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ScienceDirect
Soil & Tillage Research 93 (2007) 273–282
Soil & Tillage Research
www.elsevier.com/locate/still

Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops

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Received 29 September 2005; received in revised form 19 April 2006; accepted 5 May 2006

Abstract

Conservation management systems such as no tillage may enhance sequestration of soil C. The soil properties that contribute to soil C storage under such systems are still largely unknown, especially in subtropical agroecosystems. We investigated the influence of tillage [mouldboard plough (MP) and no tillage (NT)] on soil organic C, microbial biomass and activity, structural stability and mycorrhizal status of a field cultivated with maize (*Zea mays* L.) or bean (*Phaseolus vulgaris* L.) on a Vertisol in Northern Tamaulipas, Mexico. Crop type, tillage system and soil depth had a significant effect on soil organic C, aggregate stability and bulk density. Soil organic C, microbial biomass C and N and dehydrogenase and phosphatase activities were greater with NT than with MP, particularly under bean cultivation. In the 0–5 cm layer, microbial biomass C and N were, on average, about 87 and 51% greater in the soils cultivated with bean and maize, respectively, under NT than under MP. Higher levels of mycorrhizal propagules, glomalin related soil protein (GRSP) and stable aggregates were produced under NT than under MP in both crops. The no-tillage system can be considered an effective management practice for carrying out sustainable agriculture under subtropical conditions, due to its improvement of soil physical and biochemical quality and soil C sequestration.

Keywords: Aggregate stability; Arbuscular mycorrhizal fungi; C sequestration; Dehydrogenase activity; Glomalin related soil protein; Microbial biomass; No tillage

1. Introduction

Management practices that increase the synthesis and retention of soil organic matter are gaining increased attention in sustainable agroecosystems (Paustian et al., 2000; Roldán et al., 2003). Soil organic C sequestration is important in reducing atmospheric CO_2 accumulation that contributes to global warming, and in improving soil quality for sustained agricultural production. No tillage (NT), involving surface crop residue placement, has been proposed as a means to increase sequestration of soil C (Paustian et al., 2000). Paustian et al. (1997) compiled data on NT and tillage systems from several long-term field studies and found in most cases an increase in C content under NT. Tillage promotes soil organic matter decomposition through crop residue incorporation into the soil and physical breakdown of residues, and by increasing the turnover of soil aggregates, which accelerates the decomposition of aggregate-associated soil organic matter (Six et al., 2000).

Tillage and crop residue management practices may alter the composition, distribution and activities of the

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0167-1987/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2006.05.001

soil microbial community and enzymes (Deng and Tabatabai, 1997). Soil microbial biomass has been recognised as an important source and sink for the majority of nutrients available to plants. Thus, it can influence the growth and development of crops. Nutrient fluxes through microbial biomass are at least one order of magnitude faster than in the remaining organic matter (Dalal, 1998), leading to the suggestion that microbial biomass could be used as an important indicator of changes in soil health and soil quality produced by agricultural management practices (Spedding et al., 2004). Numerous investigations have shown soil microbial biomass to be a soil quality indicator sensitive to a variety of agricultural management practices such as NT, organic amendments, fertilisers and cover crops in temperate regions (Ndiaye et al., 2000) but data are generally sparse for subtropical agroecosystems.

A main component of the soil microbiota in most agroecosystems is arbuscular mycorrhizal (AM) fungi. AM fungi are ubiquitous symbionts of the majority of higher plants, including most crop plants. Mycorrhizal symbioses and their propagules have been recognised as being fundamental for ecosystem stability and sustainability (Van der Heijden et al., 1998; Jeffries et al., 2003). The external mycelium of AM fungi acts as an extension of host plant roots and serves as a direct link between roots and soil nutrient reserves. Arbuscular mycorrhizae interact with pathogens and other rhizosphere inhabitants affecting plant health and nutrition. Extraradical hyphae are also very important in soil conservation as they are a major factor in soil aggregate formation (Roldán et al., 1994). Moreover, AM fungi produce a glycoprotein, glomalin that stabilises soil aggregates (Wright and Anderson, 2000). Soil organic matter can be protected inside soil aggregates (Six et al., 2000), which means that AM fungi have an indirect influence on soil C storage. AM fungi are responsive to ecosystem perturbations, such as elevated atmospheric CO_2 concentrations or agricultural management practices (Rillig, 2004). Tillage of soil breaks up the AM fungi hyphal network, leading to a significant reduction in mycorrhizal colonisation of roots and in P absorption from soil (McGonigle and Miller, 1996). From the perspective of sustainable production, it is very important to understand the dynamics of AM fungi in agricultural soils as influenced by soil management strategies, such as tillage. However, little is known about the effect of tillage on the mycorrhizal inoculum potential in subtropical agricultural ecosystems.

