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Changes in soil enzyme activity, fertility, aggregation and C sequestration mediated by conservation tillage practices and water regime in a maize field

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Abstract

We examined the medium-term (3 year) effects of no-tillage, reduced tillage (subsoil-bedding and shred-bedding) and water regime on the soil profile distribution of organic matter and physical and microbiological soil quality indicators in a maize field under subtropical conditions. Soil carbon sequestration was evaluated as well. Residue on the soil surface was about 17–21-fold increased in the no-tillage plots over the mouldboard plough plots, with intermediate increases in the reduced tillage plots. In the surface 0–5 cm, organic matter decreased with increasing tillage and was increased by irrigation. The no-tilled soil had increased values of water-soluble C, dehydrogenase, urease and acid phosphatase activities, aggregate stability and glomalin compared to tilled soils, especially in the shallowest (0–5 cm) layer. The water regime had no effect on soil structural stability or total microbial activity.

Keywords: Enzyme activities; Structural stability; Labile organic C; No-tillage; Zero-tillage

1. Introduction

Soil tillage causes a rapid loss of organic matter content leading to low soil biological activity, a decline in aggregate stability and a reduction in crop productivity (Bayer et al., 2001). In addition, carbon sequestration in the soil may be reduced with some tillage practices (Aslam et al., 2000). Organic matter is involved in the enhancement of soil quality since it acts on soil structure, nutrient storage and biological activity. The quality and quantity of soil organic matter normally changes very slowly and many years (5–10 years) are required to detect changes resulting from disturbance. The extent of soil organic matter turnover is mainly controlled by the size and activity of the microbial biomass, which may respond to

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disturbance over shorter time scales (months). For this reason, soil biological and biochemical parameters may have a role as early and sensitive indicators of soil ecological stress and restoration (Roldán et al., 2003; Izquierdo et al., 2003). Bolinder et al. (1999) indicated that the soil microbial biomass is more sensitive to changes in soil quality than total organic carbon or nitrogen. Soil enzyme activities are especially significant because they control nutrient release for plant and microbial growth. Likewise, the labile pool of soil organic matter, which is closely related to soil microbial biomass, could be used as a sensitive indicator of short-term changes in soil management. The literature on water-extractable organic matter, which is a component of the labile soil organic matter, dynamics in different ecosystems is derived mainly from studies on temperate forest, grassland and arable soils, whereas very few studies have been published on sub- and tropical ecosystems (Chantigny, 2003).

Adoption of conservation tillage in Mexico, which allows crop residues to remain on the soil surface and minimises soil disturbance, is growing because of heightened interest in sustainable agriculture (Roldán et al., 2003). Soil organic matter distribution, nutrient cycling and microbial activity are influenced by the type and the degree of soil tillage (Salinas-García et al., 2002). Changes in soil moisture, temperature and C input can also have a large effect on the soil microbial biomass and its activity, which, in turn, affect nutrient availability due to soil organic matter turnover (Ross, 1987). Limited data, however, exist on the magnitude of changes in soil enzyme activities under different water regimes in subtropical agroecosystems.

The activity of dehydrogenase is considered an indicator of the oxidative metabolism in soils and thus of the microbiological activity (García et al., 1997), because it is exclusively intracellular and, theoretically, can function only within viable cells.

Urease catalyses the hydrolysis of urea to CO_2 and NH_3, which is of particular interest because urea is an important N fertiliser. Urease is released from living and disintegrated microbial cells, and in the soil it can exist as an extracellular enzyme absorbed on clay particles or encapsulated in humic complexes (Nannipieri, 1994). Phosphatases catalyse the hydrolysis of both organic phosphate (P) esters and anhydrides of phosphoric acid into inorganic P. Phosphatase activity may originate from the plant roots (and associated mycorrhiza and other fungi), or from bacteria (Tarafdar and Marschner, 1994).

Loss of soil organic matter following tillage practices has been attributed to the destruction of macroaggregates and subsequent mineralisation of labile soil organic matter. Thus, the structure of soil protects soil organic matter and influences organic matter turnover and soil fertility. Plant roots increase the stability of surrounding aggregates (Lynch and Bragg, 1985) through several interacting mechanisms. Roots and associated mycorrhizal hyphae may form a three-dimensional network that enmeshes fine particles of soil into aggregates. Recent studies have also indicated that arbuscular mycorrhizal (AM) fungi produces a glycoprotein, glomalin that acts as an insoluble glue to stabilise aggregates (Wright and Anderson, 2000). These authors have found that glomalin changes quickly in response to crop rotations and tillage management practices.

