

Conservation tillage in a semiarid Mediterranean environment: results of 20 years of research

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Abstract

Conservation tillage techniques are becoming increasingly popular worldwide as they have the potential to generate environmental, agronomic, and economic benefits. In Mediterranean areas, studies performed on the effects of conservation tillage [in comparison with the conventional tillage technique (CT)] on grain yield of cereal crops have reported contradictory results as well as considerable year-to-year variation, demonstrating how the impact of different soil tillage techniques on crop productivity is strongly site-specific. The present paper summarises the main results from a set of experiments carried out in Sicily during the last 20 years in which we compared no tillage (NT) to CT in terms of their respective effects on the productivity and quality of durum wheat, while at the same time varying some other crop management practices (e.g. crop sequence, N fertilisation, wheat genotype, sowing time). On average, no differences were observed between the two tillage techniques; yields were 3.84 and 3.87 Mg ha⁻¹ for CT and NT, respectively. However, NT guaranteed superior yield when water stress during the crop cycle was high, whereas CT led to higher yields when water availability was adequate. Moreover, the results suggest that the use of NT needs to be accompanied by a rational crop

sequence. In fact, a cumulative detrimental effect of NT over time was found for continuous wheat. Finally, grain quality in terms of protein content was slightly higher for CT (15.1%) than NT (14.4%). Thus, when using NT, the rate of nitrogen fertiliser application should be increased to offset this difference.

Introduction

Conservation tillage techniques are used on approximately 128 Mha worldwide (FAO AQUASTAT, 2012) or approximately 9% of global cropland. These techniques are practised mainly in North and Latin America, but they are becoming increasingly popular in Australia, China, and, more gradually, in Europe. These soil management practices (e.g. mulch tillage, strip tillage, no-till) can generate both agro-ecological and economic benefits, including mitigation of soil erosion (Jordan *et al.*, 2000), increase in soil organic matter (West and Post, 2002; Tabaglio *et al.*, 2008), enhancement of aggregation and aggregate stability (Madari *et al.*, 2005), reduction of energy consumption and carbon dioxide emissions (West and Marland, 2002), preservation of wildlife habitat and soil biodiversity (Uri *et al.*, 1999), and savings in labour and time (Kirkegaard, 1995). Despite these benefits, however, conservation tillage systems are used only rarely in the Mediterranean, where they are practised on approximately 2% of total cropland (FAO AQUASTAT, 2012). There are various reasons for the low rates of use of these techniques in the Mediterranean environments and these are primarily attributable to the lack of policies encouraging their adoption and, probably, also to prejudice on the part of farmers, as their positive effects are often not immediately apparent but can only be seen after a new equilibrium in soil properties has been established (Stubbs *et al.*, 2004). Moreover, conservation tillage techniques require access to appropriate drilling equipment and great skill and expertise. Indeed, the transition from intensive tillage to conservation tillage entails a complete reorganisation of the production system to take into account any possible interactions among all the system components occurring across space and time.

Numerous experiments have been performed in the Mediterranean environment to compare the effects of various conservation tillage techniques with those of conventional tillage (CT) (generally based on moldboard plowing) on the performance of crops (cereals, legumes, *etc.*). These studies have shown contradictory yield results, as well as considerable year-to-year variations in yield (López-Bellido *et al.*, 1996; Hernanz *et al.*, 2002; De Vita *et al.*, 2007; Mazzoncini *et al.*, 2008; Cullum, 2012; Ruisi *et al.*, 2012). The inconsistency of these results proves that the influence of different soil tillage techniques on crop performance is highly site specific. This is not surprising given the intrinsic variability in climatic conditions, soil characteristics, and duration of experiments. Moreover, these studies have shown that the effects of conservation tillage techniques on crop productivity can vary,

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just as other crop management practices do. The present paper summarises the main results from a set of experiments carried out in Sicily during the last 20 years in which we evaluated the effects of the use of the no tillage (NT) technique and compared them with the effects of CT on the productivity and quality of durum wheat (*Triticum durum* Desf.). The effects of the two techniques were studied, and some of the other crop management practices [crop sequence, nitrogen (N) fertilisation, wheat genotype, sowing time, etc.] were also varied, with the aim of identifying the key factors that influence crop performance, and determining the conditions under which conservation tillage practices are likely to be successful. Moreover, because there is great inter-year variability in the climate of the trial environment (total amount and distribution of annual rainfall is unpredictable), we studied the interactions between tillage system and seasonal climatic conditions by evaluating the effects of climatic variability on wheat responses to the treatments.

