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Chemical and biological properties as affected by no-tillage and conventional tillage systems in an irrigated Haploxeroll of Central Chile

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ABSTRACT

Soil management practices may change the soil properties. The magnitude of the change varies according to the soil property, the climate, and the type and time of implementation of a particular management system. The aim of this study was to evaluate the effects of no-tillage (NT) on the chemical and biological properties of an Entic Haploxeroll in Central Chile. Soil organic carbon (SOC), microbial biomass and associated indicators q_{CO_2}, q_{Mic}, q_{Min}, available N, P and K, pH, electrical conductivity (EC), and crop yield were determined in a field experiment having a wheat (*Triticum turgidum* L.)–maize (*Zea mays* L.) crop rotation. The change in soil chemical properties was further evaluated using a greenhouse bioassay in which ryegrass (*Lolium perenne* L.) was grown in soil samples extracted at 0–2, 2–5, and 5–15 cm depth. After nine years SOC in the NT treatment was 29.7 Mg ha^{-1} compared to 24.8 Mg ha^{-1} of CT, resulting in 4.98 Mg ha^{-1} C gain. The NT therefore resulted in an average annual sequestration of 0.55 Mg C ha^{-1} yr^{-1} in the upper 15 cm soil. The soil organic C stored under NT was mainly accumulated in the top 2-cm of soil. The biological indicators showed a greater biological soil quality under NT than under CT. Soil organic C was positively associated with available N, P, and K, but negatively with soil pH. The ryegrass bioassay yielded higher biomass in NT than CT. An improvement in the soil chemical quality of the NT soil was considered to be the main reason for this result. The maize yield under NT had the tendency to improve in time as compared to CT. Wheat, however, had lower yield under NT. It was concluded that NT increased C sequestration and SOC improving the chemical and biological properties of this soil.

1. Introduction

Dryland areas managed under no-till systems have progressively increased over time (Acevedo and Silva, 2003). This trend is in part the effect of reduced time and costs during tillage operations (Veseth, 1988; Lampurlanés and Cantero-Martínez, 2003; Juergens et al., 2004) as well as consideration to the potential benefits of NT, including reduced soil erosion and a positive effect on various soil quality indicators. No-till systems induce changes in the soil physical (Rhoton, 2000; McVay et al., 2006; Martínez et al., 2008; Fernández et al., 2010), chemical (Guzmán et al., 2006), and biological (Drijber et al., 2000; Six et al., 2002; Fernández et al., 2010) properties, which are associated to an increase of soil organic carbon (SOC) (Denef et al., 2004; Ordóñez et al., 2007). Reduced SOC is usually the consequence of increased tillage intensity (Álvarez et al., 1995; Salvo et al., 2010) along with higher CO_2 fluxes from the soil to the atmosphere (Reicosky et al., 1997). No-till systems promote SOC accumulation (Balesdent et al., 1990; Martínez et al., 2004; Thomas et al., 2007; López-Garrido et al., 2011), mainly in the topsoil (Havlin et al., 1990; Franzluebbers, 2001). In a long-term analysis, West and Post (2002) found that C sequestration in different rotations was, on average, 16.3% greater under NT than under conventional tillage (CT). However, this trend has been, to some extent questioned, because the distribution of SOC varies according to sampling depth. Higher concentrations of SOC near the soil surface have been found to be associated to conservation tillage, while higher concentrations of SOC at deeper soil layers were associated to CT management (Baker et al., 2007). Reicosky et al. (1997) and recently Babujia et al. (2010) reported that CT had greater CO_2 soil–atmosphere fluxes than NT and other tillage systems. Such fluxes occurring immediately after tillage are the result of the physical disruption of soil aggregates and the early oxidation of the most labile fraction of SOC.

Soil organic C affects other chemical properties such as soil pH, CEC, and nutrient availability. Different functional groups, that are part of the soil organic matter pool (e.g., carboxylic groups), can release H^+, thereby creating a more acidic environment in alkaline soils or buffering an already acidic environment in acid soils.

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Martínez et al. (2004) found a decrease in pH in the first centimeters of an Haploxeroll of Central Chile after four years on NT implementation, which was attributed to an increase in the partial pressure of CO_2 in the soil atmosphere caused by the higher SOC content. Such increase allows the combination of CO_2 with water, followed by the generation of carbonic acid, that releases H^+ after its dissociation (Carrasco, 1992). The CEC is controlled by the permanent charge of the clay particles, which virtually does not change with tillage systems, and by the pH-dependent charge of the organic colloids which is highly affected by SOC and consequently, by the tillage system. Total N (N_{tot}), as well as available P and K can be positively affected by no-tillage systems. Thomas et al. (2007) found no decreases in N_{tot} in NT while CT N_{tot} decreased in the top-30 cm of soil in a typic Natrsutalf of Australia, managed for nine years under NT. In the same study, available P and K were greater at the top 10-cm soil under NT as compared to CT.

