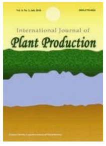

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Cropping systems, tillage and fertilization strategies for durum wheat performance and soil properties

F. Montemurro[a,*], M. Maiorana[b]

[a]*Consiglio per la Ricerca e la sperimentazione in Agricoltura - Research Unit for the Study of Cropping Systems-Metaponto (MT), Italy.*
[b]*Consiglio per la Ricerca e la sperimentazione in Agricoltura-Research Unit for Cropping Systems in Dry Environments-Bari, Italy.*
*Corresponding author. E-mail: francesco.montemurro@entecra.it

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Abstract

Many sustainable agronomical practices can be adopted to contain environmental risks of crop production and, at the same time, sustain yield and quality. In this framework, the aim of this research was to study the effects of continuous cropping (CC) and crop rotation, tillage and fertilization strategies on durum wheat (*Triticum durum* Desf.) production. The responses of soil properties were further investigated. The research was carried out from 1998 to 2006 in two two-year rotations repeated two times and in a continuous cropping. The wheat yield and total nitrogen (N) uptake mean value were significantly higher in rotation (by 9.7 and 21.5%, respectively) than in CC. Moreover, the broad bean-wheat rotation significantly increased wheat performance, in particular yield (+35.2 and 47.9% in conventional and in minimum tillage, respectively) compared to sugar beet-wheat rotation. The minimum tillage increased total organic carbon compared to the conventional one and this enhancement was observed both in CC and rotation (+11.6 and 10.6%, respectively). The reduced tillage also increased total N in both cropping systems and mineral N (+25.4%) in rotation. On the whole, the findings of this research provide an opportunity to identify best cultivation strategies to improve wheat performance in rainfed farming systems.

Keywords: Minimum tillage; Rotation systems; Fertilizer application; Wheat yield; Soil quality.

Abbreviations: CT, conventional tillage; MT, minimum tillage; CC, continuous cropping; RC, wheat in rotation; SB-W, sugar beet-wheat rotation; BB-W, broad bean-wheat rotation.

Introduction

In the recent years, the sustainability of agricultural production has been elevated to its past importance, especially when it is related to limited agronomical inputs, adverse environmental conditions and soils with low fertility. In these situations, crop rotation is one of the main agronomical practices able to increase yield and to allow sustainable production (Ryan et al., 2008a). In fact, crop rotation is one of the most effective disease and pest control strategy and it can improve nutrient- and water-use efficiency (Tilman et al., 2002). However, in some Mediterranean environments, the continuous cropping is still widespread. This is particularly evident in Southern Italy (Maiorana et al., 1992; Montemurro, 2009), where, since a large share of land consists of poor and non-irrigated fields, durum wheat is the most cultivated crop. Lithourgidis et al. (2006) suggested that in the areas with difficult climatic conditions and low soil fertility other crops cannot be profitably cultivated. Therefore, the continuous wheat cropping is frequently considered as the most competitive “rotation” and the ability to minimize yielding losses can provide the best option to increase profitability. Nevertheless, it is well known that continuous cropping causes productive losses, being often associated with increased infestation of weed, pests and diseases and less efficient use of nutrients and water (Tilman et al., 2002). López-Bellido et al. (2000) found that the continuous wheat cropping showed the lowest yield, while the two-year faba bean-wheat rotation was more productive. Moreover, Pala et al. (2007) showed that wheat-legume rotation systems not only can maintain sustainable production, but can also efficiently use the limited rainfall in Mediterranean environment.

Different authors (López-Bellido et al., 1997; Melero et al., 2011) also found a significant interaction between crop rotation and tillage, pointing out the differential effect of the management system on the organic matter content and N status of soil. The improvement of soil quality in single-crop system is one of the critical issues to sustaining agricultural productivity and environmental quality (Reeves, 1997). The increase of inputs and technologies in conventional agriculture can often compensate the yield losses associated with the reduction of soil quality. However, intensive cultivation methods reduce economic sustainability and step up both the negative impact on the environment and deterioration of soil fertility (Lal, 2008). The continuous cropping could also reduce soil organic carbon content, even if the level of this reduction depends on soil tillage, climate and soil characteristics (Reeves, 1997). By contrast, Biswas et al. (2006) found positive residual effects on yield of subsequent crops when the crop rotation was used, as well as maintenance or improvement of soil organic matter and nutrient availability. In the Mediterranean conditions, Montemurro (2009) highlighted a different behavior of wheat after industrial crops, in particular showing the best results of wheat after sugar beet. Melero et al. (2011) pointed out that, in similar conditions, combination of no-tillage with biannual rotations could be an adequate sustainable management in order to improve soil quality, as compared to continuous wheat.

Several management strategies (soil tillage, mineral fertilization, varieties and seed rate) have been investigated to balance the yielding losses due to continuous wheat cropping (Sieling et al., 2005). Even if the benefits of crop rotation have been identified, many of the rotation factors, processes and mechanisms, which increase yield and quality, need to be further investigated. Furthermore, there is a substantial lack of knowledge of the most suitable crop sequences for wheat under reduced tillage and different fertilization strategies. On the light of these considerations, the objectives of this research were to evaluate the effects of: i) continuous cropping and two-year rotations on wheat production; ii) different agronomical techniques (soil tillage depths and fertilization strategies) on wheat yield and quality; iii) cropping systems, soil tillage and fertilization strategies on soil total organic carbon, mineral N and total N. To accomplish these aims, wheat performance was determined in a field experiment carried out in Southern Italy (Mediterranean conditions) from 1998 to 2006.

Materials and Methods

Site of Study, Experimental Design and Crop Management

The research was carried out at the experimental farm of the CRA-Research Unit for Cropping Systems in Dry Environments (Foggia, 41° 27’ lat. N, 3° 04’ long. E, 90 m a.s.l., Southern Italy). The climate in the area of experimental field is classified as “accentuated thermomediterranean” (UNESCO-FAO, 1963). The weather is characterized by winter temperatures that can often fall below 0 °C and summer ones that can rise above 40 °C. The rainfall is unevenly distributed during the year, being concentrated mainly in the winter months.

The soil of the experimental field is a Vertisol of alluvial origin, classified by Soil Taxonomy-USDA as Fine, Mesic, Typic Chromoxerert. The main initial soil properties were as follows: total N=1.22 g kg^{-1}; mineral N=16.25 mg kg^{-1}; organic matter=20.7 g kg^{-1}; available P=27 mg kg^{-1}; exchangeable K=1018 mg kg^{-1}; pH=8.13; sand=29.2%, clay=37.5% and silt=33.3%; bulk density=1.16 kg m^{-3}.