The objective of this study was to determine the medium-term (3 year) effects of conservation management practices, such as no-tillage and reduced tillage (subsoil-bedding and shred-bedding), and water regime on the soil profile distribution of organic matter and on physical and microbiological soil quality indicators in a maize field under subtropical conditions. We also ascertained whether the changes in these indicators can be related to soil C sequestration.

2. Materials and methods

2.1. Site description

This research was conducted at the Río Bravo experimental site, in Northern Tamaulipas, Mexico (25°57′N, 98°01′W). The dominant soil type is Vertisol (FAO, 1988), developed from alluvial sediments with a clay texture (28% sand, 41% clay and 31% silt), 1.2% organic matter and a pH of 7.8 (1:2, soil:water). The climate of the region is classified as warm subtropical, with hot, wet summers and dry winters. The annual temperature averages 23 °C and the annual rainfall averages 635 mm. The topography of the area is mainly flat and slopes do not exceed 3%. Before the experiment was established the field was

planted with either maize or sorghum in a crop–fallow sequence. Crop–fallow sequence (fallow–maize or fallow–sorghum), means a year crop sequence when a period of time is left in fallow (August to January) and then a maize or sorghum cropping period (February to July).

2.2. Experimental design and layout

The experiment was conducted using a factorial design in randomised blocks, with two factors and three replicates. The first factor included four tillage treatments: mouldboard plough (disking stalks after harvest, followed by mouldboard plough and disking, then building the rows), subsoil-bedding (shredding stalks after harvest, followed by subsoiling on row centres and forming beds in the same operation), shred-bedding (shredding stalks after harvest, followed by bedding on the old rows) and no-tillage (shredding stalks after harvest and spraying glyphosate [1.5 l ha^{-1}] and 2,4 D-amine [1.5 l ha^{-1}] as needed for weed control). The second factor involved two water regimes: irrigated or non-irrigated. Plots measured 22.4 m × 52 m. *Zea mays* L. (hybrid maize Pionner 2725) was planted in early February and harvested in the first half of June each year from 2001 to 2003. Irrigated field were flooded to 10-cm water layer. The first irrigation was carried out 55 days after planting, coinciding with the flowering stage, and the second at 75 days after planting, when the grain was mature. The cumulative rainfall during the four and a half months of the growth period was about 95 mm and about 440 mm during the fallow period.

2.3. Soil sampling

Soil samples were collected during the 2003 maize-growing season, in late April. Soil samples from each plot consisted of five composite subsamples that were taken with a probe (6.0-cm diameter core) and divided into segments of 0–5 and 10–15 cm. Field-moist soil samples were divided into two subsamples. One subsample was sieved at 2 mm and stored at 2 °C for biochemical analysis and the other subsample was air-dried at room temperature and sieved at 2 mm for physical–chemical and chemical analysis or at 0.2–4 mm for aggregate stability. Visible pieces of crop residues and roots were removed.

Surface crop residues were collected after primary tillage from two midrow to midrow 1 m^2 areas that were representative of each tillage treatment, dried (60 °C, 48 h) and weighed then converted to kg ha^{-1} (Steiner et al., 1994).

Surface percentage of cover was determined using a line-transect measurement, by stretching a 10-m string with 100 marks (10 cm apart) across the field at a 45° angle to the rows. The number of times residue was found under a mark indicated the percentage of cover (Steiner et al., 1994).

2.4. Chemical analyses

Total organic C was determined by oxidation with potassium dichromate in a sulphuric medium and excess dichromate evaluated using Mohr's salt (Yeomans and Bremner, 1988). Water-soluble carbon in soil aqueous extracts (1:5, w/v) was determined by wet oxidation with $K_2Cr_2O_7$ and measurement of the absorbance at 590 nm (Sims and Haby, 1971). Available P (with 0.5 M sodium bicarbonate, pH 8.5) was determined by colorimetry, according to Murphy and Riley (1962). Inorganic NO_3–N was measured using the cadmium reduction method, following extraction with 2 M KCl (1:4, w:v) and shaking for 30 min.