Soil biological properties, such as microbial activity, have been widely used as sensitive indicators for soil quality (Pompili et al., 2006; Babujia et al., 2010). Chemical–biological properties such as SOC, microbial biomass-C, and soil basal respiration (laboratory incubations of 7 or 21 days), are considered good indicators of the soil microbial activity (Zagal and Córdova, 2005). These properties, when used together, can be utilized as ecological indicators (Anderson and Domsch, 1990; Agnelli et al., 2001; He et al., 2011). The most used biological indicators are the metabolic quotient qCO_2 (Anderson and Domsch, 1990), the microbial quotient q_{Mic}, and the mineralization quotient q_{Min} (Zagal and Córdova, 2005).

The effect of NT and CT cropping systems on crop yield has had contrasting results. Fuentes et al. (2003), did not find consistent differences in winter wheat yield between CT and NT systems in a Ultic Haploxeroll. Similar results were obtained by Merrill et al. (1996) in a Pachic Haploboroll under spring wheat. In contrast, Lawrence et al. (1994) found increased winter wheat yields growing under NT in a Typic Natrustalf as compared to CT. In a Typic Hapludalf soil of India, Acharya and Sharma (1994) found that maize yield decreased after six years of NT when compared to CT but, wheat yield did not differ between the two soil management systems. Wilhelm and Wortmann (2004) studied maize in a Typic Argiudoll managed under NT for 16 years. Decreased maize yield under NT in this case, was attributed to lower soil temperatures during spring, affecting initial plant growth.

Crop type, precipitation regime, soil temperature and soil texture are the most important factors regulating yield in NT and CT. In Mediterranean environments, water is the most limiting factor (Angás et al., 2006). In Chile, around 90% of the crop production comes from Mediterranean environments, in which most precipitation occurs during the cold winter months and to a lesser extent during the spring season. Summers are hot and dry, with high evaporation rates. Thus, crop production is highly dependent on the efficient use of water, which in summer crops such as maize is mostly regulated by irrigation management. NT systems can be seen as a positive choice in these environments in order to maintain soil moisture, particularly under rain-fed conditions. However, the general effect of NT systems on soil properties and yield in irrigated Mediterranean areas is not well known.

Our hypothesis is that NT management under irrigated-Mediterranean environments creates better soil biological and chemical conditions and allows a significant sequestration of C. The objectives of this study were to determine the effects of NT and CT systems on the chemical and biological properties of an irrigated Entic Haploxeroll in Central Chile, and to evaluate the grain yield of wheat and maize after six years of NT management.

2. Materials and methods

2.1. Sites and cropping system description

The study was performed with data obtained during eight growing seasons (1998–1999 to 2006–2007) obtained from NT and CT trials located at the Antumapu Experiment Station of the University of Chile (33°40′S, 70°38′W; 608 m elevation). The soil is a sandy clay of alluvial origin (coarse loamy over sandy, skeletal, mixed, thermic Entic Haploxeroll; Santiago Series CIREN, 1996). The climate of the area is Mediterranean, with dry and warm summers (mean maximum temperature of 28.7°C) and cold winters (mean minimum temperature of 3.4°C). Rainfall is concentrated in winter with an annual mean of 330 mm and a dry period of eight months (Santibáñez and Uribe, 1990).

Two trials comparing NT and CT had been established at contiguous sites. The sites varied in the time at which the NT and CT trials were implemented; one was established in year 1997 (S97) and the other site in year 2000 (S2000). We use two experiments (6 and 9 years of NT) each having a field experiment design of a randomized complete block with two treatments (NT and CT) and three replications. The plot size was 20 m long and 10 m wide under S97 and 40 m long and 10 m wide under S2000. Both sites were cropped with a durum spring wheat *(Triticum turgidum L. subsp. durum (Desf.) Husn.) cv. Llareta INIA*–maize (*Zea mays L.*) rotation. Selected soil chemical and physical properties previous to no-tillage implementation were described in Martínez et al. (2008).

Under NT, maize residues were mechanically chopped and uniformly distributed on top of the soil (equivalent to 8796 kg C ha^{-1}). In the CT treatment, maize residues (equivalent to 7565 kg C ha^{-1}) were mechanically shredded and buried with a moldboard plow to a depth of 20 cm. The soil was disked twice using a disk harrow before wheat planting. In both tillage treatments, wheat was planted on June at a density of 300 plants m^{-2} using a NT drill (Semeato SHM 11/13, Brazil). During the wheat rotation phase, the soil was fertilized with urea and triple super phosphate. Sixty kilograms of nitrogen per hectare and 80 kg P_2O_5 ha^{-1} were applied at planting and 90 kg N ha^{-1} of urea were broadcasted at the end of tillering. The weeds were controlled using Glyphosate (3 L ha^{-1}, acid equivalent of 1.44 kg ha^{-1} of isopropylamine glyphosate salt) before planting. The weed control also included a mixture of 1 L 2,4-D and 8 g Metsulfuron-methyl ha^{-1} at tillering to control broadleaf weeds. Aphids were controlled at the beginning of stem extension with Chlorpyrifos (0.35 L ha^{-1}).