The objective of this study was to determine the effects of agricultural management practices using mouldboard ploughing (MP) and NT on soil organic C, microbial biomass and activity, structural stability and mycorrhizal status of a field cultivated with maize and bean under subtropical conditions.

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), 7.0 g kg^{-1} organic C 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%. The climax vegetation of this area has almost disappeared due to agriculture, which is currently represented by shrub species, such as *Prosopis juliflora* and *Acacia farnesiana*, and halophytic pasture.

2.2. Experimental design and layout

The experiment was conducted using a factorial design with three factors and three-fold replication. The first factor included two agricultural management practices: mouldboard plough (MP, disking stalks after harvest, followed by mouldboard plough to a depth of 20 cm and disking, then building the rows) and no-tillage (NT, 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 according with Rosales-Robles et al. (2005)). The second factor involved two soil depths: 0–5 cm and 5–15 cm. The third factor involved two crop types: maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.). Plots measured 22.4 m × 52 m. All cropping systems were established in 2000, as described previously (Roldán et al., 2005). Maize and bean were planted in late January and harvested in the first half of June each year from 2000 to 2004.

2.3. Soil sampling

Soil samples were collected in the second half of May 2004. 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 cm and 5–15 cm. Field-moist soil samples were divided into two subsamples. One subsample was sieved at 2 mm and stored at 2 °C for biochemical and biological analyses and another was allowed to dry at room temperature. One air-dried subsample was sieved at 2 mm for chemical analyses and another sieved between 0.2 and 4 mm for physical analyses.

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). The data of surface residues of maize and bean crops are shown in Table 1.

Surface cover was determined using a line-transect measurement, stretching a 10 m string with 100 marks (10 cm apart) across the field at a 45° angle to the rows. Walking along the line, looking straight down, and counting the number of times a piece of residue was under the mark, the number of ''hits'' indicated the percentage of cover (Steiner et al., 1994).

2.4. Chemical analyses

Soil pH was determined in a 1:2 (w:v) soil–water extract. Electrical conductivity was measured on a saturated paste. 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). Available P (with 0.5 M sodium bicarbonate, pH 8.5) was determined by colorimetry, according to Murphy and Riley (1962). Extractable K (with ammonium acetate) was determined by flame photometry. 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.

2.5. Biological and biochemical analyses

Mycorrhizal potential of soil was measured by a dilution technique (Sieverding, 1991) that allowed calculation of the most probable number (MPN) of mycorrhizal propagules able to colonize the root of a test plant. The procedure is based on the probability of whether or not an infection is established in serially diluted media, consisting of sand, vermiculite and autoclaved soil from the experimental area. Four-fold dilution series with five replications per dilution level were carried out with soil pasteurised by steaming for 1 h on 3 consecutive days. Seedlings of *Sorghum bicolor* were placed individually into each of five replicates of each soil dilution treatment. After 1 month of growth, infection was recorded in root fragments cleared and stained with trypan blue (Phillips and Hayman, 1970). The number of infective propagules (d) was calculated according to the formula from Fisher and Yates (1970):

$$d = 10^{\log(x \log a - k)}$$

where x is the mean number of cups with infection, a the factor of dilution, and k is the constant from table VIII of Fisher and Yates (1970) for four-fold dilutions.

Glomalin related soil protein (GRSP) 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 as described by Wright and Upadhyaya (1996).

