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Conservation tillage: long term effect on soil and crops under rainfed conditions in south-west Spain (Western Andalusia)

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Abstract

The effect of long term conservation tillage (CT) application on the stratification ratio (SR) of soil organic carbon (SOC), soil nutrient (P and K) contents, loss of the soil $CaCO_3$ and on the crops performance was studied. The SR was established dividing the SOC content at 0-5 cm and 5-10 cm soil depths by the SOC at deeper depths (10-25 cm and 25-35 cm). Results were compared with those obtained under traditional tillage (TT). The study was conducted in a wheat-sunflower crop rotation established in 1991 under rainfed conditions in south-west Spain; results shown here correspond to the years 2001 (sunflower) and 2002 (wheat). The results show that, under studied conditions, CT improved soil quality by reaching a greater SR (> 2) than that in TT (< 2) (SR > 2 indicates better soil quality), decreasing the loss of $CaCO_3$ and increasing the P and K contents at the soil surface (0-5 cm and 5-10 cm). Crop performance was in general better under CT than under TT.

Key words: organic carbon, calcium carbonate, soil quality, crop nutrition, crop yield.

Resumen

Laboreo de conservación: efecto a largo plazo sobre suelo y cultivos de secano (Andalucía occidental)

Se han estudiado a largo plazo los efectos del laboreo de conservación (LC) sobre la razón de estratificación (RE) del contenido de carbono orgánico del suelo (CO), contenido de nutrientes (P y K), pérdidas de $CaCO_3$ y desarrollo de los cultivos. La RE se estableció dividiendo el contenido de CO de la profundidad de 0-5 cm y 5-10 cm por el contenido de CO a mayores profundidades (10-25 cm y 25-35 cm). Los resultados se han comparado con los obtenidos bajo laboreo tradicional (LT). El estudio se realizó sobre una rotación de trigo-girasol establecida en 1991 bajo condiciones de secano, en el sur de España. Los resultados presentados corresponden a los años 2001 (girasol) y 2002 (trigo). Bajo las condiciones indicadas, LC aumentó la calidad del suelo mediante la consecución de una RE (> 2) superior a la obtenida con LT (< 2) (valores de RE > 2 son indicadores de una mayor calidad de suelo), mitigando las pérdidas de $CaCO_3$ y aumentando los contenidos de P y K en superficie (0-5 cm). En general, el desarrollo de los cultivos fue mejor con LC que con LT.

Palabras clave: carbono orgánico, carbonato cálcico, calidad del suelo, nutrición de los cultivos, rendimiento.

Introduction

Conservation tillage is universally accepted to reduce soil erosion and facilitate water storage. It is especially important in semi-arid climate regions where the correct management of crop residues is essential to achieve sustainable yields (Du Preez *et al*., 2001).

However, implementation of this kind of tillage has occasionally caused yield losses, especially in the no tillage method (Rao, 1996; Kirkegaard *et al*., 1995; Silgram and Shepherd, 1999). As Warkentin (2001) pointed out, the global experience with minimum tillage, or direct drilling, results in equal, and even slightly smaller, harvests than traditional tillage (by using mouldboard ploughing). According to this author, conservation tillage only produces profitable yields with correct management.

Any tillage system should adapt to the local characteristics of soil, climate and crop. These variables determine the management required in each specific situation. Conservation tillage usually has positive re-

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percussions on soil quality and crop yield mainly due to the improvements achieved in soil water storage, especially in regions where this parameter is often limiting under conditions of drought.

Several authors have demonstrated that under our edapho-climatic conditions conservation tillage (reduced tillage) can lead to important improvements in the water storage in the soil profile (Pelegrín *et al.*, 1990; Moreno *et al.*, 1997, 2001). Under these conditions, improvements were also obtained in crop development and yield, especially in very dry years (Pelegrín *et al.*, 1990; Murillo *et al.*, 1998, 2001).