The NT maize was also planted over mechanically chopped and homogeneously dispersed wheat residues (equivalent to 3843 kg C ha^{-1}) in September using the NT drill ("Mexico" hybrid up to 2003 and "Mexico CL" from 2004 onwards). In the CT treatment, wheat residues (equivalent to 4640 kg C ha^{-1}) were mechanically chopped and buried with a moldboard plow to a depth of 20 cm. In both NT and CT treatments, maize was planted with a NT drill (Semeato SHM 11/13, Brazil) at a plant density of 11 plants m^{-2} (110,000 plants ha^{-1}). The maize crop was fertilized with 250 kg ha^{-1} of N (urea) and 60 kg P_2O_5 ha^{-1} (Triple super phosphate) at planting. Additionally, 200 kg ha^{-1} of N (urea) were broadcasted at V_8 growth stage. Until 2004, weeds were controlled with a mixture of 1 L 2,4-D and EPTC (thiocarbamate, 8 L ha^{-1}). From 2004 and afterwards, weeds were controlled in both NT and CT treatments with Imazapic + Imazapyr (imidazolinone, 114 g ha^{-1}). In addition, the NT treatment considered the application of Glyphosate (3 L ha^{-1}) before planting. The trials were sprinkler irrigated using the soil water balance. A total of 12–14 irrigation events were applied to maize (30–45 mm per event) and three to four irrigation events to wheat (15–30 mm per event) from booting to physiological maturity.

2.2. Soil sampling and measurement of soil chemical properties

Composite soil samples, at depth intervals of 0–2, 2–5, and 5–15 cm, were obtained from CT and NT replicate plots under the wheat phase of the rotation during January of each year. Each composite sample was obtained from 20 sub-samples randomly taken in each plot. The soil samples were air dried for 48 h, sieved at 2 mm, and then stored at 5 °C until analysis.

Soil chemical analyzes were made in the years 0, 3, 5, 8, and 9 of NT, and 0, 2, 4, 5, and 6 of NT for the S97 and S2000 sites, respectively. For the sampling year 0, composite soil samples were taken from 0 to 15 cm-depth in both, NT and CT plots. Soil chemical properties were evaluated according to Sadzawka et al. (2004). Briefly, SOC was determined by wet combustion and colorimetric determination of the reduced chromate. Total N (N_{tot}) by Kjeldalh modified digestion and later determination of NH_3 by titration. Nitrate-N (N-NO_3^-), and ammonium-N (N-NH_4^+) by KCl extraction, distillation and later determination of NH_3 by titration. Available P (P_{Olsen}) by extraction with $NaHCO_3$ 0.5 mol L^{-1} at pH 8.5 and colorimetric determination. Extractable potassium (K^+) by extraction with ammonium acetate 1 mol L^{-1} at pH 7.0 and determination by atomic absorption spectrophotometry, with La. Soil pH was measured potentiometrically in a 1:3 (w:v) soil to water suspension. Electric conductivity (EC) was determined with a conductivimeter in extracts obtained from saturated soil samples.

2.3. Soil biological and ecological indicators

On June 2006, and previous to wheat planting, composite soil samples from the top 2-cm were taken from six and nine years NT plots and from the six years CT plots. Soil samples were sieved at 2 mm and stored at 5 °C until laboratory analysis. Microbial biomass-C (C_{bio}) was estimated by the chloroform fumigation method (Horwath and Paul, 1994). Three replicates of 25 g (equivalent dry weight) per composite sample were used for the study. Each soil replicate was placed in a mason jar (1000 cm^3) with one vial of 10 mL 1 N NaOH and another vial with 10 mL of deionized water. After placement of the vials the jars were sealed and stored at 23 °C for 10 days. The soil was incubated at 60% of water retention at 0.3 kPa. Each replicate considered a fumigated and a non-fumigated subsample. Microbial biomass-C was calculated according to (Horwath and Paul, 1994):

$$C_{bio} = \frac{C_f - 0.18C_{min}}{k_c} \quad (1)$$

where C_f ((mg CO_2)/100 g soil) is the CO_2 produced from a chloroform fumigated sample, C_{min} is the CO_2 produced from a non-fumigated (control) sample ((mg CO_2)/100 g soil), and k_c is the fraction of C_{bio} that is mineralized to CO_2. The value of k_c is considered a constant equal to 0.41 (Horwath and Paul, 1994). Following the recommendations of Smith et al. (1995), we used 18% of the measured value of C_{min} for our calculations.

With the data of *SOC*, C_{min}, and C_{bio}, the ecological indicators: microbial metabolic quotient (q_{CO_2}), microbial quotient (q_{Mic}), and mineralization quotient (q_{Min}) were calculated as:

$$q_{CO_2} = \frac{C_{min}}{C_{bio}} \quad (2)$$

$$q_{Mic} = \frac{C_{bio}}{SOC} \quad (3)$$

$$q_{Min} = \frac{C_{min}}{SOC} \quad (4)$$

2.4. Ryegrass bioassay

The productivity of Ryegrass (*Lolium perenne* L.) growing in soils collected from the NT and CT plots was evaluated in the 2002–2003 and 2006–2007 seasons. This bioassay assessed the potential effects on plant productivity of the chemical and biological changes between the NT and CT soils. With this trial, we isolated the effect of the physical changes (infiltration, porosity, compaction, soil temperature) from the chemical and biological changes occurring between the CT and NT systems. Polyvinyl Chloride pots of 1200 cm^3 were filled with sieved (2-mm) soil from the NT and CT trials. Soils were taken at 0–2, 2–5, and 5–15 cm depth intervals. Each pot was seeded with 2 g of ryegrass. No fertilizer was applied and the aboveground biomass of ryegrass was harvested every 30 days for a period of nine harvests.