Soil microbial biomass C and N were estimated using the chloroform fumigation-incubation method (Jenkinson and Powlson, 1976) with the following modifications. Approximately 35 g air-dry soil was placed in 50-ml beakers, brought to a water potential of −0.03 MPa with deionised water, preincubated for 5 days, fumigated, and incubated in 1-l airtight canning jars in the presence of 10 ml of 1 M KOH at 25 °C for 10 days (Franzluebbers et al., 2000). The amount of CO_2–C trapped in the alkali was determined by titration. Soil microbial biomass C was determined using the following equation: SMBC = (mg CO_2–C kg^{-1} soil 10 $days^{-1}$)fumigated/K_C, where $K_C = 0.41$. Non-fumigated soils taken just prior to fumigation (i.e. 5-day preincubation) and those fumigated and incubated for 10 days were dried at 60 °C for 24 h and sieved to pass a 2-mm screen. A 7-g portion was extracted in 28 ml of 2 M KCL for 30 min on a reciprocating shaker. The soil extract was analysed for NH_4^+–N using spectrophotometer techniques. Soil microbial biomass N was calculated as the difference between the NH_4^+–N concentration extracted of fumigated soil and the NH_4^+–N concentration extracted of non-fumigated soil, using the following equation: SMBN = [(mg NH_4^+–N kg^{-1} soil 10 $days^{-1}$)fumigated − (mg NH_4^+–N kg^{-1} soil)non-fumigated]/K_N, where $K_N = 0.41$. The NH_4^+–N extracted of non-fumigated soil represents the initial inorganic soil N.

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% INT (2-*p*-iodophenyl-3-*p*-nitrophenyl-5-phenyltetrazolium chloride) in distilled water for 20 h at 22 °C in darkness. The INTF (iodo-nitrotetrazolium formazan) 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.

Acid phosphatase activity was determined using *p*-nitrophenyl phosphate disodium (0.115 M) as substrate. Two milliliters of 0.5 M sodium acetate buffer at pH 5.5 (Tabatabai and Bremner, 1969) 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 of 0.5 M $CaCl_2$ and 2 ml of 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). A 4-g aliquot of sieved (0.2–4 mm) air-dried soil was placed on a 0.25 mm sieve (7.5 cm diameter) and wetted by spray. After 15 min the soil was subjected to an artificial rainfall of 150 ml with an energy of 270 J m^{-2}. The remaining soil on the sieve was put in a previously weighed capsule (T), dried at 105 °C and weighed (P1). Then, the soil was soaked in distilled water and, after 2 h, passed through the same 0.25 mm sieve with the assistance of a small stick to break the remaining aggregates. The residue remaining on the sieve, which was made up of plant debris and sand particles, was dried at 105 °C and weighed (P2). The percentage of stable aggregates relative to the total aggregates was calculated as $(P1 - P2) \times 100/(4 - P2 + T)$.

Soil bulk density was calculated from the dry weight (105 °C) of samples taken with hammer-driven core sampler (Blake, 1965).

2.7. Statistical analysis

Aggregate stability was arcsin-transformed, and the other parameters were log-transformed to compensate for heterogeneity of variance, before analysis of variance. The effects of tillage system, soil depth and type of crop on measured variables was tested by a three-way analysis of variance, and comparisons among means were made with the least significant difference (LSD) test, calculated at $P < 0.05$. Statistical procedures were carried out with the software package SPSS 10.0 for Windows.

Table 1
Surface residues of maize and bean crops as affected by tillage systems

	Residue cover (%)	Residue amount (kg ha^{-1})
Maize		
Mouldboard	6 c	1200 b
No-tillage	95 a	5826 a
Bean		
Mouldboard	3 d	183 d
No-tillage	9 b	537 c

Values in columns followed by the same letter do not differ significantly ($P < 0.05$) as determined by the LSD test.

3. Results

3.1. Soil chemical properties

Tillage system had a significant effect on electrical conductivity and pH of soils cultivated with maize or bean (Table 2). Soil pH was greater under MP than under NT, but soil electrical conductivity was lower under MP than under NT (Table 3). A significant interaction was observed between soil tillage and soil depth. In the 5–15 cm layer, there were no differences in soil electrical conductivity between tillage systems for either crop.

Soil nitrate was influenced by tillage system (Table 2). Soil under NT had higher nitrate than under MP (Table 3). Available P and extractable K were not affected by tillage system, soil depth or type of crop (Table 2).