The field experiment occurred during the following wheat crop inter-annual periods: 1998-99, 1999-00, 2000-01, 2001-02, 2002-03, 2003-04, 2004-05 and 2005-06 (from now on indicated as 1999, 2000, 2001, 2002, 2003, 2004, 2005 and 2006, respectively).

The experimental design was a split-split-plot with three factors and three replications. The main factor was assigned to the soil tillage and the following treatments were compared: i) conventional tillage (CT); ii) minimum tillage (MT). The CT treatment consisted of a moldboard plowing (40-45 cm depth) during the summer, two disk harrowing and a vibrating tine cultivator in autumn to control weeds, incorporate fertilizers and prepare seedbed. The MT treatment was characterized by a disk harrowing (to a depth of 15-20 cm) and a vibrating tine cultivator before sowing in autumn. Within each soil tillage the following two-year crop rotation (second factor) were compared: 1) sugar beet (*Beta vulgaris* L., cv. Puma)-durum wheat (cv. Ofanto) from 1999 to 2002 (SB-W); 2) broad bean (*Vicia faba* L. minor Beck, cv. Vesuvio)-durum wheat, from 2003 to 2006 (BB-W). The durum wheat, usually sown in October-November and harvested in June, was also cultivated in continuous cropping (CC) system (from 1999 to 2006), for comparing its performance with that of wheat in rotation (RC) (Table 1). Finally, in the CC the following different times of application of mineral N (100 kg ha^{-1}) were compared (Table 2): 1) in one solution, as ammonium nitrate, in February-March (N_{DUR}); 2) in two rates, 50% as urea, in autumn (on straw and stubble) at the time of main soil tillage and 50%, as ammonium nitrate, in February-March ($N_{PRE+DUR}$); 3) in one solution, as urea, in autumn (on crop residues) at the time of main soil tillage (N_{PRE}). When the wheat was cultivated in rotation after sugar beet and broad bean, in absence of wheat straw and stubble, the 100 kg N ha^{-1} of fertilizer were distributed on wheat as follows: 1) in one solution, as ammonium nitrate, in February-March (N_{DUR}); 2) in two rates, 50% as urea, a few days after wheat sowing and 50%, as ammonium nitrate, in February-March ($N_{PRE+DUR}$); 3) in one solution, as urea, some days after the sowing (N_{PRE}). For sugar beet cropped after wheat, in presence of straw and stubble, 100 kg N ha^{-1} were applied as follows: 1) in one solution, as ammonium nitrate, at the stage of the 12th - 14th leaf (N_{DUR}); 2) in two rates, 50% as urea, in autumn on wheat crop residues and 50%, as ammonium nitrate, on sugar beet at the stage of the 12th - 14th leaf ($N_{PRE+DUR}$); 3) in one solution, as urea, in autumn (on wheat straw and stubble) at the time of the main soil tillage (N_{PRE}). No N fertilization was supplied to broad bean, since this crop is a N_2-fixing plant. In particular, according to Jensen et al. (2010), senescent leaves may contain up to 90 kg N ha^{-1} and the shoot residues can account for substantial amounts of additional N. Also, the quantitative role of N rhizodepositions have been estimated to be up to 100 kg N ha^{-1}. Each elementary plot, as a result of split-split-plot experimental design, consisted of 230 m^2. The wheat crop residues were always incorporated into the soil, both in CC and RC.

Table 1. Different treatments carried out in the experiment.

Trial years	Continuous cropping (CC)	Wheat in rotation (RC)
1998-99	Wheat, cv. Ofanto	Sugar beet, cv. Puma (SB-W)
1999-00	Wheat, cv. Ofanto	Wheat, cv. Ofanto
2000-01	Wheat, cv. Ofanto	Sugar beet, cv. Puma (SB-W)
2001-02	Wheat, cv. Ofanto	Wheat, cv. Ofanto
2002-03	Wheat, cv. Ofanto	Broad bean, cv. Vesuvio (BB-W)
2003-04	Wheat, cv. Ofanto	Wheat, cv. Ofanto
2004-05	Wheat, cv. Ofanto	Broad bean, cv. Vesuvio (BB-W)
2005-06	Wheat, cv. Ofanto	Wheat, cv. Ofanto

Table 2. Different times of 100 N kg ha^{-1} applied in wheat continuous cropping and in rotation.

	Wheat in continuous cropping	Rotation	
		Wheat after sugar beet or broad bean	Sugar beet
N_{DUR}	One solution as top dressing (ammonium nitrate)	One solution as top dressing (ammonium nitrate)	One solution as top dressing (ammonium nitrate)
$N_{PRE+DUR}$	50% at main soil tillage (urea) 50% as top dressing (ammonium nitrate)	50% few days after sowing (urea) 50% as top dressing (ammonium nitrate)	50% on wheat crop residues at main soil tillage (urea) 50% as top dressing (ammonium nitrate)
N_{PRE}	One solution at main soil tillage (urea)	One solution few days after sowing (urea)	One solution on wheat crop residues at main soil tillage (urea)

For each crop and year, the phosphorus (P) fertilizer (100 kg P_2O_5 ha^{-1}, as super phosphate) was applied at the time of main soil plowing for the CT treatment and before the first disk harrowing for MT. No potassium (K) fertilizer was distributed throughout the field experiment, since the soil presented a large amount of initial K level and according to the suggestion of Giardini (1982). The irrigations were made in each year after sowing and at the most important phenological stages for sugar beet, while no irrigation was planned both for wheat and broad bean. Finally, all of the combinations resulting from soil tillage, wheat in rotation or in continuous cropping and fertilization strategies, were simultaneously implemented every year, to avoid the possible effects due to the different climatic conditions.

Measurements

At the wheat harvesting time, the grain and straw yields were determined in the middle of each elementary plot, on a test area of 100 m^2. Samples of grain and straw were randomly collected in ten points of each elementary plot, for determining their dry weights (70 °C until constant weight) and the total N content (Fison CHN elemental analyzer mod. EA 1108), allowing the calculation of the total N uptake (N content x biomass dry weight). The grain protein contents were obtained multiplying the grain N content by 5.70 (Baker, 1979). The number of seeds per hectare was obtained on the basis of the fertile ears number, seeds number per ear and 1000 seeds weight, determined on five samples of one square meter for each elementary plot.