2.5. Crop yield

Grain yield of wheat was determined by harvesting the above ground biomass in random rows of 1 m length replicated four times per plot. The plants were dried at 65 °C until constant weight. Then, the grain was separated using a Vogel-type thresher, dried at 70 °C for 48 h, and weighed. Maize yield was determined by harvesting 20 plants located in the central rows of each plot. The plants were dried at 65 °C until constant weight. Then, grain was separated from the cob and weighed. Grain yield was calculated as a function of grain weight per plant and the number of plants per m^2.

2.6. Statistical analysis

We studied the effect of the management system (CT and NT), of year of implementation of NT (six and nine years), and soil depth (0–2, 2–5, and 5–15 cm-depth) using a combined variance design (year of implementation × soil depth). Differences between means of crop yield and soil properties were determined using the least significance difference (LSD). The ANOVA and LSD procedures were run with MSTAT-C (Freed and Eisensmith, 1989). Prior to analysis the data were tested for homogeneity of variance and residuals distribution. If the data did not accomplish with these tests, the Kruskal and Wallis (1952) non-parametric test was used. In addition, the multivariate association between management systems, year of implementation, soil, and crop properties was studied using principal component analysis (PCA) with the statistical software InfoStat (V. 2005 P.1, Universidad Nacional de Córdoba, Argentina). For the chemical properties made, the interaction tillage system×time as well as the effect of time was not significant for Nitrate-N, ammonium-N, available P, extractable K, pH, and EC. Thus, we show the average of all sampling years for NT and CT.

3. Results and discussion

3.1. Soil organic carbon

Soil organic C under NT showed a stratified pattern with increased concentrations near the soil surface (Fig. 1). This is a common trend under NT systems (Franzluebbers, 2001). Under CT, SOC had no stratification, thereby we used a mean weighed average of SOC for the top 15 cm depth (Figs. 1 and 2). Soil organic C in the top 2 cm depth, increased with time under NT, until it reached an equilibrium value of about 18.5 g C kg^{-1} soil. According to Schneider (2007), the time necessary to reach equilibrium varies with time, the soil type, and the amount of initial SOC. Soil organic C did not vary with time at the 2–5 and 5–15 cm depth intervals (Fig. 1). Such trend has also been reported (e.g., Ortega et al., 2002),