Crop type, tillage system and soil depth had significant effects ($P < 0.001$) on soil organic C (Table 2). In the 0–5 cm layer, organic C was greater under NT than under MP, particularly in the soil cultivated with bean (Table 3). Below the 0–5 cm layer, organic C was lower under both tillage systems, but smaller values were with bean. Mouldboard ploughing resulted in the lowest organic C content throughout the 0–15 cm soil layer.

3.2. Soil biological and biochemical properties

Microbial biomass C and N and dehydrogenase and phosphatase activities were significantly affected by soil depth and tillage system, but not by crop type (Table 2). Microbial biomass C and N were greater under NT than under MP (Table 4). Greater microbial biomass C and N under NT than under MP were more pronounced in the soil cultivated with bean. In the

Table 2
Three factor ANOVA (crop type, tillage type and soil depth) for all parameters studied in the soil cultivated with maize and bean

Source of variation	Crop type (C)	Tillage (T)	Soil depth (D)	Interactions			
				C–T	C–D	T–D	C–T–D
pH	<0.001	<0.001	0.68	0.05	0.11	<0.001	<0.001
Electrical conductivity	0.30	0.01	0.64	0.27	0.12	0.01	0.10
Organic carbon	<0.001	<0.001	<0.001	<0.001	<0.001	0.99	0.92
Nitrate	0.27	<0.001	0.69	0.21	0.25	0.12	0.45
P available	0.67	0.10	0.96	0.14	0.24	0.59	0.96
K extractable	0.89	0.12	0.61	0.86	0.74	0.05	0.70
MBC	0.21	<0.001	<0.001	<0.001	0.03	<0.001	0.03
MBN	0.11	<0.001	<0.001	<0.001	0.45	<0.001	0.19
Dehydrogenase	0.91	<0.001	<0.001	<0.001	0.75	<0.001	0.66
Phosphatase	0.76	<0.001	<0.001	<0.001	0.18	<0.001	0.06
GRSP	0.15	<0.001	<0.001	<0.001	0.70	<0.001	0.21
MPN	0.42	<0.001	0.12	0.72	0.13	<0.001	0.001
Aggregate stability	<0.001	<0.001	0.001	0.69	0.56	0.99	0.67
Bulk density	<0.001	<0.001	<0.001	0.35	0.99	0.03	0.25

P significance values. MBC: microbial biomass C; MBN: microbial biomass N; GRSP: glomalin related soil protein; MPN: most probable number.

0–5 cm layer, microbial biomass C and N were, on average, 87 and 51% greater in soils cultivated with bean and maize, respectively, under NT than under MP. Microbial biomass C and N decreased with soil depth, particularly under NT.

Higher dehydrogenase and phosphatase activities were recorded under NT than under MP (Table 4). Dehydrogenase and phosphatase activities were stratified with depth under NT, but uniform with depth under MP. In the 5–15 cm soil layer, there were no differences in dehydrogenase and phosphatase activities between tillage systems or between crop types.

Glomalin related soil protein and AM propagules were significantly higher under NT than under MP at a depth of 0–5 cm (Table 4). At 5–15 cm depth, differences between tillage systems and crop types were minimal. The highest value of AM propagules was reached in the soil cultivated with bean under NT in the surface (0–5 cm) layer.

3.3. Soil physical properties

Crop type, tillage system and soil depth had significant effects on soil aggregate stability and bulk density (Table 2). Soil aggregate stability was higher under NT than under MP and under maize than under bean (Table 5). Bulk density was greater under NT than under MP at both depths and in both crop types (Table 5). The lowest value of bulk density was found in the soil cultivated with bean under MP.