Other important soil parameters, such as the contents of organic carbon, carbonates and nutrients, can also undergo important improvements under conservation tillage either by increasing their concentration at the surface (carbon and nutrients), or reducing their leaching to deeper layers (alkaline-earth carbonates). However, variations in some of these parameters, such as organic carbon, are not always appropriately studied or noticed, such as occurs with carbonate leachate.

Under our climatic conditions, high temperatures limit the accumulation of organic carbon at the soil surface. Therefore, the simple determination of total contents may not be the best indicator of improvements in soil quality resulting from conservation tillage. Under arid or semi-arid climates, it is more useful to determine the stratification ratio of soil organic carbon (surface contents relative to the contents in deeper substrates). In general, in any edaphoclimatic context, a high stratification ratio is a good index of soil quality, since ratios above 2 are not common in degraded systems (Franzluebbers, 2002a, 2002b; Mrabet, 2002).

In this work we have studied the long term influence of the conservation tillage on selected chemical properties of the soil (stratification and concentration of organic carbon, and concentration of carbonates and nutrients) and crop development, comparing the results with those obtained with traditional tillage. This study was carried out on a wheat-sunflower crop rotation set up in 1991 in a soil representative of Western Andalusia, under rainfed agriculture. This work forms part of a larger research objective for which, annually numerous physical and chemical parameters of soils are determined as well as several characteristics of the crops. The results presented here correspond to years 2001 (sunflower) and 2002 (wheat), although occasionally references are made to results obtained in previous years.

Material and Methods

Study area: climatological characteristics and experimental plot

The experiment was set up in 1991 at the experimental farm of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), in Coria del Rio, Sevilla (37º 17´ N, 6º 3´ W). The region has a typically mediterranean climate, with a mean annual rainfall of 550 mm (hydrological year; 1971-1992) and an annual average of 2890 hours of sunshine (1987-1991), with maximum values of solar radiation exceeding 1,000 W m^{-2}.

Precipitations in the hydrological years of the sunflower (September 2000-August 2001) and wheat crops (September 2001-August 2002), were 642 mm in the first case (above the annual average) and 521 mm in the second case. The climatic parameters referred to in this work were measured by the farm's weather station, situated around 200 m from the experiment.

For the experiment, an experimental plot with an area of 2,500 m^2 was chosen, with a Xerofluvent, clay-sandy loam soil (Soil Survey Staff, 1996). At the start of the experiment (year 1991), the soil (0-20 cm) had an organic carbon content of around 0.8% with 29% alkaline-earth carbonates.

Initially (Autumn 1991), the whole plot was cropped with wheat, which was harvested in June 1992. Immediately after, the plot was subdivided into six subplots of around 300 m^2 each, setting up two tillage treatments: traditional tillage in three subplots and conservation tillage in the other three (random blocks, with three replicates per treatment). All subplots were cultivated under a non-irrigated rotation of wheat-sunflower, very frequent in Andalusia.

In the traditional tillage, the soil was ploughed by mouldboard, to a 30 cm depth, after burning the straw of the preceding crop. In the conservation tillage (minimum tillage) the residues of the previous crop were left on the soil surface, as mulch, and a minimum vertical tillage (chiseling, 25 cm depth) and disc harrowing (5 cm depth) were carried out, the latter immediately before sowing. The wheat was fertilized annually with 400 kg ha^{-1} of a complex fertilizer 15N-15P_2O_5-15K_2O (basal dressing) and 200 kg ha^{-1} of urea (top dressing); in the final year (2002), this was only fertilized with 100 kg ha^{-1} of fertilizer complex, removing the topsoil fertilizer. The sunflower crop was not fertilized. More information about the operations carried out, both to the soil and the crops, can be found in Moreno *et al*. (1997).

To demonstrate that in conservation tillage the soil surface covered by residues exceeded 30% (a requirement for this tillage method), before sowing each crop this percentage was estimated by measuring directly the coverage by stretching a 10 m cord (marked every 10 cm) diagonally across several rows per each subplot of LC. The number of marks touching a piece of crop residue is the percent of coverage (Plaster, 1992). The sunflower crop (cv. florasol) was sown on 2 April, 2001, with a final density of 60,000 plants ha^{-1} after thinning. The wheat crop (cv. Mellaria R2) was sown on 30 November, 2001.