Materials and methods

All experiments were conducted under rain-fed conditions in the period 1991-2012 at the Pietranera farm (Santo Stefano Quisquina, AG; 37°30' N, 13°31' E), which is located in a hilly area of the Sicilian inland. The farm covers approximately 700 ha and shows a variety of soil types, morphologies, and orographies. It has a semiarid Mediterranean climate with a mean annual rainfall of 552 mm, most of which falls in the autumn/winter (74%) and spring (18%). There is a dry period from May to September. The mean air temperature is 15.9°C in autumn, 9.8°C in winter, and 16.5°C in spring.

Descriptions of the various treatments applied in the experiments are given in Table 1, along with references that provide more details on how each trial was performed. In all experiments, the NT technique (which consisted of sowing by direct drilling) was evaluated and compared with the CT technique (which was based on moldboard plowing carried out in the summer at a depth of 30 cm, followed by one or two shallow harrowing operations to prepare a proper seedbed). All plots were planted using a no-till seed drill with hoe openers (Sider.Man.) in all tillage treatments (CT and NT), making the appropriate adjustments to ensure a homogeneous planting depth (3-5 cm). The effects of the soil management system were evaluated while other crop management practices were varied: sowing time, crop sequence, wheat genotype, N

fertiliser rate, and method of N fertiliser distribution. Moreover, within the framework of a trial, we conducted an in-depth study to determine the N fertiliser recovery of durum wheat ($\%^{15}\text{N}_{\text{REC}}$, *i.e.* percentage of the N added as fertiliser that was recovered by the crop) (Hauck and Bremner, 1976) with the different treatments, calculated as follows:

$$\%^{15}\text{N}_{\text{REC}} = \frac{N_{\text{total}} \times \text{atom}\%^{15}\text{N}}{N_{\text{fert}} \times \text{atom}\%^{15}\text{N}_{\text{fert}}} \times 100 \quad (1)$$

where:

N_{fert} is the amount of N applied;

N_{total} is the amount of aboveground N yield from durum wheat;

$\text{atom}\%^{15}\text{N}$ and $\text{atom}\%^{15}\text{N}_{\text{fert}}$ represent the $\text{atom}\%^{15}\text{N}$ excess of durum wheat and of fertiliser.

Finally, following Rizza *et al.* (2004), a crop water stress index (WSI) was calculated for each year and experimental site on the basis of the soil water balance to quantify the water stress experienced by the crop during its entire cycle, using the following formula:

$$\text{WSI} (\%) = \left(1 - \frac{\sum_1^n \text{AET}}{\sum_1^n \text{PET}} \right) \times 100 \quad (2)$$

where:

n is the number of days of the wheat life cycle (from sowing to maturity);

PET is the daily reference evapotranspiration estimated using the Hargreaves and Samani (1985) method;

AET is the daily actual evapotranspiration, calculated as:

if $\text{WS} \geq (0.5\text{AWC})$, then $\text{AET}=\text{PET}$;

or if $\text{WS} < (0.5\text{AWC})$, then $\text{AET}=\text{PET} \times (\text{WS}/0.5\text{AWC})$ (3)

where:

WS is the actual plant-available soil water content (*i.e.* the soil water content minus the content at the permanent wilting point) and AWC is the available soil water capacity (moisture content between -33 and

Table 1. Description of treatments applied in the experiments.

Experiment	Treatments	Duration (y)	Sites (no.)	References
A	Tillage: CT; NT; RT Crop sequence: Wheat-wheat; Faba bean-wheat; Berseem clover-wheat	18	1	Giambalvo <i>et al.</i> , 2012; Amato <i>et al.</i> , 2013
B	Tillage: CT; NT; RT Crop sequence: Wheat-wheat; Faba bean-wheat; Vetch+oat-wheat	4	1	Stringi and Giambalvo, 1996
C	Tillage: CT; NT Genotype: Early cultivar; Late cultivar Sowing time: Usual date; Advance date (only in NT)	1	5	Giambalvo <i>et al.</i> , 2001; Amato <i>et al.</i> , 2004
D	Tillage: CT; NT Genotype: Early cultivar; Late cultivar Sowing time: Usual date; Advance date (only in NT) Distribution of N fertiliser: 100% pre-sowing; 50% pre-sowing and 50% end of tillering	1	4	Amato <i>et al.</i> , 2004
E	Tillage: CT; NT Genotype: Modern cultivar; Sicilian landrace N fertilisation: 0; 40; 80; 120; 160 kg N ha ⁻¹	1	4	Unpublished

CT, conventional tillage; NT, no tillage; RT, reduced tillage.