Before the beginning of the research, ten soil samples (0-30 cm layer) were taken from the whole field, air dried, ground to pass a 2-mm sieve and then analyzed for determining the following parameters: total N; mineral N (sum of NO_3^--N and NH_4^+-N); soil organic matter; available P; exchangeable K; pH (1:2.5 soil water suspension); sand, clay and silt (hydrometer method); bulk density. Soil total N was determined by Kjeldahl digestion and distillation method. Soil mineral N was extracted by 2M KCl (1:10 w/v) and measured by continual flow colorimetry, according to Krom (1980) and Henriksen and Selmer-Olsen (1970) for NO_3^--N and NH_4^+-N, respectively. The total organic carbon was determined by wet mineralization with K dichromate in acidic environment (0.1 N $K_2Cr_2O_7/H_2SO_4$) at 160 °C for 10 minutes (Springer and Klee, 1954). The available P was determined by Olsen and Sommers method (Olsen and Sommers, 1982), while the exchangeable K by Thomas method (Thomas, 1982).

At the end of the research, five soil samples (0-30 cm depth) were taken from each elementary-plot, pooled in one sample, air dried, ground to pass a 2-mm sieve and then analyzed. The following parameters were determined: soil mineral N (as the sum of NO_3^--N and NH_4^+-N), total N and total organic carbon. The soil sampling was performed immediately after the harvesting.

Statistical Analysis

Statistical analysis was carried out using the SAS software package (SAS Institute, 1990), considering the years as random and the experimental treatments as fixed factors. The effects of the treatments were assessed through the General Linear Model procedure. Differences among treatments were evaluated with the protected Least Significant Difference (LSD) and the Duncan Multiple Range Test (DMRT) at $P \leq 0.05$ probability level, for two and more than two values, respectively. The LSD and DMRT differences for the main effects and interaction comparisons were calculated using the appropriate standard error term. At last, the arcosin transformation of data was used to evaluate statistical differences among the variables expressed as percentages. For most of the parameters measured, the full analysis of variance, which involved the first order variables and interactions, was significant both for main effects and interactions, hence the data presentation was divided following these subcategories.

Results

Weather Conditions

Figure 1 shows the inter-annual and the seasonal rainfall through the experimental years and the long-term average (1952-1997). During the trial period the weather conditions were characterized by great variability. Season weather varied across years (Table 1), with 2000-01 as the driest period and 2003-04 as the wettest (-30% and +20% as compared to the long term average). Furthermore, the best rainfall distribution occurred during the last trial year (2006), while the worst in the fifth one (2003).

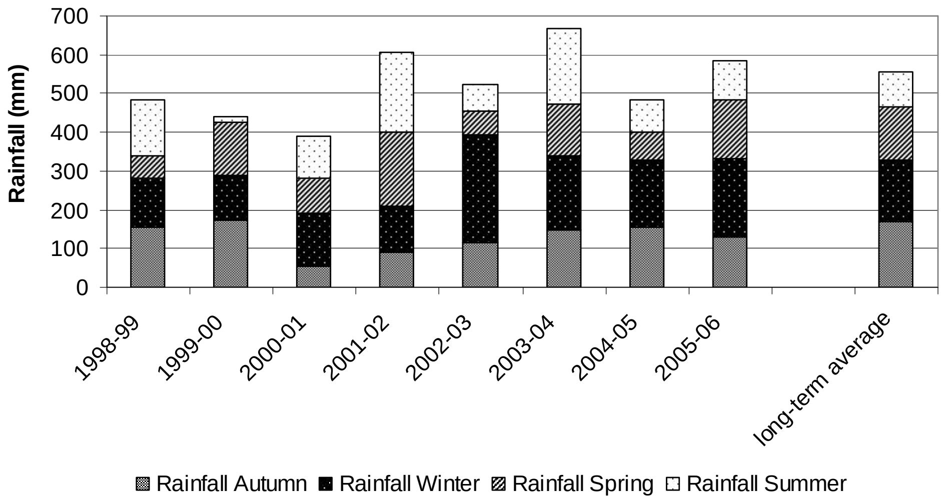


Figure 1. Seasonal and annual rainfall during the trial period compared to the long-term (1952-1997) average.

Effects of Continuous Cropping and Rotation on Durum Wheat Responses

The analysis of variance of grain yield, protein content, total N uptake and seeds number showed that the interaction "year × soil tillage × crop rotation × fertilization strategies" was not significant (Table 3). Therefore, the wheat grain yields for each tillage-crop rotation combination were presented following the main treatments effect.

Table 4 shows the grain yield and the protein content of wheat grown in CC and in RC (mean of sugar beet and broad bean rotations), divided by soil tillage, fertilization strategies and years. As mean values, the grain yield was significantly higher in RC (+9.7%) than in CC while the increase of protein content in RC was not significant. The results of our research also pointed out an inverse relationship between grain yield and protein content (Figure 2). However, the significant linear regression was found only in the wheat cropped in rotation, while no relationship was found in CC. As regards total N uptake (Table 5) the mean value was significantly higher in RC (+21.5%) in comparison with CC. A similar behavior was also observed in the seeds number for square meter (10.2% higher in RC than in CC).

Table 3. Analysis of variance of grain yield, protein content, total N uptake and seeds number of durum wheat in experiment on soil tillage, cropping systems and fertilization strategies.

Source	d.f.	Grain yield (t ha^{-1})	Protein content (%)	Total N uptake (kg ha^{-1})	Seeds number (n m^{-2})
Years (Y)	3	***	***	***	***
Soil Tillage (T)	1	n.s.	n.s.	n.s.	n.s.
Y×T	3	**	n.s.	*	*
Error a	14				
Cropping Systems (C)	1	*	n.s.	**	**
Y×C	3	**	*	*	*
T×C	1	n.s.	n.s.	n.s.	n.s.
Y×T×C	3	*	n.s.	n.s.	n.s.
Error b	24				
Fertilization Strategies (F)	2	n.s.	n.s.	n.s.	*
Y×F	6	*	*	n.s.	*
T×F	2	n.s.	n.s.	n.s.	n.s.
Y×T×F	6	n.s.	n.s.	n.s.	n.s.
C×F	2	n.s.	n.s.	n.s.	n.s.
Y×C×F	6	n.s.	n.s.	n.s.	n.s.
T×C×F	2	n.s.	n.s.	n.s.	n.s.
Y×T×C×F	6	n.s.	n.s.	n.s.	n.s.
Error c	96				

*, **, ***= Significant at the P≤0.05, 0.01 and 0.001 probability levels, respectively.
n.s.= not significant.