Glomalin was extracted from soil samples with 20 mM sodium citrate (pH 7.0) at a rate of 0.25 g of soil in 2 ml of buffer. Extracts were autoclaved at 121 °C for 30 min (Wright and Anderson, 2000); then centrifuged at 10,000 × *g* for 15 min to remove soil particles. Protein in the supernatant was determined by the Bradford dyebinding assay using bovine serum albumin as the standard.

2.5. Biochemical analyses

Dehydrogenase activity was determined according to García et al. (1997). For this, 1 g of soil at 60% of its field capacity was exposed to 0.2 ml of 0.4% 2-*p*-iodophenyl-3-*p*-nitrophenyl-5-phenyltetrazolium chloride (INT) in distilled water for 20 h at 22 °C in darkness. The iodo-nitrotetrazolium formazan (INTF) formed was extracted with 10 ml of methanol by shaking vigorously for 1 min and filtration through a Whatman No. 5 filter paper. The INTF was measured spectrophotometrically at 490 nm.

Urease activity was determined in 0.1 M phosphate buffer at pH 7; 1 M urea was used as substrate. Two millilitres of buffer and 0.5 ml of substrate were added to 0.5 g of sample, which was incubated at 30 °C for 90 min. Activity was determined as the NH_4^+ released in the hydrolysis reaction (Nannipieri et al., 1980).

Acid phosphatase activity was determined using *p*-nitrophenyl phosphate disodium (PNPP, 0.115 M) as substrate. Two millilitres 0.5 M sodium acetate buffer at pH 5.5 (Nannipieri et al., 1980) and 0.5 ml of substrate were added to 0.5 g of soil and incubated at 37 °C for 90 min. The reaction was stopped by cooling at 2 °C for 15 min. Then, 0.5 ml 0.5 M $CaCl_2$ and 2 ml 0.5 M NaOH were added, and the mixture was centrifuged at 2287 × *g* for 5 min. The *p*-nitrophenol (PNP) formed was determined by spectrophotometry at 398 nm. Controls were made in the same way, although the substrate was added before the $CaCl_2$ and NaOH.

2.6. Physical analyses

The percentage of water stable aggregates was determined by the method described by Lax et al. (1994).

Bulk density was calculated from dry soil weights (105 °C; 48 h) and the volume of samples taken with a hammer-driven core sampler (55-mm diameter) (Blake, 1965).

2.7. Statistical analysis

Treatment effects on measured variables were tested by analysis of variance and comparisons among treatment means were made using a least significant difference (LSD) test calculated at $P < 0.05$. Statistical procedures were carried out with the software package Statgraphics for Windows 7.0.

3. Results

3.1. Surface crop residue

Surface crop residue was significantly affected by tillage practices and water regime (Table 1). Irrigated no-tillage produced the highest residue amount (about 3.7-fold more residue than mouldboard plough), and the greatest residue cover (21-fold more covered than the soil under mouldboard plough) on the soil surface. The soils under mouldboard ploughing showed the least residue. There were no significant differences between subsoil-bedding and shred-bedding with respect to surface crop residue.

3.2. Soil chemical properties

In the surface 0–5 cm, organic matter decreased with increasing tillage and was increased by the irrigation in all tillage treatments (Table 2). The content of organic matter in soil under no-tillage with irrigation was 27% greater compared with the average of the other tillage treatments. Mouldboard ploughing resulted in the lowest organic matter content throughout the 0–5-cm soil depth. Below the surface 0–5 cm, organic matter decreased and there were no significant differences due to treatments or irrigation.

Soil nitrate to a depth of 15 cm was consistently higher under irrigated and non-irrigated no-tillage than the other tillage treatments, with greater differences in the shallowest (0–5 cm) layer (Table 2). Nitrate did not vary with soil depth in the soils under shred-bedding or subsoil-bedding tillage. The irrigation only had an effect on soil nitrate under no-tillage and subsoil-bedding. Tillage treatments, soil depth and water regime had no significant effect on available P (Table 3).