–1500 kPa) determined at the beginning of the experiment. More details on the methodology used to calculate this index are available in Amato *et al.* (2013).

Measured and calculated data were analysed separately for each experiment using R software (R Development Core Team, 2011). Moreover, linear regression analyses were performed using all data (procedure REG in SAS 9.2; SAS Institute, 2008) by plotting the wheat yield differences between NT and CT *versus* the WSI or years since initiation of the experiment (for experiments lasting >1 year).

Results and discussion

Figure 1 shows the grain yields obtained with CT and NT in the various trial conditions during the experimental period. On average, no differences in yield were observed between the two tillage techniques (3.84 and 3.87 Mg ha⁻¹ in CT and NT, respectively). This finding is in agreement with the results of a long-term experiment carried out by Hernanz *et al.* (2002) in a semi-arid area of central Spain. Although the two tillage techniques resulted in similar average grain yields, great variability in the response to the tillage system was observed, as shown by the dispersion of the points with respect to the bisector (Figure 1). Moreover, regression analysis revealed the superiority of the NT approach over the CT technique when grain yields were low and, conversely, an advantage of CT in the opposite case (the value of *b*, which is the regression coefficient, was significantly $\neq 1$ at $P < 0.02$).

In the semi-arid Mediterranean environments, the factor that most affects wheat productivity is soil water availability, which in those areas is often a limiting factor for plant growth due to low and erratic rainfall patterns during the growing season. Thus, the yield differences between NT and CT observed in the various trial conditions were related to the water stress level suffered by wheat during its cycle. Analysis of Figure 2 reveals net superiority for grain yield of CT over NT when water stress was low or absent (*i.e.* WSI < 25), substantial equivalence when water stress was moderate (25 < WSI < 45), and, finally, an advantage of NT over CT when water stress was high (WSI > 45). Furthermore, the latter effect increased as the WSI value increased.

These results, which are in agreement with the findings of other authors (Bonfil *et al.*, 1999; De Vita *et al.*, 2007; Su *et al.*, 2007), can be explained by the greater availability of water for the crop in NT than in CT (Bescansa *et al.*, 2006). This is generally attributable to: i) the enhancement of the hydraulic characteristics of the soil that occurs with NT with respect to water infiltration, storage, transport, and drainage (Kay and VandenBygaart, 2002) as the result of a change in soil porosity into more small pores and fewer large pores; ii) the creation of a more continuous pore system from decaying roots and soil macrofauna activity. This is generally depressed in soils treated with CT (Guzha, 2004); and finally iii) enhancement of soil organic matter (West and Post, 2002). The greater soil water availability with NT compared to CT is also attributable to decreased soil water evaporation in NT as a consequence of the minor soil surface roughness generated by soil cultivation (Lampurlanés and Cantero-Martínez, 2006) and, above all, to the presence of crop residues on the soil surface (Blevins and Frye, 1993).

The variability observed in wheat productivity in response to the tillage system can be explained partly by considering its interactions with other agronomic factors. In this regard, in our studies, a key role was played by crop sequence. Analysis of the data from Experiment A, in which the NT and CT techniques were applied continuously for 18 years in three different crop sequences (continuous wheat, faba bean-wheat, berseem clover-wheat) showed a significant interaction between the two factors. Specifically, NT was, on average, superior to

CT only when wheat was grown after a legume crop (both faba bean and berseem clover), whereas when wheat was grown continuously, a higher grain yield was obtained with CT (Figure 3). Moreover, the study showed that the detrimental effects of the application of NT in continuous wheat increased progressively over time (Figure 4), whereas, when wheat was grown after faba bean or berseem clover, the influence of the tillage system on grain yield remained stable over time. A probable cause of the decrease in grain yield over time with the combination of NT and continuous wheat is the progressive increase in the incidence of some pathogens of wheat, mainly crown, foot, and root rot