Sampling and soil analysis

Sampling of the soil of the sunflower crop was carried out on 30 November, 2001 (just before sowing the wheat). Two samplings were carried out for wheat, one on 10 January, 2002, after the crop has already germinated (around 40 days after basal dressing), and the other on the 20 March of the same year. On all cases two samples were taken in all the subplots of each treatment, at depths of 0-5 cm, 5-10 cm and 10-25 cm by using a spiral auger. In the two last sampling (2002), samples were also taken at a depth of 25-40 cm.

In the laboratory, the samples were air dried, ground and sieved (particle size < 2mm). Organic carbon determination was carried out according to Walkley and Black (1934), $CaCO_3$ according to Demolon and Leroux (1952) and the nutrients P and K by extraction with sodium bicarbonate at pH 8.5 (P: Olsen *et al*., 1954) and ammonium acetate at pH 7 (K: Dewis and Freitas, 1970).

Plant sampling and analysis

Both crops, sunflower and wheat, were sampled during different stages of growth. This work only refers to the analysis of sunflower seeds and wheat grain. In the case of wheat, nutrient uptake by the crop was also taken into consideration at the growth stage 10.1 (Feekes scale; Large, 1954), by analyzing the nutrient contents in the dry matter generated per unit area.

To estimate yield, a 16 m^2 plot was established for each subplot covered with a mesh at the start of fruit formation to protect it against birds. For the wheat crop, the total grain yield for each subplot was also obtained, a parameter that could not be measured for the sunflower crop because birds ate almost the whole yield. However, as mentioned below, the results obtained with individual plants from protected plots (and those corresponding to thousand kernel weight) seem to demonstrate that in both treatments, yield could have exceeded 2,000 kg ha^{-1}, without notable differences between these.

Plant matter was cleaned by brief washings with distilled water (acidulated in the first wash), ground and stored at 4°C until analysis. N was determined by Kjeldahl digestion and the remaining elements by treating the sample under pressure with concentrated HNO_3 in a microwave and determination by ICP-OES (inductively coupled plasma-optical emission spectrometry).

Data were studied by analysis of variance, and the separation of means was carried out by the Tukey test, adopting in all cases a significance level of $P < 0.05$.

Results and Discussion

Effect of tillage on soil properties: organic carbon

In the two years of this study, it was checked that more than 60% of the soil of the subplots treated with conservation tillage (minimum tillage) was covered by residues, conclusive proof that this tillage treatment was established correctly.

One of the main advantages of conservation tillage in any modality, is to achieve larger organic carbon contents in the first soil layers, an important benefit taking into account the gradual impoverishment in organic matter of cultivated soils (Bullock, 1997). The organic carbon content (organic matter) of the surface soil layer is essential to control erosion, water infiltration and conservation of nutrients, and is related with the soil quality.

Nevertheless, the stratification ratio of the organic carbon of a soil is a more precise indicator of quality (Franzluebbers, 2002a, 2002b). Ratios above 2 would not be common in degraded soils, so this value can be considered as an approximate threshold under which the soil would have a poorer quality (with the lowest ratios corresponding to the poorest qualities). Higher values would indicate the opposite, always within the limits established by the specific conditions of each particular edapho-climatic region.

For a specific parameter (often organic C, although others could be considered instead), the stratification ratio is defined as the quotient between the surface value (often at a depth of 0-5 cm) and its value at greater depth, for example, the lower limit of the arable layer. The choice of both depths: surface and greater depths, is an important aspect to take into account. Depending on the edapho-climatic characteristics of each specific region, the depths chosen can give more or less conclusive results. This is an aspect which, according to Franzluebbers (2002a) should be studied in different edapho-climatic scenarios.