Table 1
Crop residue on the soil surface as affected by different management tillage systems

	Residue cover (%)		Residue amount (kg ha^{-1})	
	Non-irrigated	Irrigated	Non-irrigated	Irrigated
Mouldboard	4.3 ± 0.2	5.7 ± 0.4	1133 ± 12	1500 ± 38
Shred-bedding	9.7 ± 0.2	12.0 ± 0.3	3048 ± 3	3865 ± 94
Subsoil-bedding	10.3 ± 0.2	13.0 ± 0.3	3122 ± 9	3891 ± 152
No-tillage	91.0 ± 0.3	96.0 ± 0.3	4557 ± 30	5492 ± 82

Values are mean ± S.E.

Table 2
Organic matter and nutrients of the soil under different management tillage systems subjected to two water regimes ($n = 3$)

	Soil depth (cm)											
	Organic matter (%)				$N–NO_3^-$ ($\mu g\ g^{-1}$)				Available P ($\mu g\ g^{-1}$)			
	0–5[a]	10–15[a]	0–5[b]	10–15[b]	0–5[a]	10–15[a]	0–5[b]	10–15[b]	0–5[a]	10–15[a]	0–5[b]	10–15[b]
Mouldboard	2.49 ± 0.01	2.51 ± 0.05	2.58 ± 0.01	2.57 ± 0.01	20 ± 3	11 ± 2	22 ± 1	13 ± 2	11 ± 1	12 ± 1	13 ± 1	12 ± 0
Shred-bedding	2.64 ± 0.02	2.47 ± 0.04	2.66 ± 0.02	2.49 ± 0.01	11 ± 1	9 ± 1	10 ± 1	10 ± 1	15 ± 2	14 ± 2	12 ± 3	11 ± 1
Subsoil-bedding	2.66 ± 0.04	2.52 ± 0.03	2.73 ± 0.02	2.62 ± 0.01	17 ± 1	17 ± 3	8 ± 2	5 ± 1	12 ± 2	12 ± 2	13 ± 3	12 ± 2
No-tillage	3.14 ± 0.01	2.54 ± 0.05	3.38 ± 0.02	2.55 ± 0.02	44 ± 2	25 ± 1	29 ± 1	18 ± 1	13 ± 3	12 ± 1	11 ± 1	11 ± 1

Values are mean ± S.E.
[a] Non-irrigated
[b] Irrigated

The tillage system and water regime had a significant effect on water-soluble C (Table 3). However, water-soluble C was not affected by soil depth. Tilled soils presented water-soluble C values lower than in the soil under no-tillage (Table 4). Excepting the soil under intensive tillage (mouldboard), irrigation increased water-soluble C in the upper 0–5 cm, especially for the subsoil-bedding treatment (about 46% more with respect to non-irrigated soil). At lower depths, there appeared to be no effect of irrigation on water-soluble C.

3.3. Soil biochemical properties

Dehydrogenase activity was decreased significantly by intensive tillage, as shown in Table 4. The interaction between the tillage treatments and soil depth affected dehydrogenase activity to a very significant degree ($P = 0.001$). Thus, the differences in dehydrogenase activity between no-tilled and tilled soils (mouldboard, shred-bedding and subsoil-bedding) decreased with soil depth. The water regime did not affect dehydrogenase activity (Table 3).

Tillage system and water regime had significant effects on soil urease and acid phosphatase activities. Tillage reduced the urease and acid phosphatase activities at all soil depths, particularly with the adoption of mouldboard (Table 4). The irrigation increased the phosphatase activity and decreased urease activity. Likewise, the irrigation of maize plants significantly increased the positive effect of the no-tillage treatment on phosphatase activity. Only phosphatase activity was influenced by soil depth (Table 3).

Table 3
Three factors ANOVA (soil depth, tillage systems and water regime) for all parameters studied

Source of variation	Depth (D)	Tillage (T)	Water regime (WR)	Interactions			
				$D \times T$	$D \times$ WR	$T \times$ WR	$D \times T \times$ WR
Organic matter	<0.001	<0.001	0.004	<0.001	0.334	0.652	0.366
Nitrates	<0.001	<0.001	0.072	0.103	0.011	0.056	<0.001
Available P	0.666	0.226	0.130	0.961	0.436	0.090	0.939
Water-soluble C	0.590	<0.001	<0.001	<0.001	0.047	0.814	<0.001
Dehydrogenase	0.002	<0.001	0.738	0.001	0.912	0.064	0.005
Urease	0.152	<0.001	0.002	0.128	0.557	0.577	0.419
Phosphatase	0.003	<0.001	<0.001	<0.001	0.028	0.007	0.744
Aggregate stability	0.242	0.002	0.280	0.002	0.010	0.022	0.247
Glomalin	0.068	<0.001	0.692	<0.001	0.698	<0.001	0.272
Bulk density	<0.001	<0.001	<0.001	<0.001	0.174	0.425	0.434
Residue cover	–	<0.001	<0.001	–	–	0.017	–
Residue amount	–	<0.001	<0.001	–	–	0.159	–

P significance values.