Table 4. Grain yield and protein content of durum wheat cropped in continuous cropping (CC) and in rotation (RC) and their means, divided by soil tillage, fertilization strategies and years.

	Grain yield			Protein content		
	CC	RC	Mean	CC	RC	Mean
	(t ha^{-1})			(%)		
Soil tillage						
CT	3.26	3.67	3.46	13.52	14.24	13.88
MT	3.32	3.55	3.43	13.44	14.45	13.94
Fertilization strategies						
N_{DUR}	3.23	3.82	3.52	13.46	14.33	13.89
$N_{PRE+DUR}$	3.35	3.45	3.40	13.42	14.59	14.00
N_{PRE}	3.30	3.56	3.43	13.55	14.12	13.83
Years						
2000	2.79^{c}	2.34^{d}	2.56^{c}	14.33^{a}	15.50^{a}	14.91^{a}
2002	3.34^{b}	3.64^{c}	3.49^{b}	14.56^{a}	14.94^{a}	14.75^{a}
2004	3.83^{a}	4.40^{a}	4.11^{a}	13.72^{b}	13.82^{b}	13.77^{b}
2006	3.21^{b}	4.06^{b}	3.63^{b}	11.30^{c}	13.13^{c}	12.21^{c}
Mean	3.29^{b}	3.61^{a}	3.45	13.48	14.35	13.91

Note: within each experimental treatment (soil tillage, fertilization strategies and years), the values in each column followed by different letters are significantly different according to LSD (two values) and DMRT (more than two values) at the P≤0.05 probability level. The mean values of CC and RC followed by a different letter are significantly different according to LSD at the P≤0.05 probability level.

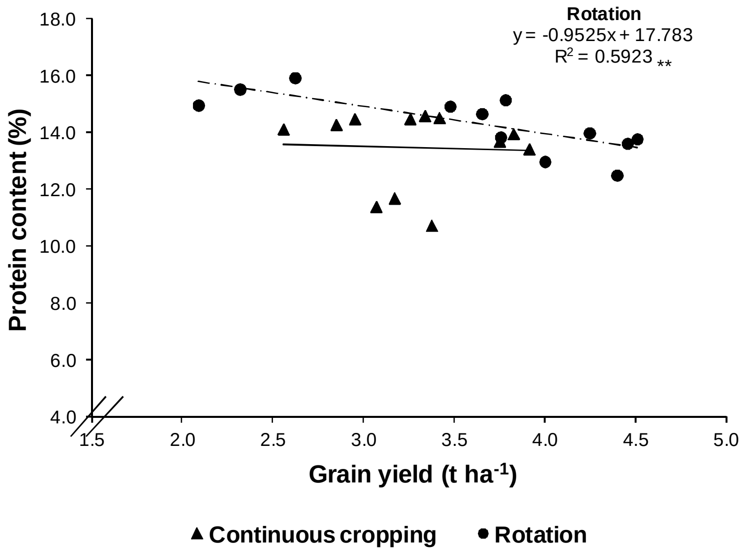


Figure 2. Relationship between protein content and grain yield of durum wheat grown in continuous cropping and rotation.
** significant at the P≤0.01 probability level.

Table 5. Total N uptake and seeds number of durum wheat cropped in continuous cropping (CC) and in rotation (RC) and their means, divided by soil tillage, fertilization strategies and years.

	Total N uptake (kg ha^{-1})			Seeds number (n m^{-2})		
	CC	RC	Mean	CC	RC	Mean
Soil tillage						
CT	122.8	151.1	136.9	8079	9271	8675
MT	124.7	149.5	137.1	8383	8868	8626
Fertilization strategies						
N_{DUR}	120.6	155.2	137.9	8068	9428^{a}	8748
$N_{PRE+DUR}$	125.0	145.7	135.3	8303	8645^{b}	8474
N_{PRE}	125.7	149.9	137.8	8323	9136^{ab}	8729
Years						
2000	112.9^{b}	115.2^{c}	114.1^{d}	7396^{b}	7127^{c}	7261^{b}
2002	138.3^{a}	151.0^{b}	144.7^{b}	8659^{a}	8848^{b}	8753^{a}
2004	133.3^{a}	175.2^{a}	154.3^{a}	8655^{a}	9974^{a}	9314^{a}
2006	110.6^{b}	159.6^{b}	135.1^{c}	8215^{a}	10330^{a}	9273^{a}
Mean	123.7^{b}	150.3^{a}	137.0	8231^{b}	9070^{a}	8650

Note: within each experimental treatment (soil tillage, fertilization strategies and years), the values in each column followed by different letters are significantly different according to LSD (two values) and DMRT (more than two values) at the P≤0.05 probability level. The mean values of CC and RC followed by a different letter are significantly different according to LSD at the P≤0.05 probability level.

Effects of Conventional and Minimum Soil Tillage on Durum Wheat Responses

The analysis of variance (Table 3) showed no significant difference in wheat performance between soil tillage depths, as main factor and as first and second interactions.

As mean values, the grain yields of CT and MT were almost similar and this trend was recorded both in CC and RC (Table 4). The same behavior was also found for the protein content, since no significant variation in mean values between CT and MT treatments was observed. Anyway, the absolute values of protein contents of RC were higher than in CC, with a (not significant) increase of 5.3 and 7.5% for CT and MT, respectively. Again no significant variation was observed in mean values both of N uptake and seeds number (Table 5).

Effects of Fertilization Strategies on Durum Wheat Responses

Among the main effects, the analysis of variance of fertilizing treatments (Table 3) showed no significant difference in CC and RC both for wheat grain yield and protein content. However, in RC the highest yield, in absolute value, was obtained with N_{DUR} treatment, i.e. +10.7 and 7.3% in comparison with $N_{PRE+DUR}$ and N_{PRE}, respectively (Table 4). Likewise, the best protein contents, although the differences were not significant, were always obtained by the wheat in rotation. This higher absolute value was evident when N fertilizer was applied in two rates ($N_{PRE+DUR}$) (Table 4). In conformity with the behavior previously observed in wheat yield and protein content, no significant difference was found among the fertilization strategies in total N uptake, as mean values and both in CC and RC (Table 5). Finally, significant difference was recorded for seeds number for N_{DUR} (+9.1%) compared to $N_{PRE+DUR}$.