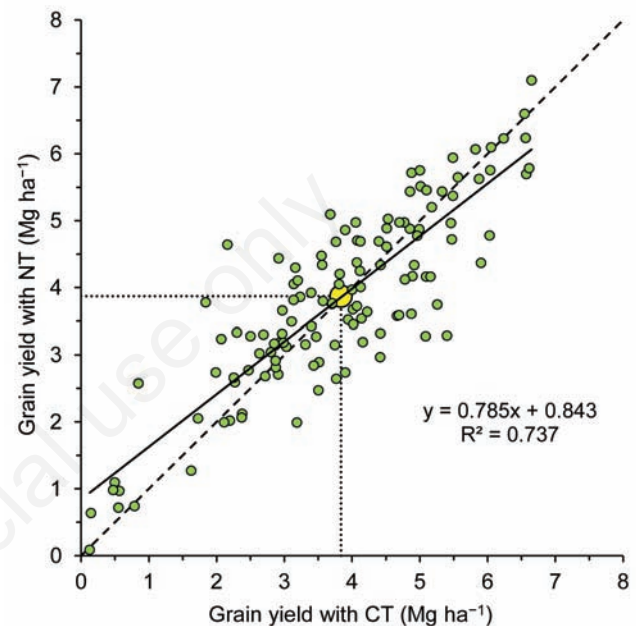


Figure 1. Relationships between grain yields obtained with conventional tillage (CT) and no tillage (NT) in the various trial conditions during the experimental period ($n=128$; green symbols). The bisector (dotted line) indicates identical grain yields with the two tillage techniques. The yellow circle indicates the overall mean value.

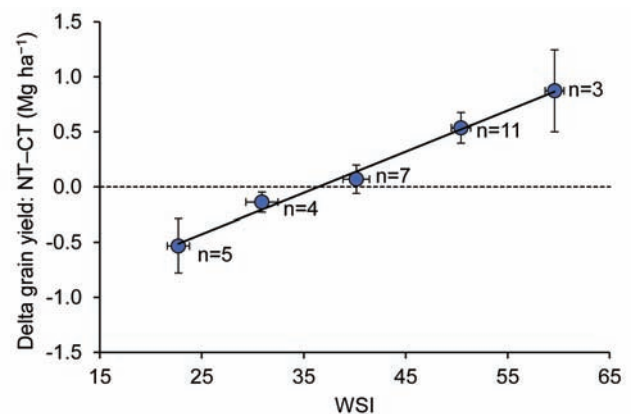


Figure 2. Relationships between water stress index (WSI) and the differences in the grain yield of wheat between no tillage (NT) and conventional tillage (CT). Data were grouped by WSI value into five classes (beginning with the interval 5-25 and with steps of 10; n =number of data in each class). Horizontal and vertical bars indicate the standard errors of each mean value.

pathogens (*Gaeumannomyces graminis*, *Rhizoctonia solani*, *Pythium* spp., and other species belonging to the genus *Fusarium*) (data not shown). This is in agreement with previous findings (Bockus and Shroyer, 1998; Paulitz *et al.*, 2002). It is well known that both tillage system and crop sequence can have a strong impact on the soil fauna, including deleterious organisms. In NT, the retention of crop residues on the soil surface can favour those pathogens that find refuge and food during their saprophytic period in the infected residues, and so infect the subsequent crop. In contrast, with CT, the residues are buried and exposed to microbial degradation, which kills the residue-borne pathogens. In the light of these considerations, it is clear that when NT and continuous wheat (with wheat residue retained on the surface of the soil) are combined, some residue-borne pathogens can become extremely problematic, as was observed in Experiment A.

The results of Experiment E showed a strong grain yield advantage of CT over NT (on average, approx. 1 Mg ha⁻¹ of grain) with no N fertilisation (Figure 5). This benefit decreased progressively with increases in the N fertiliser rate, to the point that, at 160 kg ha⁻¹ of N, differences between CT and NT were negligible. These results, even though obtained in trials in which the NT technique was applied for one year only, highlighted the fact that the lower soil N availability as a result of the application of NT can play a crucial role in determining the differences in grain yield between the two tillage systems, in accordance with the report of Huggins and Pan (1993). On the other hand, soil cultivation (*i.e.* the application of CT) generally increases the amount of N that is potentially available for crops by intensifying the rates of organic matter mineralization, altering soil structure, temperature and aeration, and changing the distribution of crop residues along the soil profile (Silgram and Shepherd, 1999). However, even though organic N mineralisation rates are often higher in plowed systems, a gradual accumulation over time of a greater organic matter in NT systems may compensate for this effect (Salinas-Garcia *et al.*, 1997).