Table 3
Physical–chemical properties, organic carbon and nutrients concentration of the soil cultivated with maize and bean under different tillage systems ($N = 3$)

	Soil depth (cm)	pH (H_2O)	EC (mS cm^{-1})	Organic carbon (g kg^{-1})	Organic carbon (kg m^{-2})	N–NO_3^- (mg kg^{-1})	P available (mg kg^{-1})	K extractable (mg kg^{-1})
Maize								
Mouldboard	0–5	8.1 b	0.8 c	11.0 d	1.93 d	5 ab	12 abc	427 a
	5–15	8.1 b	0.9 bc	10.5 e	1.92 d	4 b	12 abc	407 a
No-tillage	0–5	8.0 c	1.1 a	11.6 c	2.18 b	6 a	11 c	433 a
	5–15	8.0 c	0.9 bc	11.0 de	2.08 c	7 a	12 abc	460 a
Bean								
Mouldboard	0–5	8.2 a	0.9 bc	12.2 b	2.10 c	4 b	13 ab	427 a
	5–15	8.1 b	1.0 ab	9.9 f	1.75 e	4 b	12 abc	400 a
No-tillage	0–5	8.0 c	1.0 ab	14.5 a	2.61 a	6 a	11 c	413 a
	5–15	8.2 a	1.0 ab	11.6 bc	2.12 bc	7 a	11 c	470 a

Values in columns followed by the same letter do not differ significantly ($P < 0.05$) as determined by the LSD test. EC: electrical conductivity.

Table 4
Biological and biochemical properties of the soil cultivated with maize and bean under different tillage systems ($N = 3$)

	Soil depth (cm)	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Dehydrogenase (μg INTF g^{-1})	Phosphatase (μmol PNPg^{-1} h^{-1})	GRSP (μg g^{-1} soil)	MPN of AM propagules (100 g^{-1} dry soil)
Maize							
Mouldboard	0–5	372 c	41 c	43 b	0.38 c	812 cd	41 (19–88) cd[a]
	5–15	335 de	36 d	38 bc	0.31 cde	888 c	44 (21–94) cd
No-tillage	0–5	564 b	61 b	65 a	0.51 b	1278 b	78 (37–167) b
	5–15	310 f	33 e	36 c	0.28 de	809 cd	75 (35–160) b
Bean							
Mouldboard	0–5	329 e	36 d	38 bc	0.25 e	656 e	35 (16–75) d
	5–15	307 f	33 e	35 c	0.28 de	760 d	55 (26–118) c
No-tillage	0–5	620 a	67 a	71 a	0.67 a	1472 a	112 (52–239) a
	5–15	341 d	36 d	39 bc	0.35 cd	850 cd	42 (20–90) cd

MBC: microbial biomass C; MBN: microbial biomass N; GRSP: glomalin related soil protein; MPN: most probable number. Values in columns followed by the same letter do not differ significantly ($P < 0.05$) as determined by the LSD test.
[a] In parenthesis, lower and upper limit of confidence at 95% probability.

Table 5
Physical properties of the soil cultivated with maize and bean under different tillage systems ($N = 3$)

	Soil depth (cm)	Aggregate stability (%)	Bulk density (g cm^{-3})
Maize			
Mouldboard	0–5	30.2 de	1.17 c
	5–15	34.0 bcd	1.22 b
No-tillage	0–5	36.4 ab	1.25 a
	5–15	39.4 a	1.26 a
Bean			
Mouldboard	0–5	22.6 f	1.15 d
	5–15	24.8 f	1.18 c
No-tillage	0–5	29.0 e	1.20 b
	5–15	31.8 cde	1.22 b

Values in columns followed by the same letter do not differ significantly ($P < 0.05$) as determined by the LSD test.

4. Discussion

4.1. Soil chemical fertility

An accumulation of organic matter in soil confers important improvements in soil quality, soil fertility and sequestration of C (Six et al., 2000). In this study, NT led to greater organic C than under MP to a depth of 15 cm. Greater soil organic C under NT may have been a result of reduced contact of crop residues with soil. Surface residues tend to decompose more slowly than soil-incorporated residues, because of greater fluctuations in surface temperature and moisture and reduced availability of nutrients to microbes colonising the surface residue (Schomberg et al., 1994). Compared with NT, MP incorporates residues into a larger volume of soil and therefore increases the rates of organic matter decomposition and C mineralisation (Salinas-García et al., 2002), by increasing the contact between soil microorganisms and crop residues (Henriksen and Breland, 2002) and by disruption of soil organic matter protected within aggregates (Six et al., 2000). Conservation tillage, especially NT, is an effective method for increasing sequestration of soil C in subtropical agroecosystems, which would mitigate atmospheric CO_2 enrichment.