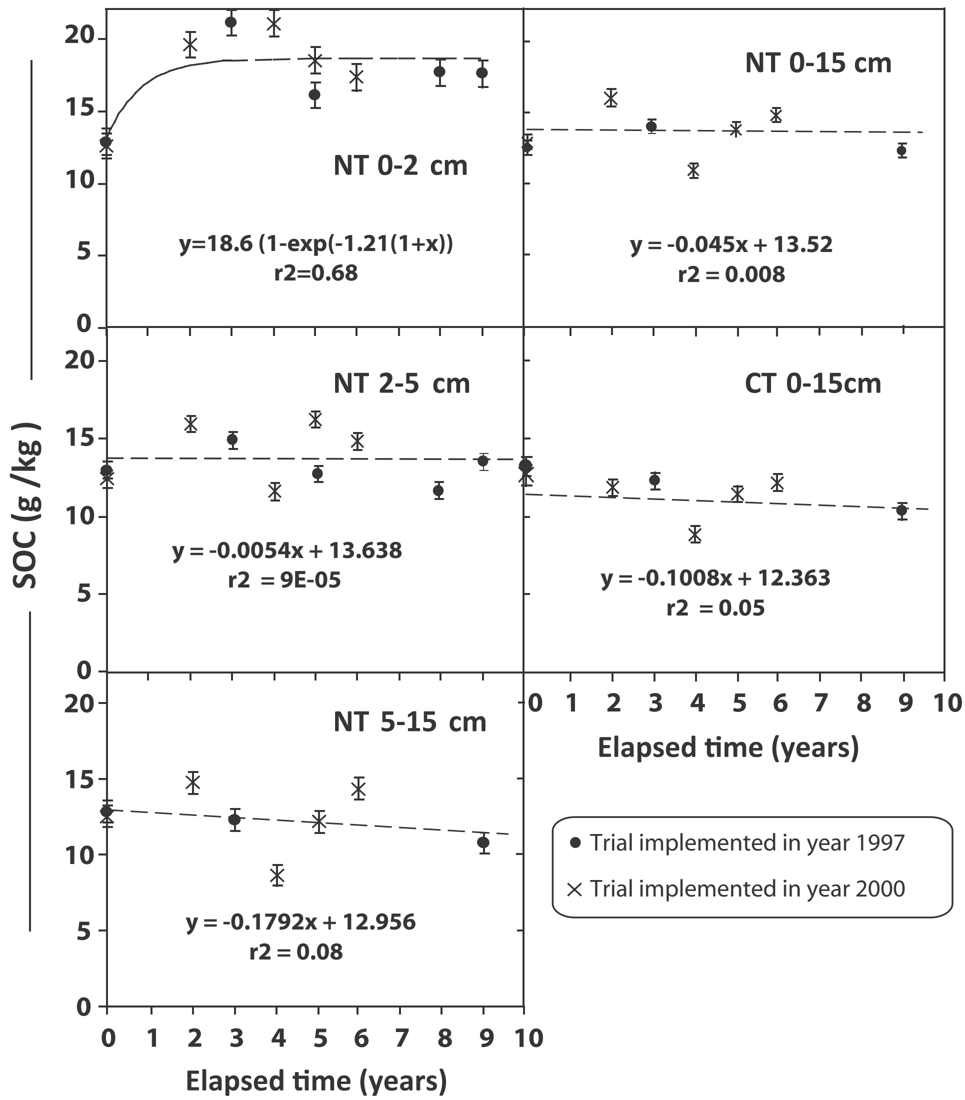

Fig. 1. Accumulation of SOC under no-tillage (NT) and conventional tillage (CT) treatments.

and may be attributed to the slow decomposition of soil residues in an usually more compacted soil surface, which acts as a physical barrier for organic matter decomposition. When comparing the accumulation of SOC in the 0–15 depth interval of the two tillage systems, the soil under NT had greater mean SOC (13.6 g C kg^{-1} of soil) as compared to CT (11.8 g C kg^{-1} of soil). After nine years, NT increased soil C in 4980 kg ha^{-1} above CT (Fig. 2), implying an average rate of C sequestration of 553 kg ha^{-1} $year^{-1}$. Other studies have reported a mean C sequestration rate between

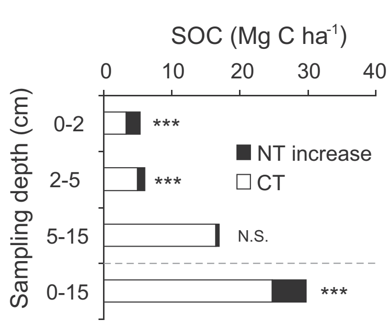

Fig. 2. Total SOC after nine years of no-tillage (NT) and conventional tillage (CT) management. *Least Significant Difference ($p < 0.05$).

325 ± 113 and 570±140 kg C ha^{-1} $year^{-1}$ (Six et al., 2002; West and Post, 2002) or even values as high as 840 ± 520 kg C ha^{-1} $year^{-1}$ (Marland et al., 2004). Considering soil databases of various long-term NT and CT agricultural experiments, located in different climates and soil types of the world, Six et al. (2002) as well as West and Post (2002) indicate that the time in which soil C reaches an equilibrium with NT implementation is 15–20 years or 20–25 years. In our work, only the top 2 cm of soil reached an equilibrium after four years of NT. It is unknown, at the current stage of the experiment, if the soil under NT will continue to accumulate C at depth. Based in soil trials that consider deeper soil sampling than ours, Baker et al. (2007) concluded that C sequestration might be greater under CT than under NT due to better thermal and physical conditions that enhance root growth and distribution, particularly at deeper depths. This pattern of SOC accumulation is not consistent in the literature. Salvo et al. (2010) found in an Argiudoll under a 10-year rotation of annual crops and pastures, that SOC significantly increased in NT than in CT, but only in the top 3 cm of soil. At deeper depths (up to 80 cm), SOC was the same between both management systems.

3.2. Soil biological and ecological indicators

Microbial activity evaluated by C_{bio} was higher in NT compared to CT. The differences between the two management systems

Table 1
Tillage system effects on microbial biomass-C (C_{bio}), soil basal respiration (C_{min}), soil organic carbon (SOC), microbial quotient (q_{Mic}), metabolic quotient (q_{CO_2}), and mineralization quotient (q_{Min}). Data obtained from samples taken from NT plots of six and nine years, and from the CT plots of six years.

Management system	Years	C_{bio} (mg C-CO$_2$ 100 g^{-1})	C_{min} (mg C-CO$_2$ 100 g^{-1} d^{-1})	SOC (%)	q_{Mic} (%)	q_{CO_2} (%)	q_{Min} (μg C mg SOC^{-1} d^{-1})
No-tillage	6	791	43	2.4	3.3	5.4	179.1
	9	1081	20	2.2	4.9	1.9	90.9
Conventional tillage	6	250	32	1.4	1.8	12.8	228.6
MSMD[a]		474	N.S.[b]	0.1	2.1	N.S.	N.S.

[a] Minimum significant mean difference using Least Significant Difference (LSD) ($p \leq 0.05$).
[b] Not significant.

increased with time (Table 1). Microbial activity near the soil surface under CT can decrease as a result of soil erosion (Castillo and Joergensen, 2001), soil hydraulic properties and extreme changes in microclimatic conditions. In contrast, the NT system maintains a layer of residues on the surface which decreases the probability of soil erosion and also creates a microclimatic environment that controls soil temperature fluctuations and reduces water evaporation, thereby creating a better environment for microbial development (Singh and Singh, 1993). A higher C_{bio} can be indicative of a better biological quality of the soil under the NT management (Doran and Parkin, 1994). The q_{Mic} value indicated that under NT the soil had a greater capacity of sequestering SOC, what is in agreement with the experimental data observed in Fig. 2. In epipedons, a reduced q_{Mic}, such as the one found under CT, implies an accelerated SOC turnover (Meyer et al., 1996). In contrast, the greater q_{Mic} in NT can be the result of a higher amount of surface residues (Anderson and Domsch, 1989).