Moreover, in a 2-year study performed within experiment A in a mature phase of the experiment (*i.e.* after 15 years of continuous application of the treatments), aimed at evaluating the N fertiliser recovery (¹⁵N_{REC}) of durum wheat with NT or CT, or with changes in the method of N fertiliser distribution (100 kg ha⁻¹ of N, all applied before sowing, or 50 kg ha⁻¹ of N before sowing and 50 kg ha⁻¹ N at the end of tilling), we found a significant reduction in ¹⁵N_{REC} with the NT technique *versus* the CT method; this reduction was particularly evident when all of the N fertiliser was applied before sowing (Figure 6). Such a result can be explained by hypothesising an increase in N losses from soil caused by the higher volatilisation in NT than in CT, due to the lack of incorporation of N fertiliser into the soil (Fox and Piekielek, 1993; Angás *et al.*, 2006). In the light of these considerations, it is plausible that both phenomena (*i.e.* different intensity of soil organic matter mineralisation and the difference in the extent of N losses between NT and CT) occur and that they jointly contribute in determining differences in the effective soil N availability in the two tillage systems. Furthermore, these effects would be variable, depending on other factors (climate conditions, soil type, soil organic matter content, and other management practices).

Figure 7 shows the grain protein content obtained with CT and NT in the various trial conditions during the experimental period. On average, in agreement with López-Bellido *et al.* (1998), the grain protein content was significantly higher with CT than with the NT method (15.1% *vs* 14.4%, respectively). However, other studies have found that the tillage system has no effect on wheat grain protein content (Carr *et al.*, 2003; Rieger *et al.*, 2008; Gürsoy *et al.*, 2010). Since on average no difference in grain yield was detected between the two tillage systems (Figure 1), the lower grain protein content observed with NT was almost certainly influenced by the negative effects on the N dynamics

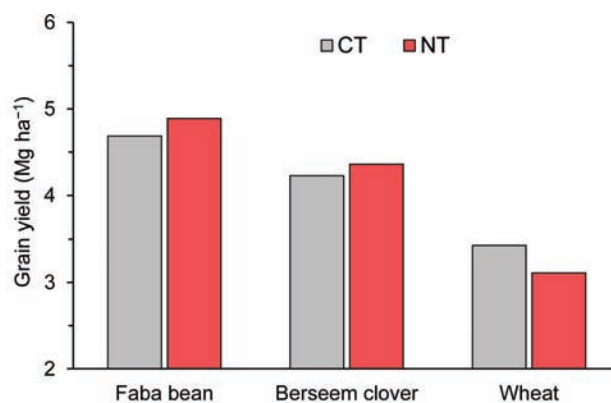


Figure 3. Experiment A: wheat grain yields obtained with conventional tillage (CT) and no tillage (NT) approaches in three crop sequences (continuous wheat; faba bean-wheat; berseem clover-wheat). The tillage \times crop sequence interaction was significant at $P \leq 0.01$. Data are means of 18 years of continuous application of the treatments.

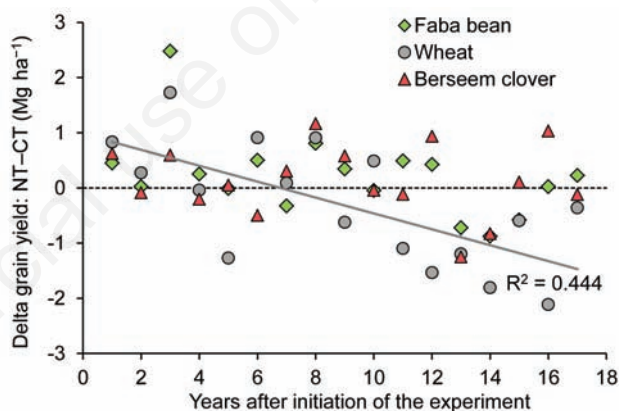


Figure 4. Experiment A: trends over time in differences in wheat grain yield between no tillage (NT) and conventional tillage (CT) for each crop sequence (continuous wheat; faba bean-wheat; berseem clover-wheat). Modified from Amato *et al.* (2013).