Crop residue type plays an important role in C sequestration and organic matter cycling due to differences in C/N ratio or quality of residue (Potter et al., 1998). In our study, maize and bean residues differed in their capacity to affect soil organic C. Bean residues were the most effective in increasing soil organic C. Maize residues are, in contrast with bean residues, poor in easily-utilisable sugars and proteins, but rich in cellulose and hemicelluloses. As a consequence, the organic matter from maize residues may have been more slowly incorporated within soil organic matter than bean residues, due to its structural characteristics. Decomposition of maize residue is reduced when it is placed on the soil surface, as compared with burial in soil, because it depends on an appropriate colonisation and growth of microorganisms producing extracellular cellulases and hemicellulases, an activity in which fungi play a prominent role (Henriksen and Breland, 2002). Reduced decomposition of maize residue can be found under NT, possibly due to a poor contact with microorganisms that degrade holocellulose. Thus, reduced decomposition of maize

residue under NT could explain why tillage system had less effect on soil organic C than with bean.

Lower soil nitrate under MP than under NT indicates that the incorporation of crop residues accelerated organic matter mineralisation, which led to nitrate loss by percolation or uptake by weeds during the preparation and sowing period of the following crop (Salinas-García et al., 2002). Our results differed from those of Carefoot et al. (1990), who found that greater nitrate accumulated in loam and clay loam texture soils cropped under conventional tillage than under NT in a semiarid region of Alberta.

In both crops, available P and extractable K were unaffected by tillage system, despite the increased accumulation of organic residues. The low solubility of P was probably due to the slightly alkaline pH (El-Baruni and Olsen, 1979).

4.2. Soil mycorrhizal status

The number of mycorrhizal propagules able to colonize plant roots is the most realistic response variable for expression of mycorrhizal inoculum potential of a soil (Brundrett et al., 1996). Maize and bean are considered obligatory mycorrhizal species: their roots are readily-colonized by many non-host-specific AM fungi (Khalil et al., 1994) and are able to provide mycorrhizal propagules to soil. The NT system produced the highest levels of mycorrhizal propagules under both crops, following the same trend as soil organic C. Bean under NT had the highest capacity for development of AM propagules by natural colonisation. Extraradical hyphae are thought to be the main source of inoculum in soil (Sylvia, 1992), which is important in an annual crop when they remain active from a previous crop. To ensure that the mycorrhizal infectivity is maintained, hyphae or other propagules should be robust enough to survive disturbance, since the ability of these structures to survive and to initiate new mycorrhizal infections may be extremely important for long-term survival of fungi. Enhancement of mycorrhizal symbiosis with NT could lead to a significant source of inoculum for subsequent mycorrhizal crops. Thus, NT may be a practical solution to the costs and problems associated with introduction of inoculum, as long as the native population contains at least some efficient AM fungal species.

4.3. Soil biological fertility

Microbial biomass C and N can be considered sensitive indicators of soil quality and are closely related to soil fertility (Wardle et al., 1999). Soil microbial biomass C and N followed a trend similar to that observed for soil organic C with respect to tillage system. Soil subjected to NT accumulated crop residues and organic C, which are substrates for soil microorganisms near the soil surface. As a consequence, the soil microbial biomass and various soil microbial processes increased in surface soils under NT. The ratio of biomass-C/TOC is regarded by some authors as a good index of the changes in SOM quality (Insam and Merschak, 1997). The proportion of the total organic C as microbial biomass C was higher under NT (4.6%) than under MP (3.1%), at 0–5 cm depth. The microbial biomass C-to-N ratio under both tillage systems was >5, indicating fungal rather than bacterial dominance, since the C-to-N ratio ranges from 3 to 5 for bacteria and from 4 to 15 for fungi (Paul and Clark, 1989).

Dehydrogenase is an oxidoreductase, the activity of which depends on the metabolic state of the soil biota. This enzyme has been considered a sensitive indicator of soil quality (Nannipieri, 1994) and it has been proposed as a valid biomarker to indicate changes in total microbial activity due to changes in soil management, under different agronomic practices and climates (Kandeler et al., 1999). Dehydrogenase activity responded to tillage treatments in a similar manner as soil organic C, increasing with the adoption of NT. Since active dehydrogenase can use O_2 and different compounds as terminal electron acceptors, this enzyme should reflect the oxidative capacity of the total soil microflora. Riffaldi et al. (2002) found a negative correlation between dehydrogenase activity and soil aeration condition. So, deficient soil aeration conditions under NT might also explain the high dehydrogenase activity.