Given the high variability detected for C_{min}, differences in this variable as well as in q_{CO_2}, and q_{Min} were not significant between management systems (Table 1). Despite the non significant differences, the tendency was to a greater q_{CO_2} in CT than in NT, and a decrease of q_{CO_2} in time from NT implementation (Table 1). This trend is indicative of a greater C conversion efficiency of the microorganisms developed under NT. The mineralization quotient q_{Min} estimates the microbial activity as a function of basal respiratory responses (C_{Min}) and the amount of organic substrate. When the inputs of organic matter become larger, C_{min} and SOC are expected to increase (García-Gil, 2001; Pompili et al., 2006). The change in q_{Min} is a function of the amount and quality of organic matter inputs (García-Gil, 2001) and the microbial capacity for the synthesis and decomposition of organic compounds.

The principal component analysis of biological and ecological indicators as well as soil chemical properties (Fig. 3), separated tillage systems (PC1) and years under no-tillage (PC2). Six years of management under NT (NT6), was positively associated with SOC, exchangeable K, EC, total N, and available N ($NO_3^- + NH_4^+$). When the time from NT implementation increased, the association between variables also changed; nine years of management under NT (NT9) was positively associated with C_{bio}, q_{Mic}, and available P; and negatively associated with soil pH, q_{CO_2}, and q_{Min}. The soil managed under NT had a greater level of nutrients, which were associated to an increased biological quality. Such pattern is in agreement with other studies (e.g., Teklay et al., 2005).

3.3. Soil pH, electrical conductivity, and available N, P, and K

The acidity increased under NT in the top 15-cm of soil as compared to CT (Table 2). The larger decrease (0.16 pH units) was found in the top 2-cm of soil. Nitrogen fertilizers, particularly urea, acidify the soil near the seeding zone. In our case, urea is applied at planting and during the first phenological stages of the crops, which explain the general decrease in pH of the first 15 cm of soil. But the major decrease found in the top 2 cm of soil can be explained by the decomposition of the residues, which releases H^+ ions. Soil pH was negatively correlated to SOC ($R = -0.91$, $p < 0.001$). This negative correlation has been found by others (e.g., Thomas et al., 2007). It is expected that H^+ ions will move down throughout the soil profile, but the slow infiltration rate

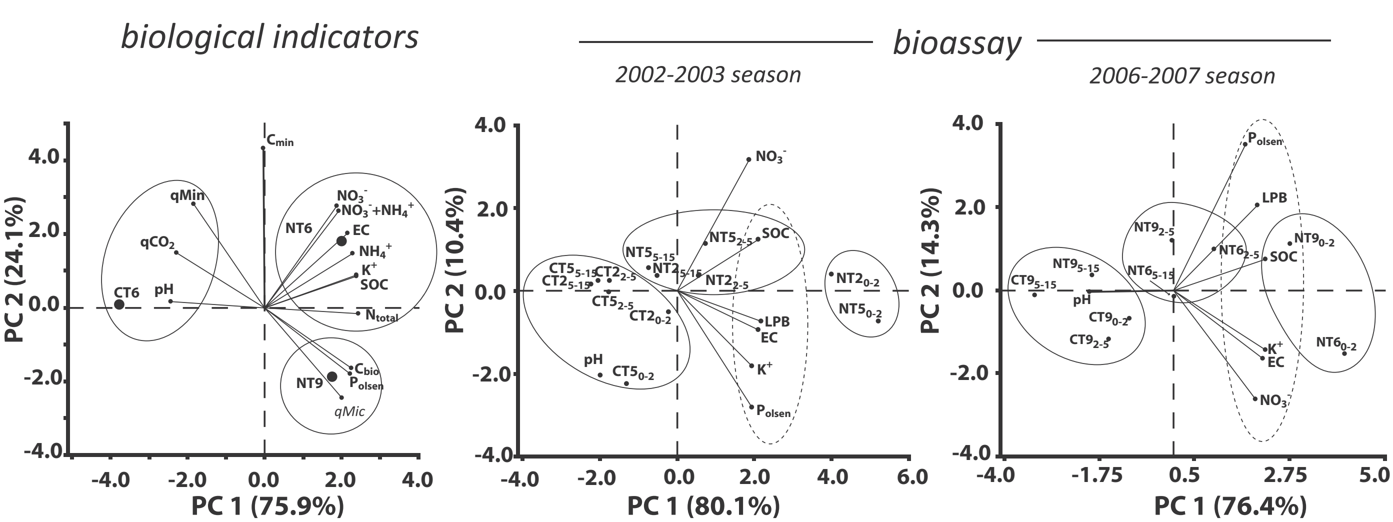

Fig. 3. Principal component diagram for chemical and biological soil properties after six and nine years of no-tillage (NT6 and NT9) and conventional tillage (CT) (left), and principal component diagrams for the ryegrass experiment. Diagrams show tillage system × soil depth × year interaction for shoot dry weight of ryegrass (LPB), and soil chemical properties in the 2002–2003 (center) and 2006–2007 (right) seasons.