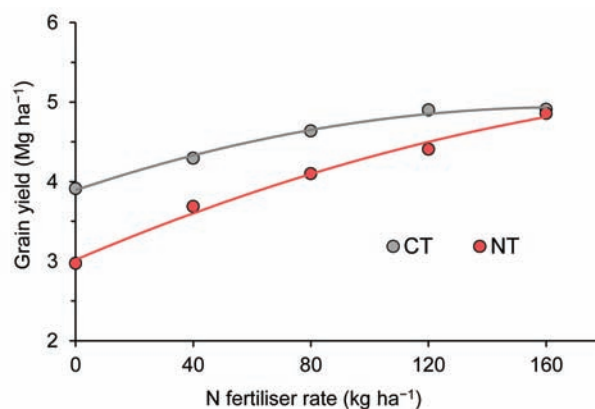


Figure 5. Experiment E: wheat grain yield obtained with conventional tillage (CT) and no tillage (NT) at five N fertilisation levels. The tillage \times N level interaction was significant at $P \leq 0.01$. Data are means of four sites.

in the soil produced by NT. Regardless of this, it must be emphasised that the inconsistent results are not surprising, since the responses of N dynamics to the tillage system may vary considerably with climatic conditions, soil type, and other cultivation practices (MacKenzie *et al.*, 1998; McConkey *et al.*, 2002) and can also change over time. Rice *et al.* (1986) suggested that the lower availability of N frequently observed in NT soils can sometimes be a transient effect. However, as seen in experiment A (in which the NT and CT techniques were applied continuously for 18 years), there was no effect over time of tillage system on grain protein content (*data not shown*); therefore, there was unlikely to have been any transient effect in this experiment.

Because the trials included in the present study were performed in soils that differed in their physical, chemical, and mineralogical characteristics, it was deemed appropriate to verify if and in what way such pedological diversity affected the wheat response under CT and NT techniques. The results showed that yields were similar in CT and NT in soils classified as Typic Calcixerpt (USDA Soil Taxonomy, 2010), which are generally characterised by moderate water permeability and agronomic potential. In contrast, an advantage of NT over CT was found in soils classified as Typic Haploxerert (USDA Soil Taxonomy, 2010), which are generally characterised by a high content of montmorillonitic clays (which give the soil a self-structuring ability) and a high agronomic potential (Figure 8).

Because the transition from a moldboard plow system to an NT system produces marked effects on the entire agro-ecosystem, and because a full expression of the potential of the NT approach is necessary to enhance the positive interactions among all components of an agro-ecosystem, in-depth studies have been conducted on some of the experiments carried out with the aim of evaluating the effects of NT application when other agronomic factors are varied (sowing time: usual date *vs* advance date; wheat genotype: late cultivar *vs* early cultivar). However, neither an advanced sowing date nor the use of late genotypes had significant effects on wheat grain yields in comparison with the usual management practices (Giambalvo *et al.*, 2004).

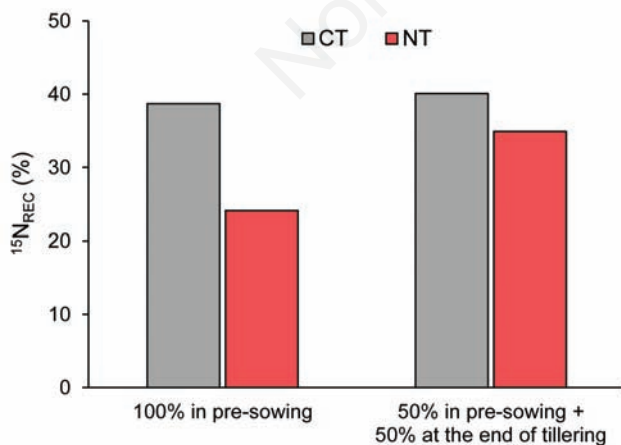


Figure 6. Experiment A: recovery of ¹⁵N fertiliser by wheat as affected by tillage (conventional tillage, CT; no tillage, NT) and fertiliser distribution system (100% applied in pre-sowing; 50% in pre-sowing and 50% at the end of tillering). The tillage × N fertiliser distribution system interaction was significant at $P \leq 0.01$. Data are means over 2 years.