In our case, after 12 years of experimentation, in CT (0-10 cm depth) organic matter values have been reached close to the minimum content of 2% (1.1% organic C, Table 1) considered necessary for most agricultural practices carried out in European Occidental soils (Bullock, 1997). These are indeed moderate values, and would not justify the implementation of conservation tillage systems (aimed at achieving a high surface organic matter content).

However, when the stratification ratio is studied, (data from 2002, Fig. 1), we found that this is greater in CT than in TT, although the threshold of 2 is only reached when relating surface layers (0-5 cm and 5-10 cm depths) to the 25-35 cm depth, an aspect that reflects the aforementioned importance of the choice of depths. Under our conditions of soil, climate and crop management, it is important to compare the surface layer with relatively deeper soil layers.

On the other hand, it has been demonstrated that the 0-5 cm depth and the 5-10 cm depth equally reflect the better soil quality achieved with CT, since its ratios with the 3rd and 4th layers are almost equal, especially in the first sampling (January, Fig. 1). Hernanz *et al.*, (2002) have also shown in soils from the Spanish Centre (Madrid, semi-arid conditions) that both depths, 0-5 and 5-10 cm, similarly reflect the benefits obtained with conservation tillage.

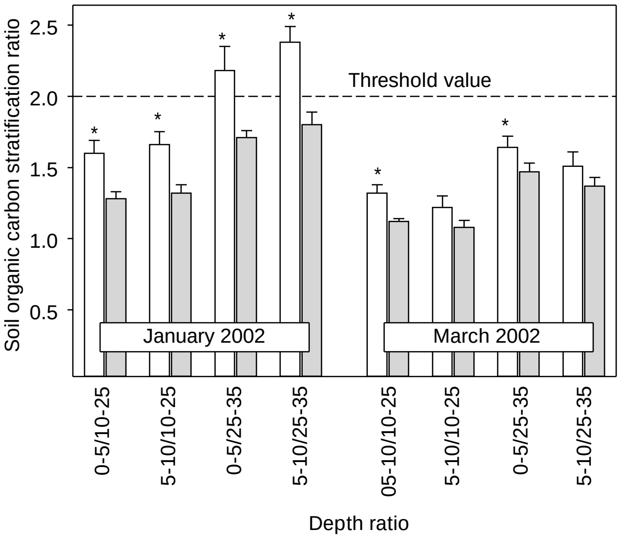

Figure 1. Soil organic carbon (SOC) stratification ratio obtained for the soil under conservation tillage (white bars) and traditional tillage (grey bars) at different dates. For each depth ratio, significant differences are marked with asterisks ($P < 0.05$).

As well as depth, the sampling season must also be chosen when studying the stratification ratio. In this study, the threshold value was only reached in the January sampling (Fig. 1). This is because, with the exception of the 5-10 cm depth in CT, the organic carbon contents are higher in the March sampling, probably due to a larger amount and activity of the roots at this time. According to Franzluebbers (2002a),

Table 1. Mean values of organic carbon ($g\ kg^{-1}$) in the soil treated by conservation tillage (CT) and traditional tillage (TT) for the years 2001 (sunflower) and 2002 (wheat)

Depth (cm)	Treatment	Year		
		2001 (November)	2002 (January)	2002 (March)
0-5	CT	9.8*	9.3*	11.1*
	TT	8.1	8.1	8.6
5-10	CT	9.5*	9.6	10.2*
	TT	8.1	8.5	8.3
10-25	CT	6.5	5.9	8.5
	TT	6.7	6.4	7.6
25-40	CT	—	4.4	6.9
	TT	—	5.0	6.1

Significant differences ($p < 0.05$) between treatments, per year and depth, are expressed by asterisks.

the roots and their breakdown products can accumulate during the growing season, as seems to have occurred in our case.

Calcium carbonate and P and K nutrients

Conservation tillage, compared to TT, notably reduces the loss of calcium carbonate that occurs in the soil, as a consequence of continuous tillage and biannual fertilization (wheat). The calcium carbonate content of this soil, before starting the experiment, was around 29% (López, 1992; Moreno *et al.*, 1997). Carbonate losses occur both in CT and in TT but these are greater under TT (Table 2).