Table 2
Tillage system effect on total nitrogen (N_{tot}), nitrate ($N\text{-}NO_3^-$), ammonium ($N\text{-}NH_4^+$), P_{Olsen}, extractable potassium (K^+), pH (1:3 soil to water ratio), and soil electrical conductivity (EC). Average of all sampling years for NT and CT.

Management system	Soil depth (cm)	N_{tot} (mg kg^{-1})	$N\text{-}NO_3^-$ (mg kg^{-1})	$N\text{-}NH_4^+$ (mg kg^{-1})	P_{Olsen} (mg kg^{-1})	K^+ (mg kg^{-1})	pH	EC (dS m^{-1})
No-tillage	0–2	1671.1	38.7	8.8	25.1	288.5	8.0	0.7
	2–5	1176.1	19.7	5.2	18.4	197.8	8.1	0.4
	5–15	1140.8	14.6	6.9	14.2	169.9	8.1	0.4
	0–15	1218.6	18.8	6.8	16.5	191.3	8.1	0.4
Conventional tillage	0–15	1069.6	12.4	7.0	10.2	142.4	8.1	0.3
LSD[a]		114.4	7.6	3.2	4.6	21.4	<0.1	0.1

[a] Least Significant Difference ($p \leq 0.05$).

under NT (see (Martínez et al., 2008)) increases the probability of maintaining the released H^+ ions near the soil surface. Similar results were found by Rhoton (2000) in a silt loam soil of Mississippi, under NT and CT treatments, with soil pH decreases of about 0.2–0.3 units in the top 2.5 cm depth. Franzluebbers and Hons (1996) also found a decrease in soil pH but in a highly alkaline silty clay loam soil. In their study, the decrease was of the order of 0.1–0.2 pH units in the NT soil.

The electric conductivity of the soil was less than 1 dS m^{-1} in both NT and CT systems, which is indicative of no salinity problems. Under NT, the EC was higher in the top 2-cm soil depth as compared to CT (Table 2). From 2 to 15 cm and from the 0–15 depth interval no significant differences were found in EC between the two management systems. The higher EC observed in the first 2-cm soil under NT can be associated to the greater biological activity in this system. Biological processes such as nitrification, increases the transformation of SOM and the liberation of H^+ ions. These ions compete with the non acid ions for the colloidal exchange sites, thereby favoring the release of non-acidic ions to the soil solution. Such ions can form salts, creating an increase in EC (García-Gil, 2001).

Total soil N increased in the top 15 cm of soil under NT and it mainly concentrated in the top 2 cm (Table 2). This increase implied a net gain of 252 kg N ha^{-1} after nine years of NT management. Total N had also a significant positive correlation with SOC ($r = 0.79$, $p \leq 0.05$). This correlation pattern has also been reported in a Typic Natrustalf of Australia (Thomas et al., 2007). Soil NO_3^- under NT was also higher than under CT, but no effect of management systems was found for the NH_4^+ concentration (Table 2). Similarly, available P significantly increased in NT as compared to CT (Table 2) with major effect in the top 5 cm of soil. When considering the 5–15 cm depth of NT and 0–15 cm depth of the CT, the soil differences in available P were not significant. This particular pattern of major increases of P in the top cm of soil has been widely reported. Unger (1991), found increased extractable P in the first 2 cm of soil under NT as compared to CT, but such differences disappeared at deeper sampling depths. Robbins and Voss (1991) found a higher amount of available P in the top 5 cm depth in a silt loam soil managed under NT as compared to ridge tillage. Ismail et al. (1994) found greater extractable P in the top 5 cm of a silt loam soil after 20 years under NT management. From 5 to 30 cm depth extractable P was lower under NT than under CT. The effect of NT management in the available P distribution, at deeper depths, was reported by Thomas et al. (2007). In their study, available P was higher in the top 10 cm depth of a Typic Natrustalf managed under NT as compared to a moldboard plowed soil. Extractable K had a pattern similar to N and P (Table 2) with significant increases under NT as compared to CT in the 0–2, 2–5, 5–15, and 0–15 cm depth. Greater differences in extractable K occurred in the first cm of soil. The studies of Ismail et al. (1994), Franzluebbers et al. (1995), Franzluebbers and Hons (1996), as well as Thomas et al. (2007), have reported similar patterns, with increases in available K^+ even to 60 cm soil depth.

The increased amounts of total N, as well as available forms of N, P, and K under NT can be related to the residues on the soil surface, which generate a better environment for microbial activity and organic matter mineralization (Franzluebbers et al., 1995; Franzluebbers and Hons, 1996; Thomas et al., 2007). In case of P, the application of the P fertilizer varied between NT and CT, thereby enhancing differences in P distribution. Under CT, the P fertilizer was applied with plowing, allowing an homogeneous distribution of P in the first 30 cm of soil. Under NT, the P fertilizer was applied at planting near to the seed. Thus, the intrinsic limited mobilization of P restricts its distribution to a few cm near the plant seedling.