Effects of Years on Durum Wheat Responses

The variability of climatic conditions significantly affected grain yield, protein content, total N uptake and seeds number (Table 3). In grain yield the first order interaction was significant for all treatments (year × soil tillage, year × cropping system and year × fertilization strategies). Conversely, no significant interaction was found for the other two orders interaction.

Across years, the wheat yields were significantly different in both cropping systems and the worst production was obtained in 2000 both for continuous cropping and rotation (Table 4). In particular, in 2000 the grain yield was lower than 2004 by 46.8 and 27.1% for RC and CC, respectively. Conversely, the protein content in the same year was significantly higher than in 2004 and 2006, both in CC (by 4.4 and 26.8%, respectively) and RC (by 12.1 and 18%, respectively).

The variability of climatic conditions during the field trial significantly affected the total N uptake (Table 5). In fact, in the rainy 2004 the highest mean value was obtained, whereas the lowest mean value of N uptake was found in 2000. Finally, significant differences among years were found in seeds number and the lowest mean value was recorded again in 2000 (Table 5).

Effects of Sugar Beet-Wheat and Broad Bean-Wheat Rotations on Durum Wheat Responses

The grain yields of durum wheat grown in rotation with sugar beet and broad bean, divided by soil tillage and fertilization strategies, are reported in Figure 3. The wheat in rotation with broad bean showed higher yielding capability compared to wheat in rotation with sugar beet. This enhancement was found both with soil tillage and fertilization strategies. In particular, the yields of wheat in rotation with broad bean were higher by 35.2 and 47.9% in CT and MT, respectively, compared to sugar beet ones. Similarly, the grain yields of wheat in rotation with broad bean were 38.4, 37.9 and 48.4% higher in N_{DUR}, $N_{PRE+DUR}$ and N_{PRE} treatments, respectively, as compared to the grain yield of wheat in rotation with sugar beet.

Figure 4 shows the total N uptake of durum wheat grown in rotation, divided by soil tillage and fertilization strategies. No significant difference between the two crop rotations with durum wheat was found in N uptake when conventional tillage was applied. The application of MT in interaction with broad bean significantly increased this important parameter by 35.6%, compared to wheat in rotation with sugar beet. As found for grain yield, a significant positive effect of broad bean was also observed irrespective of the timing of fertilizer application. In fact, the N uptake values were higher in wheat in rotation with the leguminous crop, in respect to those of sugar beet, increasing by 23.3, 22.6 and 31.6% in N_{DUR}, $N_{PRE+DUR}$ and N_{PRE}, respectively (Figure 4).

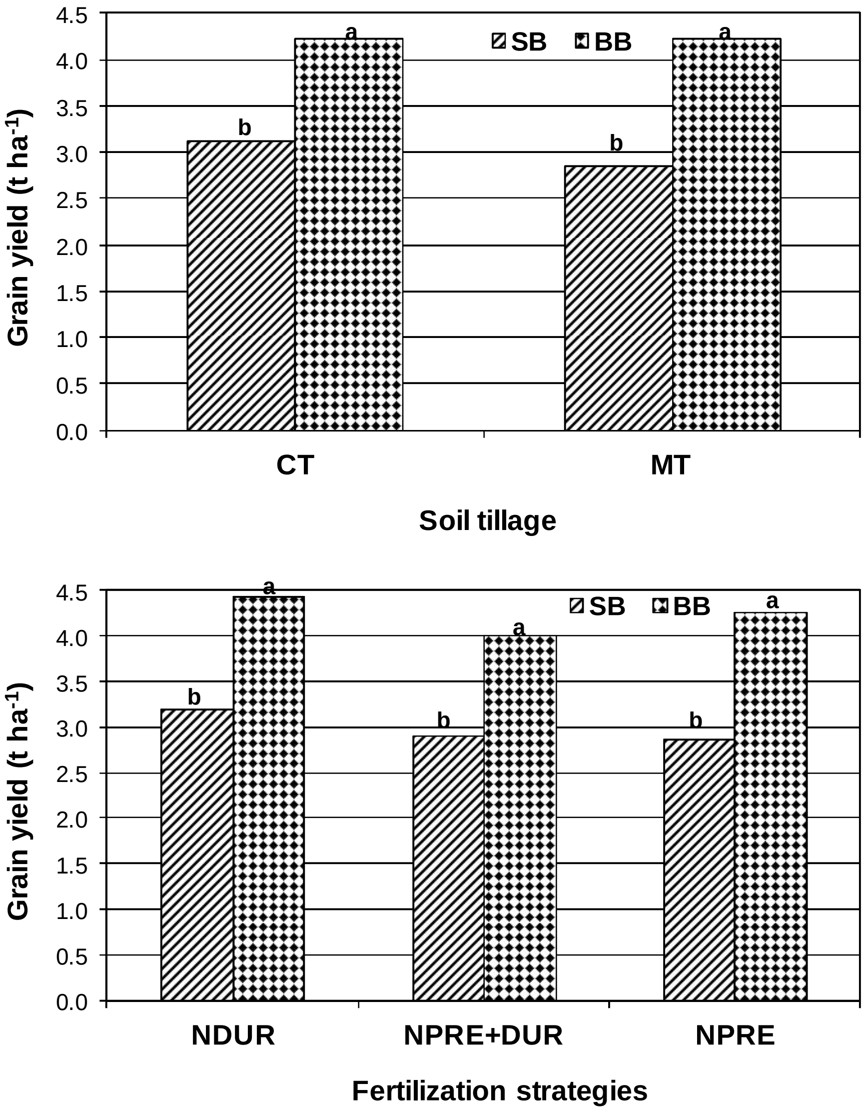
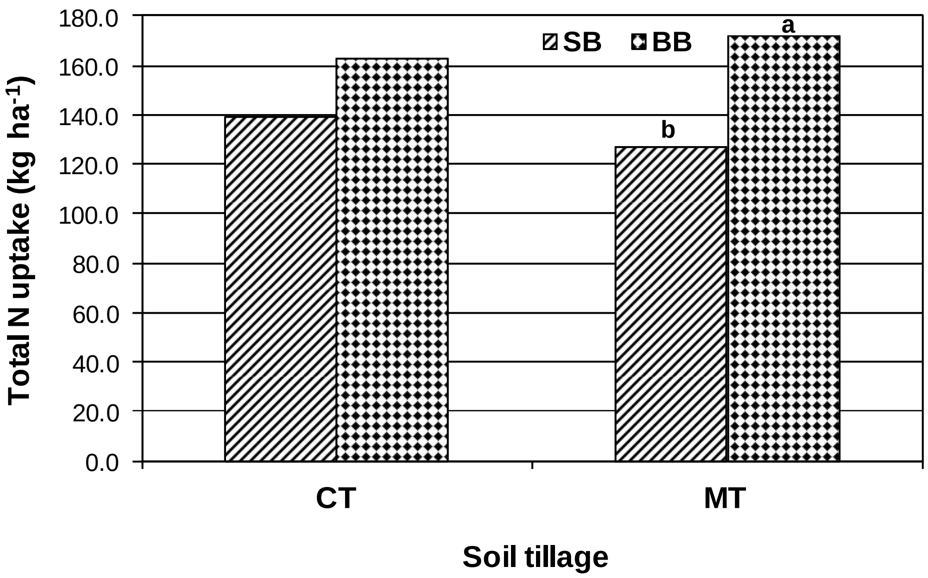