As Motta *et al*. (2002) showed, soils under no tillage usually have higher surface Ca contents compared to traditional tillage, often attributed to the greater exchange capacity of the soil and the application of calcium correctors (to correct pH) under this modality. However, these authors suggest that acidification of the soil produced by nitrogenated fertilizers can also cause important calcium losses by leaching. This circumstance was also pointed out by Blevins *et al*. (1983) and Blevins and Frye (1993).

The farmers in our region often fertilize the wheat crop generously to achieve residual fertilization for the following sunflower crop, which they do not fertilize (López-Bellido *et al.*, 2003). Following this practice, the wheat is fertilized annually with 400 kg ha^{-1} of complex fertilizer 15-15-15 (ground dressing) and a top dressing of urea (200 kg ha^{-1}) in Spring (doses frequently used in our region). This important application of N fertilizers (around 150 kg N ha^{-1} year^{-1}), could have influenced the carbonate losses produced in both treatments.

Hydrolysis of urea causes an initial rise in soil pH (very localized), although this is of short duration, given that the H^+ ions generated in the nitrification of ammonia from urea gradually reduce the pH to values lower than the original value (Hartikainen and Yli-Halla, 1996). Although this gradual acidification of the soil is very localized, it can facilitate partial dissolution of the carbonates.

It is useful to know the carbonate losses that can occur, in different soil types, under different modalities of tillage and fertilization. This is one aspect that is often largely ignored. As Wallace suggests (1994), Ca is an essential element for soil structure. It is the main cementing agent of organic matter and clays, to the extent that it is often beneficial to add Ca, together with organic residues, to achieve sufficient aggregate stability, especially when the aim is to recover organic carbon levels initially existing in soils degraded to a greater or lesser extent.

Regarding the nutrients, it is known that conservation tillage can usually lead to greater accumulation of surface nutrients, compared to traditional tillage, with soil ploughing (Franzluebbers and Hons, 1996; Holanda *et al*., 1998). Obviously, this effect can be masked when fertilizers are used, especially if the soil sample is taken a relatively short time after the fertilization. As Díaz-Zorita and Grove (2002) reported, surface enrichment of P under non tillage systems (following a similar distribution pattern to that of organic C) is observed in soils to which phosphate fertilizers have not been applied.

The dynamics of P in soils is conditioned by two cycles, organic (enzymatic hydrolysis of organic compounds with P by microorganisms and plants; Zibilske *et al*., 2002) and inorganic, in which P precipitates rapidly with metal ions and becomes deficient in many

Table 2. Mean values of $CaCO_3$ (g kg^{-1}), P (mg kg^{-1}) and K (mg kg^{-1}) in soil under conservation tillage (CT) and traditional tillage (TT) during 2001 (sunflower) and 2002 (wheat, March sampling)

Depth (cm)	**Treatment**	**$CaCO_3$**		**P**		**K**	
		2001	**2002**	**2001**	**2002**	**2001**	**2002**
0-5	CT	210*	220*	28.6*	26.0	313*	372
	TT	150	160	23.8	25.2	261	235
5-10	CT	210*	210*	27.5*	23.2	317*	310
	TT	140	160	20.1	19.0	262	324
10-25	CT	190*	210*	19.1	16.7	209	199
	TT	140	150	17.0	15.4	206	221

Significant differences ($p < 0.05$) between treatments, per year and depth, are marked with asterisks.

soils. Phosphates of Al, Fe and Ca control the solubility of P in soils where this cycle predominates. Under these circumstances, the organic input could be an important, although often insufficient, complement (Zibilske *et al.*, 2002). Since this is limiting, this input is easily masked by the fertilizer.

Moreover, the straw burning carried out in TT (a practice that is not recommendable) can contribute to a rise in the level of some nutrients in the soil (Farina *et al.*, 1997; Du Preez *et al.*, 2001). This fact could, to some degree, have masked the effects of conservation tillage (CT) on the concentration of certain nutrients in the surface, an effect that must be added to the action of fertilizer.