Conclusions

Experiments performed during the 1991-2012 period on the applicability of conservation tillage techniques suggest that NT is a valuable tillage option in the cereal-based systems of dry Mediterranean environments characterised by low and erratic rainfall patterns during the growing season. Indeed, NT guaranteed superior wheat grain yield compared with CT when water stress during the crop cycle was high. In contrast, when water availability was adequate, wheat was more pro-

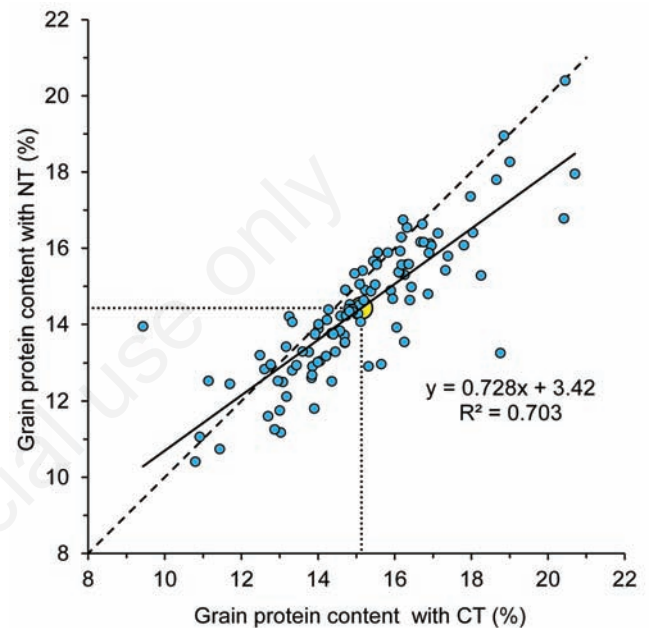


Figure 7. Relationships between the grain protein contents obtained with conventional tillage (CT) and no tillage (NT) in the various trial conditions during the experimental period ($n=105$; blue symbols). The bisector (dotted line) indicates identical grain protein content with the two tillage techniques. The yellow circle indicates the overall mean value.

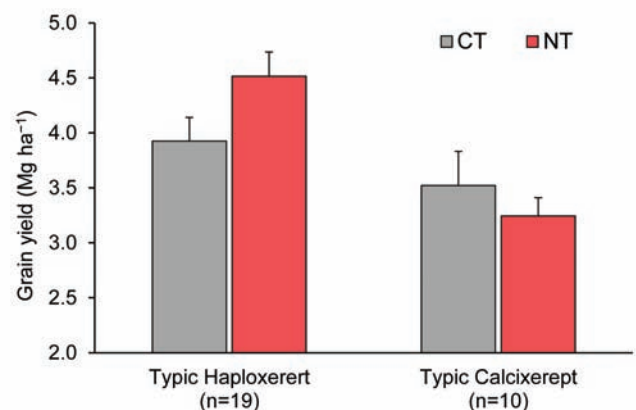


Figure 8. Wheat grain yields obtained with conventional tillage (CT) and no tillage (NT) in two soil types (Typic Haploxerert and Typic Calcixerpt). The tillage × soil type interaction was significant at $P \leq 0.01$. Vertical bars indicate standard errors of each mean value.

ductive with CT. Moreover, the results suggest that farmers, when applying the NT technique, should modify other crop management practices, considering the NT technique as a part of an integrated approach to crop management and not merely as a substitution for traditional tillage techniques and should seek to enhance the positive interactions among all components of the agro-ecosystem. In particular, for optimal expression of the potential of the NT technique, the farmer needs to: i) adopt a rational crop sequence, because a cumulative detrimental effect of NT with time was found for continuous wheat cultivation, probably a consequence of the progressive increase in the incidence of certain residue-borne pathogens of wheat; and ii) with respect to the system managed with CT, increase the rate of N fertilizer to compensate for the lower N availability in the soil that occurs in NT *versus* CT (as a consequence of both the reduction in the rate of mineralisation of the organic matter and the increase in N losses).

The latter recommendation appears to be particularly important in view of reducing the qualitative differences that were observed in the grain yields obtained under the two soil tillage techniques (*i.e.* grain protein content was significantly lower in NT than in CT). Finally, the research showed that the NT technique is likely to be more successful in those soils that are well structured and/or self-structuring (such as vertisols).

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