Figure 3. Grain yield of durum wheat grown in rotation with sugar beet (SB) and broad bean (BB), divided by soil tillage and fertilization strategies.
Note: within each experimental treatment, the histograms with different letters are significantly different according to LSD at the P≤0.05 probability level.



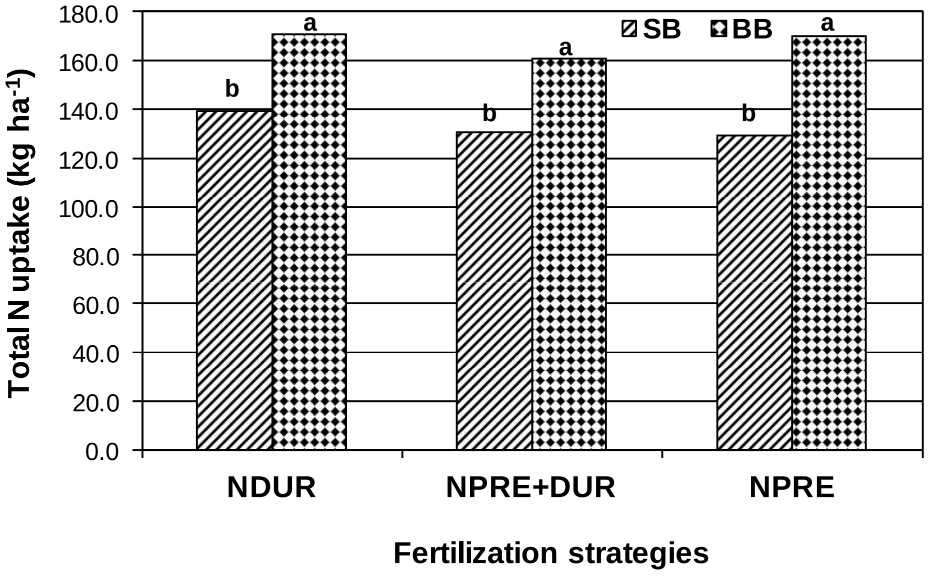


Figure 4. Total N uptake of durum wheat grown in rotation with sugar beet (SB) and broad bean (BB), divided by soil tillage and fertilization strategies.
Note: within each experimental treatment, the histograms with different letters are significantly different according to LSD at the P≤0.05 probability level.

Effects of Continuous Cropping and Rotation on Soil Mineral N, Total N and Total Organic Carbon

Table 6 reports the mineral N, total N and total organic carbon determined at the beginning (T_0) and at the end (T_f) of our study, in the soils cultivated in continuous cropping and in crop rotation. The results are divided by soil tillage and fertilization strategies. From T_0 to T_f (mean values) both cropping systems increased the levels of mineral N, total N and total organic carbon. In particular, continuous wheat cropping improved these soil characteristics by 17.8, 9.0 and 15.9%, respectively, while the increases achieved with crop rotation were 20.3, 10.6 and 12.4%. However, at the end of experiment (T_f), no substantial difference was found, as mean values, between continuous cropping and rotation in mineral N, total N and total organic carbon. At T_f the total organic carbon significantly increased for MT, both in continuous cropping (+11.6%) and in crop rotation (+10.6%) compared to CT. The MT also increased total N on average by 12.7% in comparison with CT, in both cropping systems and mineral N (+25.4%) only in rotation. Among the fertilization strategies, no significant difference was found in total N and total organic carbon, both in continuous cropping and rotation. Conversely, the mineral N showed the significantly highest value in $N_{PRE+DUR}$ in CC, while the highest values in rotation was found in N_{PRE}.

Table 7 shows the soil mineral N, total N and total organic carbon in crop rotations, divided by soil tillage and fertilization strategies. As mean values, no significant difference was found between the two rotations in the investigated parameters at the end of the experiment. On the contrary, the MT significantly increased these soil characteristics in both rotations, except for mineral N in the sugar beet-wheat rotation. Among the fertilizer strategies, significant differences were only found in mineral N and the highest increase was obtained with N_{PRE} (+110.4%) compared to N_{DUR} for wheat in rotation with sugar beet.

Table 6. Mineral N, total N and total organic carbon of soil at the beginning (T_0) and at the end (T_f) of the experiment in continuous cropping and in rotation, divided by soil tillage and fertilization strategies.

	Mineral N (mg kg^{-1})	Total N (g kg^{-1})	Total organic carbon (g kg^{-1})
		T_0	
	16.25	1.22	12.03
		T_f	
Continuous cropping			
Soil tillage			
CT	19.28	1.24^b	13.21^b
MT	19.03	1.42^a	14.74^a
	n.s.	*	*
Fertilization strategies			
N_{DUR}	15.67^b	1.29	13.76
$N_{PRE+DUR}$	26.25^a	1.33	14.08
N_{PRE}	15.53^b	1.37	14.08
	*	n.s.	n.s.
Mean	19.15	1.33	13.97
Rotation			
Soil tillage			
CT	17.36^b	1.28^b	12.86^b
MT	21.77^a	1.42^a	14.23^a
	**	*	*
Fertilization strategies			
N_{DUR}	15.26^b	1.36	13.47
$N_{PRE+DUR}$	18.77^b	1.32	13.47
N_{PRE}	24.66^a	1.37	13.70
	*	n.s.	n.s.
Mean	19.56	1.35	13.55

Note: within the continuous cropping and the rotation, the column values of each experimental treatment followed by different letters are significantly different according to LSD (two values) and DMRT (more than two values) at the P≤0.05 probability level.