In the years in which fertilizer is not used (sunflower crop), accumulation of P and K was observed in the surface (Murillo *et al.*, 1998). This was also observed in 2001 (Table 2). In 2002 (fertilized wheat crop), significant differences were not observed between CT and TT, in spite of the fact that the P and K data presented corresponded to the March sampling, around 100 days after applying the fertilizer.

Effect of tillage on crop development: nutrient uptake

During the initial stages of growth (seedlings), since the start of the experiment (1991) a positive effect of traditional tillage (TT) has been observed on the growth and nutrient uptake of seedlings, especially for the sunflower crop (Murillo *et al.*, 1998, 2001). This does not seem to be associated with any one specific factor but instead to a set of variables, with predominance of physical characteristics.

This aspect is not taken into consideration in this work in which we aim to point out that, in spite of initial improvements introduced by TT, crop growth and yield end up being similar, in normal years, in both treatments. In dry years, the benefits obtained with CT are undoubtedly, due to the greater water infiltration and storage in the soil profile under this treatment (Moreno *et al.*, 2001). The most extreme situation corresponded to 1995, a very dry year in which 1520 kg ha^{-1} of sunflower seeds were collected under CT and only 473 kg ha^{-1} under TT (Moreno *et al.*, 1997).

In the years studied, nutrient uptake by both crops was greater under CT, after passing the seedling stage, although differences were only significantly different between treatments (CT and TT) for the wheat crop, thus data are only showed for this crop (growth stage 10.1, Fig. 2).

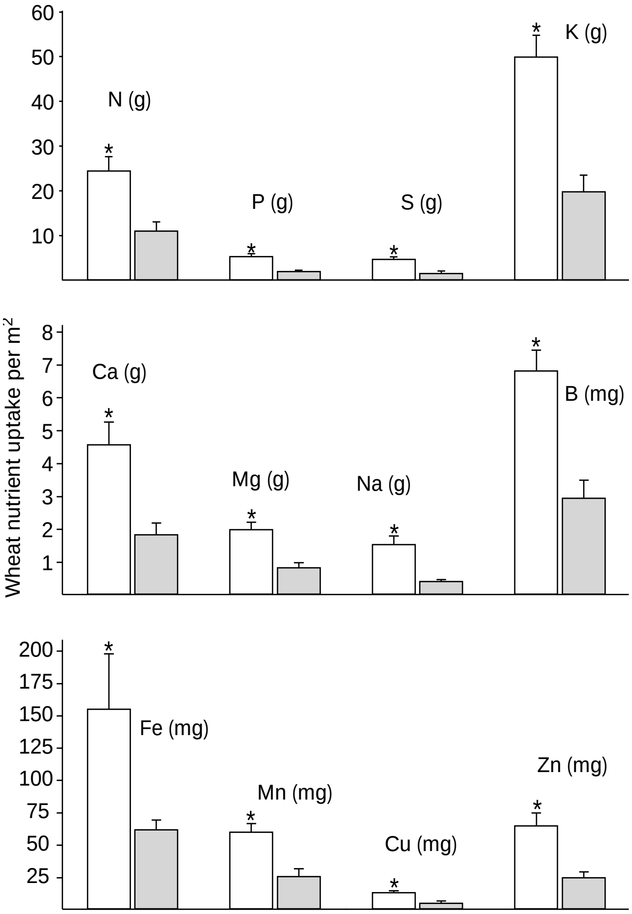

Figure 2. Wheat nutrient uptake (above-ground part; growth stage 10.1) under CT (white bars) and TT (grey bars). For each nutrient, significant differences are marked with asterisks.

The large differences in nutrient accumulation between treatments (Fig. 2) were mainly due to the greater production of biomass recorded in CT during the growth phase selected (stage 10.1) (1554 g m^{-2} of dry matter compared to only 798 g m^{-2} in TT, a statistically significant difference). This increased biomass in CT did not cause nutrient dilution since the concentrations of macro and micronutrients were, in general, higher in CT, with significant differences in many cases (data not shown). This seems to demonstrate the existence of better conditions for plant growth and nutrient uptake in CT during phases before growth stage 10.