Table 4
Labile organic matter fraction and biochemical properties of the soil under different management tillage systems subjected to two water regimes ($n = 3$)

	Soil depth (cm)							
	Water-soluble C ($\mu g\ g^{-1}$)				Dehydrogenase (μg INTF g^{-1})			
	0–5[a]	10–15[a]	0–5[b]	10–15[b]	0–5[a]	10–15[a]	0–5[b]	10–15[b]
Mouldboard	114 ± 1[†]	104 ± 3	115 ± 1	104 ± 3	27.5 ± 0.9	22.9 ± 1.7	25.6 ± 0.1	32.1 ± 3.0
Shred-bedding	98 ± 2	100 ± 1	116 ± 0	108 ± 4	26.5 ± 0.7	26.7 ± 1.3	27.1 ± 0.7	24.3 ± 0.5
Subsoil-bedding	100 ± 2	128 ± 5	146 ± 3	128 ± 6	33.5 ± 0.1	39.6 ± 0.4	35.5 ± 0.1	28.6 ± 0.4
No-tillage	176 ± 4	147 ± 6	196 ± 3	157 ± 5	42.1 ± 0.7	26.1 ± 1.0	43.4 ± 2.6	30.4 ± 0.7
	Urease ($\mu mol\ NH_3\ g^{-1}\ h^{-1}$)				Acid phosphatase ($\mu molPNPg^{-1-}h^{-1}$)			
Mouldboard	0.52 ± 0.01	0.55 ± 0.01	0.45 ± 0.01	0.57 ± 0.01	0.13 ± 0.01	0.18 ± 0.01	0.29 ± 0.02	0.29 ± 0.01
Shred-bedding	0.58 ± 0.03	0.59 ± 0.01	0.56 ± 0.03	0.50 ± 0.02	0.24 ± 0.02	0.16 ± 0.01	0.34 ± 0.01	0.17 ± 0.01
Subsoil-bedding	0.71 ± 0.02	0.71 ± 0.01	0.59 ± 0.03	0.61 ± 0.02	0.27 ± 0.02	0.30 ± 0.03	0.31 ± 0.01	0.33 ± 0.01
No-tillage	0.78 ± 0.01	0.83 ± 0.07	0.70 ± 0.01	0.77 ± 0.01	0.33 ± 0.01	0.28 ± 0.02	0.48 ± 0.02	0.31 ± 0.01

Mean ± S.E.
[a] Non-irrigated
[b] Irrigated

3.4. Soil physical properties

Tillage system affected significantly aggregate stability and glomalin (Table 3). In the 0–5-cm layer from the non-irrigated area, the levels of stable aggregates and glomalin decreased with increasing tillage (Figs. 1 and 2). Neither soil depth nor water regime had a significant effect on soil structural stability and glomalin (Table 3).

Mouldboard ploughing and shred-bedding produced the lowest bulk densities to a depth of 5 cm (Table 5). In all soils, bulk density increased with soil

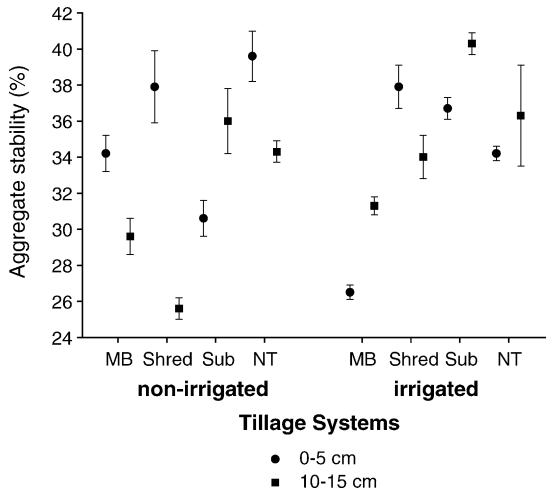

Fig. 1. Percentage of stable aggregates of the soil under different management tillage systems subjected to two water regimes ($n = 3$) (MB, mouldboard; Shred, shred-bedding; Sub, subsoil-bedding; NT, no-tillage).