*, **= Significant at the P≤0.05 and 0.01 levels respectively; n.s.= not significant.

Table 7. Mineral N, total N and total organic carbon of soil at the end of experiment in rotation after sugar beet (SB) and broad bean (BB), divided by soil tillage and fertilization strategies.

	Mineral N		Total N		Total organic carbon	
	SB-W	BB-W	SB-W	BB-W	SB-W	BB-W
	(mg kg^{-1})		(g kg^{-1})		(g kg^{-1})	
Soil tillage						
CT	19.58	15.13^{b}	1.28^{b}	1.27^{b}	13.16^{b}	12.55^{b}
MT	21.10	22.44^{a}	1.43^{a}	1.42^{a}	14.59^{a}	13.88^{a}
	n.s.	**	*	*	**	*
Fertilization strategies						
N_{DUR}	13.48^{c}	17.05^{b}	1.35	1.36	13.62	13.32
$N_{PRE+DUR}$	19.19^{b}	18.36^{b}	1.34	1.29	13.92	13.01
N_{PRE}	28.36^{a}	20.94^{a}	1.37	1.38	14.08	13.31
	***	**	n.s.	n.s.	n.s.	n.s.
Mean	20.34	18.78	1.35	1.34	13.87	13.21

Note: within the soil tillage and the fertilization strategies, the values in each column followed by different letters are significantly different according to LSD (two values) and DMRT (more than two values) at the P≤0.05 probability level.
*, **, ***= Significant at the P≤0.05, 0.01 and 0.001 levels respectively; n.s.= not significant.

Discussion

Effects of Cropping Systems on Durum Wheat Responses

Durum wheat in rotation significantly increased grain yield compared to CC, probably because of a better soil fertility condition and maximized water-use efficiency. In another field trial in Mediterranean environment, the rotations of wheat with legumes were proved to be most efficient at using rainfall, producing 27% more grain than the wheat-fallow (Pala et al., 2007). Our findings confirm the results of Yau et al. (2003), who reported that wheat production could be increased if it is included in rotation with other crops. Also, Berzsenyi et al. (2000) found that the wheat yields were lower in a continuous cropping and indicated that this reduction could be mainly attributed to pathogenic factors stimulated by environmental conditions.

In our field experiment, the rotation system showed an increasing trend for protein content. Ryan et al. (2008a) reported that rotations such as those with medic and vetch enriched the N in grain. Our result is also in agreement with the Gan et al. (2003) findings, which found that continuous crop reduced grain protein by 8 to 16%. These authors also indicated that durum wheat yields are negatively related with grain protein content, while Flagella et al. (2010) suggested that this relationship was observed when water deficit occurred throughout the growing season. In our study, an inverse relationship was found only in RC (R^2=0.5923), while no relation was observed in CC (Figure 2). Even if this relation is not very strict, since other factors (and in particular environmental conditions) play a role, the relationship is high significant ($P<0.01$) and it explains a good amount of variability. Even if our results show a reduction of protein when grain yield increased, the application of rotation enhanced the stability of protein throughout the years. These results confirm the findings of Zentner et al. (2001), who reported that wheat grain protein was higher in 11 of 18 years when it was grown in rotation.

Finally, rotating wheat crop with other crops in RC increased the N uptake, thus confirming the important role played by crop rotation on the level of this parameter (Montemurro, 2009), which is highly correlated with yielding performance (Delogu et al., 1998; Montemurro et al., 2007a). A higher seeds number for square meter was also found in RC, suggesting reasons for the reduced yield in CC. Similar findings were found by Sieling et al. (2005). Conversely, no significant differences were found on the weight of 1000 seeds among treatments (data not shown), indicating that the sustainable agronomical practices tested in this experiment influenced the fertility of plants.

Our study shows that the wheat yield is significantly higher with broad bean crop in rotation than that with sugar beet both in MT and CT (Figure 3). Similarly, Ryan et al. (2008b) indicated positive effects of legume-based rotations on cereal grain and straw yields suggesting these as alternatives to continuous cropping. The positive effect of the leguminous crop could be due to biological N_2 fixation. In particular, Jensen et al. (2010) reported that wheat may recover between 11 and 17% of the plant N remaining after legume crop.

Even if the findings of this research indicate that RC increased yield, quality and protein stability, the continuous wheat cropping is still a common practice for many farmers in Mediterranean conditions. In these areas, other crops with spring-summer cycle cannot be adopted due to drought and limited irrigation water and there are few alternative fall-winter crops as profitable as wheat (Lithourgidis et al., 2006). However, the results of our research have pointed out that the use of CC could be less frequent, since the best productive and qualitative responses were obtained by the RC.

Effects of Soil Tillage on Durum Wheat Responses

The lack of significant differences between CT and MT for both yield and protein content would confirm that, in our Mediterranean conditions, it is possible and suitable to reduce the environmental impact due to deep soil tillage, without decreasing wheat yield and quality (Montemurro, 2009). Our results agree with findings by Hammel (1995) who found that no-tillage significantly decreased wheat grain yield compared to reduced and conventional tillage, but no difference was observed between these last two soil managements. The outcomes of our research reveal a substantial stability of N uptake and seeds number between cropping systems. On the other hand, Singh et al. (2005) found that replacing a cereal in a two-year graminaceous rotation increases the N uptake and efficiency.

Our research emphasizes that when soil tillage is reduced, the available N increases, as a consequence of lower rates of mineralization and nitrification, higher N immobilization and of an enhancement of available soil water, which stimulates N demand and N_2 fixation (Kessel and Hartley, 2000). Therefore, according to Kessel and Hartley (2000), the soil conservation tillage will lead to a stimulation of N_2 fixation, at least until a new equilibrium between crops residue input and rate of decomposition is reached.