These conditions could be related to a higher water content in the soil profile under CT during these phases that could compensate to a certain extent, for the relatively low nutrient availability, derived from the little rainfall during the period December 2001-February 2002 (total of 74 mm). At the beginning of March, the soil water content (20 cm) was around 0.16 cm^3 cm^{-3} in CT and 0.14 cm^3 cm^{-3} in TT, with an even greater difference at depths greater than 70 cm (F. Moreno, unpublished data).

This shows that even in normal years (average rainfalls near to the average value recorded for the region), the conditions developed by conservation tillage in the long term (12 years in this case) can be determinant in short periods of drought.

Yield and seed quality

It was not possible to obtain yield data in the sunflower crop (2001) because birds ate almost all the crop. They even penetrated some of the protected plots making it often impossible to obtain reliable data on the yields obtained in these enclosures. From the results obtained from individual plants, in some protected plots, it can be deduced that, in both treatments, yield could have exceeded 2000 kg ha^{-1}, with no significant differences between them.

For the wheat crop, after reinforcing the netting used to protect the plots (preventing the access of birds to them) it was found that greater yields were obtained with CT, although these differences were not significant. Yields were extremely high, much higher than those obtained in the field (Table 3), where the birds had access to the ears. The estimation of the mean number of ears per m^2 (361 in CT and 349 in TT) and grain weight per ear (2.66 g in CT and 2.57 g in TT) produced values close to 9500 kg ha^{-1} in CT and 9000 kg ha^{-1} in TT.

The quality of seeds in both crops was slightly higher in CT: for similar weights the concentrations of N and Zn were higher in this treatment although the differences were not significant (Table 3). The concentrations of the other elements studied, macro and micronutrients, were the same in both treatments.

The slight increase in N in the seeds of CT is an interesting aspect that must be approached in the following years. This was also observed in the wheat crop of 2000, but not in the sunflower crop of 1999 (possibly due to its dilution in greater seed weight, Murillo *et al*., 2001). An increase in nutrients in the seeds of a crop can cause some improvements in germination and later embryonic growth (Liptay and Arevalo, 1998).

N concentrations in seeds of sunflower grown under CT and TT are below the threshold of 30 g kg^{-1} considered suitable for this crop (Blamey *et al*., 1997; Reuter and Robinson, 1997), especially in the case of TT, which seems to confirm once again that conservation tillage correctly used can be beneficial to the farmer. In the case of wheat, the concentration of N in the grain under CT was within the range considered as suitable for this crop, 17.8-23.0 g kg^{-1} (Reuter and Robinson, 1997), while under TT it was below the lower limit (Table 3).

As conclusions, the results obtained show that, in the long-term, conservation tillage (CT, reduced tillage modality), can be beneficial under our soil conditions (clay-sandy loam, calcareous) and climate (semi-arid). As well as a rise in the content and stratification ratio of the soil organic C and a reduction in calcium carbonate losses, with this treatment (CT) increases in yield (grain) and crop residues (straw) were obtained, compared to traditional tillage (TT), twelve years after having implanted both treatments. This fact could be due to the better water infiltration and storage in the soil profile under CT, that would facilitate the uptake of water and nutrients by the plant in the periods of most drought. The difference in straw production, 13,500 kg ha^{-1} in TT and 16,500 kg ha^{-1} in CT would signify an increase in organic C in CT greater than 1,000 kg ha^{-1}, compared to TT (presuming that the stubble was not burnt in TT).

Table 3. Parameters related with yield and seed composition. Mean values estimated in dry matter

Crop	Treatment	Thousand kernel weight (g)	Yield (kg ha^{-1})	N (g kg^{-1})	Zn (mg kg^{-1})
Sunflower	CT	54.5	> 2,000	25.2	26
	TT	56.0	> 2,000	19.1	23
Wheat	CT	47.3	3,094	19.1	36
	TT	46.6	2,517	17.2	29

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