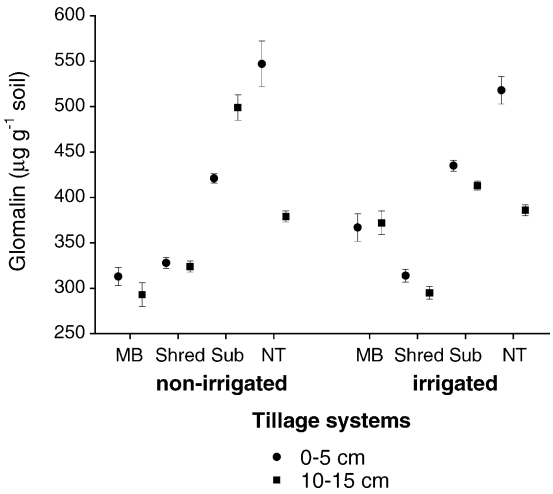

Fig. 2. Glomalin concentration of the soil under different management tillage systems subjected to two water regimes ($n = 3$) (MB, mouldboard; Shred, shred-bedding; Sub, subsoil-bedding; NT, no-tillage).

Table 5
Bulk density of the soil under different management tillage systems subjected to two water regimes ($n = 3$)

	Bulk density (g cm^{-3})			
	Non-irrigated		Irrigated	
	0–5 cm[a]	10–15 cm[a]	0–5 cm[a]	10–15 cm[a]
Mouldboard	1.11 ± 0.01	1.28 ± 0.01	1.19 ± 0.01	1.34 ± 0.01
Shred-bedding	1.11 ± 0.01	1.27 ± 0.01	1.20 ± 0.01	1.34 ± 0.01
Subsoil-bedding	1.20 ± 0.01	1.22 ± 0.01	1.29 ± 0.01	1.32 ± 0.01
No-tillage	1.19 ± 0.01	1.32 ± 0.01	1.28 ± 0.01	1.42 ± 0.01

Mean ± S.E.
[a] Soil depth.

depth and with irrigation, so that differences in bulk density among the tillage treatments disappeared in the deeper (10–15 cm) layer.

4. Discussion

The tillage treatments (mouldboard, subsoil-bedding and shred-bedding) incorporate residues into a greater volume of soil and increase the rates of organic matter decomposition and C mineralisation (Salinas-García et al., 2002). Maize residues, with a C/N ratio of about 60, are rich in cellulose and hemicelluloses. Consequently, maize residue decomposition depends on the appropriate colonisation and growth of holocellulose-degrading microorganisms. The fact that the highest accumulation of organic matter occurred in the soil under no-tillage could be due to that poor residue–soil contact reduces the decomposition of structural plant constituents through delayed colonisation by microorganisms degrading cellulose and hemicellulose (Henriksen and Breland, 2002). The lesser soil disturbance under no-tillage could have also contributed to the increase in soil organic matter content (Six et al., 2000). These results suggest that conservation tillage, especially no-tillage, is an effective method with respect to increasing sequestration of soil C, which would mitigate atmospheric CO_2 enrichment. Likewise, increased surface residues following long-term tillage practices, which do not involve incorporation of crop residues, such as no-tillage, have been shown to reduce soil erosion and water evaporation and to improve soil water retention (Tiscareño et al., 1999).

The lower nitrate content in the soils under tillage indicate that the incorporation of crop residues into soil accelerated the organic matter mineralisation, which favours nitrate loss by percolation or uptake by weeds (Salinas-García et al., 2002). Available P did not increase near the soil surface with no-tillage despite the increased accumulation of organic residues (Table 2). The low content of phosphate readily available for plant growth could be due to the fact that the soil exhibits a slightly alkaline pH, which decreases solubility of phosphorus (El-Baruni and Olsen, 1979).