Effects of Fertilization Strategies on Durum Wheat Responses

The fertilization strategies did not affect the wheat yield both in CC and RC, confirming the findings of Berzsenyi et al. (2000). Christen et al. (1992) reported that although yield of wheat after wheat was more responsive to N fertilization management, the N efficiency was lower than with wheat following other crops the timing of N fertilizer application showed no significant difference also in protein content, both in CC and RC. These findings confirm that this qualitative parameter is more affected by genetic background than agronomical practices, as found in wheat (De Giorgio and Montemurro, 2006; Montemurro, 2009), other cereals (Montemurro et al., 2002) and non-cereals (Montemurro et al., 2005; Montemurro et al., 2007b), in the same environment. Furthermore, no significant difference was found among fertilization strategies in total N uptake, both in CC and RC, confirming the strong relationship between N uptake and wheat performance (Delogu et al., 1998; De Giorgio and Montemurro, 2006; Montemurro, 2009). In the Mediterranean area, especially in Southern Italy, durum wheat is cultivated for its industrial transformation and, therefore, grain quality is as important as yield. The results of these field trials indicate that the timing of N fertilizer applications did not improve grain quality and, therefore, the farmers could adopt different fertilization strategies according with the environmental conditions. However, split application is normally known to limit the risk of N pollution and, thus, should be adopted where possible.

Effects of Environmental Conditions on Durum Wheat Responses

The climatic conditions significantly influenced wheat performance. In fact, the lowest grain production was obtained in the 2000 year, probably because of the unevenly distribution of spring rainfall, which was mainly concentrated at the beginning of the cropping cycle. By contrast it was negligible afterwards. Grüsoy et al. (2010) indicate that the amount and distribution of rainfall during cropping cycles significantly affected both wheat yield and quality. This statement is further confirmed by the above-mentioned yielding performance obtained in our experiment. Furthermore, a declining trend of wheat performance was not found across the years both in CC and RC, since the highest production was recorded 2004, confirming the results of Lithourgidis et al. (2006).

Silgram and Shepherd (1999) reported that climatic conditions also influence the mineralization rates, which were higher in conventional than reduced tillage. However, if we take into account that no significant yield variation was found between CC and MT and among fertilization strategies, our results point out that the environmental conditions overcome the variations that can be attributed to management practices. Similar results were found by Anderson (2010), suggesting that the soil water is one of the most limiting resources for crop growth in dry-land areas.

Moreover, our research shows significant differences among years in protein content. The highest values were recorded in 2000 as compared to 2004 (the wettest year) and 2006 (the year with the best rainfall distribution), in both crop rotation. This pointed out the inverse relationship between protein content and grain yield, in accordance with the results of Gan et al. (2003). Our results confirm Rharrabti et al. (2003) who indicated that rainfall distribution during cropping cycle was predominant in determining durum wheat quality traits and their relationships. As found in other studies carried out in the same environment (De Giorgio and Montemurro, 2006; Montemurro et al., 2007a), also the total N uptake was affected by climatic conditions. The different values observed across the years were probably due to the soil water deficit during vegetative stages, which affected the processes of N uptake. The same behavior of grain yield was also found for seeds number, which reached the lowest value in 2000. Except for this year, the seeds number of wheat in RC was significantly higher than in CC, confirming the results of Christen et al. (1992), who indicated a lower performance of yield components in wheat continuous cropping.

Effects of Continuous Cropping and Rotation on Soil Mineral N, Total N and Total Organic Carbon

At the end of experiment, as mean of tillage and fertilizers, no substantial difference was found in soil mineral N, total N and total organic carbon between CC and RC. These results confirm the findings of Campbell et al. (1996) which indicated that crop rotation had no effect on soil organic carbon and N contents. On the contrary, in other studies, crop rotations (especially those that include legumes) have shown positive effects on enhancing total soil organic carbon (e.g. López-Bellido et al., 2010).

In a recent review, Diacono and Montemurro (2010) pointed out that soil organic carbon is chosen, in the long-term studies, as the most important indicator of soil quality and agronomic sustainability, because of its impact on physical, chemical and biological characteristics of soil quality. In our research the application of MT significantly enhanced total organic carbon compared to CT. Deep tillage can induce higher soil aerobic conditions which promote microbial activity and degradation of soil properties. As a consequence, the mineralization process of soil organic matter increases in the long-term (Bernoux et al., 2006). The discussed results confirm those of Ghuman and Sur (2001) and Melero et al. (2011). However, the increase total organic carbon was higher in CC, thus our findings are different from the results of Reeves (1997), who reported a reduction of soil organic carbon in continuous cropping. Furthermore, an increase of this parameter was found from the beginning of the research, with the highest difference recorded with MT in CC. This enhancement, obtained after eight years, should be evaluated taking into account the presence of plant residues on the soil at the sampling time. Anyway, a comparison of carbon values could be made, since also the previous soil sampling was performed in the same conditions. Therefore, the increase of total soil carbon-pool should be explained also as an increase of the carbon-input coming from crop residues. Melero et al. (2011) found that conservation tillage increased total N in the surface layer better than conventional tillage practices, due to differences in mineralization rates of crop residues and soil organic matter. Our results confirm these statements for total N both in CC and RC and for mineral N in RC.

The organic carbon in the soil increased in sugar beet-wheat and broad bean-wheat rotations, with the application of MT management. Therefore, the application of sustainable agricultural practices could have reduced the enrichment of CO_2 atmospheric concentration. These findings support other researches (Ismail et al., 1994; Lal, 2007), which indicated that the depletion of soil organic matter is exacerbated by the conventional agricultural practices. Srinivasarao et al. (2012) showed that soil organic carbon and rate of carbon sequestration were positively correlated with cumulative carbon input. Our results point out that the soil organic carbon can be maintained or restored through best agronomical practices management, such as adequate cropping systems, soil tillage and N fertilizations.

Conclusions

The results of this research highlight that in Mediterranean conditions the use of more suitable agronomical practices could be an effective approach to sustain wheat performance. In particular, our findings have pointed out that durum wheat in rotation increases yield as compared to wheat continuous cropping. Furthermore, wheat yield was higher in the broad bean-wheat rotation than in the sugar beet-wheat one and this improvement was higher with minimum compared to conventional tillage. Therefore, the findings of this research indicate that, in our Mediterranean environment, rotation and minimum tillage may improve wheat performance.

Among the agronomical practices tested in this experiment, the fertilizer strategies did not improve wheat performance and, therefore, the farmers could modify the N fertilization according with the environmental conditions.

Finally, the highest values of total organic carbon of soil were found both in wheat continuous cropping and rotation when minimum tillage was adopted. The minimum tillage also increased total N both in continuous cropping and rotation and mineral N only in rotation. Furthermore, since no significant difference was found between conventional and minimum tillage both for grain yield and protein content, in our Mediterranean conditions it is possible to reduce environmental impact due to a deeper soil tillage.

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