture, which is considered as an efficient and profitable agricultural production. These results support the adoption and the success of conservation agriculture for rainfed durum wheat in such semi-arid Mediterranean conditions.

5. Conclusions

Based on a 2-year experiment, tillage practices (NT and CT) did not affect grain yield, grain N concentration, and gross margins. However, Tillage affected N-use efficiency, which was significantly higher when durum wheat was grown in NT. Moreover, mineral N application rate significantly

affected grain yield, nitrogen use efficiency, and gross margins of durum wheat. Indeed, durum wheat grown under rainfed semi-arid conditions became more efficient in water-use efficiency and less efficient in N use. For both tillage systems, the merit of 75 kg N ha⁻¹ is paramount to maximizing yield through a more efficient use of available nitrogen in such semi-arid Mediterranean conditions.

Under semi-arid conditions, in Northern Tunisia, having a common vetch as previous crop instead of bread wheat is considered as a real gain in terms of profit and environmentally-friendly technique, which could reduce the reliance on wasteful inputs of chemical nitrogen.

Likewise, no-tillage-based CA combined with rotation including vetch recorded the highest levels of agronomic and economic performances of rainfed durum wheat cultivation. The simultaneous increase in both yield, N-use efficiency, and gross margins is at the core of “dual economic-efficient” agriculture. Therefore, these findings, even coming from two-year experiment, support the adoption and the success of conservation agriculture for durum wheat cultivation under such semi-arid Mediterranean conditions. Furthermore, it is important that medium to long term studies on CA and nutrient management are conducted to improve the references and better guide local farmers towards successful CA adoption.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4395/10/8/1161/s1>, Table S1: Variable costs under two tillage systems (NT and CT).

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