Soil phosphatase activity, which plays an essential role in the mineralisation of organic P, was also greater under NT than under MP. It has been suggested that either the rate of synthesis and release of phosphatase by soil microorganisms or the stability of phosphatase is related to soil pH (Tabatabai, 1994). We found that lower pH under NT than under MP favoured acid phosphatase activity. Crops grown under NT may be expected to resist low P-availability better than crops under MP due to greater activity of phosphatase. Acid phosphatase activity in soil may be due to a direct fungal secretion or an induced secretion by plant roots, as pointed out by Joner et al. (2000). Higher phosphatase activity occurred with bean under NT, which also had the highest levels of mycorrhizal propagules in soil.

4.4. Soil physical fertility

Soil structure affects soil quality and fertility by controlling the establishment and viability of a stable plant cover. Soil aggregation was greater under NT concomitant with greater organic C than under MP. Loss of soil organic C with MP was likely responsible for low aggregate stability. NT significantly increased crop residue accumulation on the soil surface, which enriched soil in labile organic matter, such as polysaccharides that act as binding agents of soil aggregates (Lu et al., 1998). Likewise, NT may promote fungal growth and the proliferation of fungal hyphae that contribute to macroaggregate formation (Six et al., 1998). Mycorrhizae primarily influence the stability of macroaggregates (>250 μm) (Bearden and Petersen, 2000). According to Roldán et al. (1994), the binding effect of polysaccharides is short-lived and the maintenance and increase of aggregate stability is attributable to high microbial populations and, particularly, to the proliferation of fungal mycelium. Macroaggregation is enhanced by enmeshment of soil particles by hyphae and roots and the deposition of organic material (Miller and Jastrow, 2000; Bearden and Petersen, 2000). An important component of the organic material contained in or released by AM fungal hyphae is glomalin, a glycoprotein produced by AM fungi (Rillig, 2004). In our study, GRSP was greater under NT than under MP. GRSP has been suggested to contribute to the hydrophobicity of soil particles and also, because of its glue-like hydrophobic nature, to participate in the initiation of soil aggregates. Likewise, there is evidence that AM fungi-derived GRSP can also make large, direct contributions to soil C storage. Carbon and N in GRSP made a substantially larger contribution to the total soil C and N pools than microbial biomass (Rillig et al., 2001). Greater soil aggregate stability under NT than under MP could have resulted from the production of GRSP by AM fungi.

Maize plants, with a greater root mass than bean, had a more marked effect on improving soil aggregate stability than bean plants, which could have been due to larger production of root exudates (Haynes and Francis, 1993). Roots may form a three-dimensional network that aggregates small soil particles. In the 0–5 cm layer, root density was 450 g m^{-3} under maize and 42 g m^{-3} under bean. Greater root density of maize (1050 g m^{-3}) than of bean (30 g m^{-3}) at 5–15 cm depth would also support the observed increases in aggregate stability with soil depth.

The effect of tillage on bulk density depends on the mechanical manipulation and loosening of soil (Salinas-García et al., 1997). In our study, MP produced the lowest bulk density. High soil clay content leads to an important intrinsic compaction, which can be reduced effectively by tillage. In contrast, the highest soil organic C content under NT was not effective in mitigating compaction during the short duration of this experiment. A relevant effect of NT on soil bulk density would require a major accumulation of organic C, which in turn, would take a long time due to the rapid decomposition rate of organic residues under subtropical conditions.

5. Conclusions

No tillage promoted surface accumulation of crop residues and was more effective in improving soil physical and biochemical quality than mouldboard system. The beneficial effects of conservation management on soil quality were more noticeable in the surface 0–5 cm than below. In addition, no tillage was found to promote mycorrhizal propagule production and AM fungi-derived glomalin, which may contribute to the long-term sustainability of agricultural ecosystems under subtropical conditions.

Acknowledgement

The research was partially supported by the Produce Tamaulipas Foundation of Mexico.

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