3.4. Reygrass biomass

Above ground ryegrass biomass (LPB) can be used as an adequate indicator of soil chemical fertility. Ryegrass has a high regrowth capacity, allowing the extraction of an important part of soil nutrients along successive biomass cuttings. The soil under NT significantly favored LPB, particularly in the topsoil samples (Table 3). The greater LPB under NT is mainly explained by its positive associations with SOC, P Olsen, extractable K, and soil NO_3^- (Fig. 3) and the negative association of LPB with soil pH. In the two experimental trials (2002–2003 and 2006–2007), soil pH in all treatments was moderately alkaline (Table 2). Thus, a slight decrease in this variable may indicate a more adequate condition in terms of nutrient balance and microbial activity. The positive association of LPB and COS was also reflected in a significant positive correlation ($R = 0.87$, $p \leq 0.05$). With the isolation of physical variables by sieving of soil samples, it was possible to demonstrate that NT management can enhance soil chemical fertility and thereby the productive capacity of the soil. Physical restrictions such as soil compaction, decreased infiltration (demonstrated in the study of Martínez et al. (2008), made in the same experimental trial), play an important role in limiting plant productivity in the studied soil.

Table 3
Shoot dry weight of ryegrass growing in pots filled with soil from no-tillage (NT) and conventional tillage (CT). Soil samples obtained in the 2002–2003 season (nine cuts made).

Management system	Soil depth effect			LSD
	D1	D2	D3	
No-tillage	4.52	3.37	3.19	0.45
Conventional tillage	3.13	2.66	2.58	

[a] Pots filled with soil extracted at 0–2 (D1), 2–5 (D2) and 5–15 (D3) cm depth.
[b] Least Significant Difference ($p \leq 0.05$).

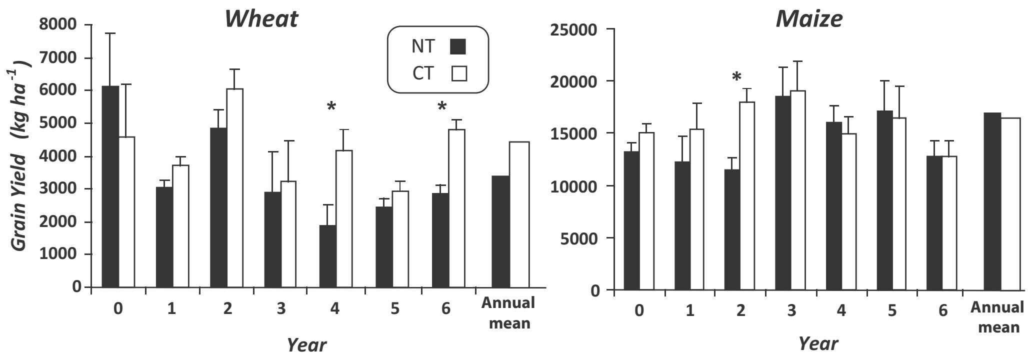

Fig. 4. Yields of wheat and maize crops over the studied period for no-tillage (NT) and conventional tillage (CT) management systems. Error bars indicate one standard deviation of the mean.

3.5. Crop yield

Crop yield in NT tended to decrease with increased years of NT, with significant differences between CT and NT at the fourth and sixth year after NT implementation (Fig. 4). The annual average of wheat yield was smaller in NT as compared to CT (3367 and 4708 kg ha^{-1}, respectively) (Fig. 4). Plant emergence had a heterogeneous pattern under NT causing an irregular wheat cover. Furthermore, during the flowering stage, wheat of NT had fungi problems (i.e. Fusarium). In general, fungi diseases intensify their damage when the soil has infiltration problems or when only gramineae are considered in the rotation. In this trial, the wheat-maize rotation along with a decrease in soil water infiltration due to soil compaction (see Martínez et al., 2008) could have increased fungi damage. No significant differences in maize yield were found between NT and CT, with the only exception of year 2 (Fig. 4). Maize yield decreased during the first three years after NT implementation. This trend was reverted during the following years. As a result, the annual average of maize yield was greater in NT as compared to CT (16,543 and 16,241 kg ha^{-1}, respectively) (Fig. 4).

4. Conclusions

After nine years of no-tillage implementation, a significant amount of C was sequestered in no-tillage as compared with conventional tillage, particularly in the top-cm of soil. Based on our results in terms of soil biological properties and crop yields, we believe that the rate of loss of SOC under NT is lower than of CT. Decreased C inputs created by lower wheat yields are counteracted by greater maize yields and thereby more residue inputs under NT. Incorporation of residues under CT creates an accelerated process of decomposition, where mineralization is the governing force rather than humification, particularly under the first years of residue decomposition. Therefore, NT promotes a more efficient use of the SOC, promoting soil C accumulation in time. Soil chemical fertility increased under NT, with higher levels of N, P, and K and a slight decrease of soil alkalinity, with major changes being observed in the top 5 cm of soil. These chemical changes are mainly attributed to the maintenance of crop residues on the soil surface, which contribute with a slow release of nutrients throughout mineralization and to the development of a better environment for microbial activity. The ryegrass bioassay made with sieved soil samples from NT and CT systems is indicative of a better productive capacity of the soil under NT from a chemical point of view. Consequently, the deterioration of the soil physical properties by compaction may cause the major restriction for better crop yields under NT. This is of particular importance for wheat crops, which seem to be more sensitive to changes from CT to NT as compared to maize crop under this sandy clay soil.

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