The labile organic C fractions only account for a small fraction of soil organic matter, but are used by the soil microbial community as an energy source for metabolic activity. The study of these fractions is important in agricultural soils, since they determine soil microbial activity (Janzen et al., 1992) and perform a structural function (Metzger and Yaron, 1987). In the soil under no-tillage, there was a very significant increase in the levels of the soluble C fractions, pointing to a greater degree of biological activity. Other authors, too, such as Sparling et al. (1998) have observed positive correlations between the soluble C fractions and microbial biomass. Increased biological activity in the no-tillage soil was also revealed by the variations in dehydrogenase activity. The lack of changes in dehydrogenase activity due to irrigation could be due to the fact that the sampling was carried out in May after the first spring rains, when the highest total microbial activity could be expected (Lax et al., 1997). Dehydrogenase activity in the top 0–5 cm responded to the treatments in a similar manner to the water-soluble C fraction; increasing with the adoption of no-tillage, in direct proportion to the accumulation of crop residues at the soil surface. The decomposition of crop residues in soil releases essential nutrients, such

as N, P and S, required for both plant and microbial growth. Riffaldi et al. (2002) found a negative correlation between dehydrogenase activity and the soil aeration conditions due to soil management. The high dehydrogenase activity in the soil under no-tillage could be due to its higher bulk density and compaction, which decrease air-filled macroporosity resulting in deficient aeration conditions in this soil.

Measurement of soil hydrolases provides an early indication of changes in soil fertility, since they are related to the mineralisation of nutrients such as N, P and C. Soil management influences soil microorganisms and soil microbial processes through changes in the quantity and quality of plant residues in the soil profile (Kandeler et al., 1999). In conventionally cultivated soils, organic matter is more thoroughly distributed than in reduced tillage soils, where crop residues are concentrated on the soil surface (Salinas-García et al., 2002). As a consequence, urease activity was evenly distributed throughout the plough layer in the tilled systems. However, soil depth had a significant effect on phosphatase activity. In contrast, Naseby and Lynch (1997) reported no changes in phosphatase activity with soil depth due to this enzyme being predominantly secreted by plant roots and AM fungi.

The loss of soil organic matter promoted by tillage could be responsible for the fact that the lowest aggregate stability occurred in tilled soils. However, changes in aggregate stability following land use changes have been observed without changes in total soil organic matter content (Puget et al., 1999). These results may indicate that only some soil organic matter fractions are involved in soil structural stability or that stability is quicker to change than total organic carbon. For example, in the water-soluble C fraction there are extracellular polysaccharides, from bacteria or fungi, and root mucilages that act as binding agents of soil aggregates (Roldán et al., 1996). In our study, no-tillage significantly increased crop residue accumulation on the soil surface, which enriched this soil in labile organic matter. The roots themselves and the presence of fungi, possibly arbuscular mycorrhiza, could bind soil particles together mechanically with stabilisation being enhanced by polymers produced either directly by the fungus or by bacteria associated with the hyphae. Likewise, there is evidence that AM fungi-derived glomalin can also make large, direct contributions to soil aggregate stability (Wright and Anderson, 2000). Maize is an obligatory mycorrhizal species and its roots are readily colonised by many non-host-specific AM fungi (Khalil et al., 1994). Thus, increased aggregate stability in the soil under no-tillage could also have resulted from the production of glomalin by AM fungi.

Tillage loosens the soil and reduces the soil bulk density, which results in increased soil macroporosity of surface soil (Salinas-García et al., 1997). In our case, mouldboard and shred-bedding produced the lowest bulk densities. The high clay content in the soil studied leads to an important intrinsic compaction, which can be reduced effectively by tillage. On the other hand, the organic carbon of residue may affect the bulk density of a soil by improving its structural stability. However, the slow incorporation of organic matter from crop residues in the no-tillage soil, due to the rapid decomposition rate of such residues under subtropical conditions, impeded the decrease of soil bulk density during the short duration of the experiment.

In conclusion, the water regime had no effect on soil structural stability. Likewise, dehydrogenase activity indicated that water regime had no effect on total microbial activity. However, irrigation was effective with respect to increasing crop residue levels on the soil surface. The no-tillage system, which promotes surface accumulation of crop residues, was the most effective for improvement of soil physical and biochemical quality and for increasing the storage of organic matter in the soil, which may contribute greatly to the long-term sustainability of agricultural ecosystems under subtropical conditions. The beneficial effects of this conservation tillage system on soil quality were more noticeable in the surface 0–5 cm. The increases in glomalin suggest that the proliferation of AM fungi could have mediated the improvement in soil aggregate stability under no-tillage.

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