Earthworm activity and soil structural changes under conservation agriculture in central Mexico

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ABSTRACT

Crop residue mulching combined with zero tillage and crop rotation, known as conservation agriculture (CA), is being promoted as an alternative system to revert soil degradation in maize-based farming in the central highlands of Mexico. The goal of this paper was to determine the effects of CA vs. conventional tillage systems on soil quality, with a special focus on the role of earthworms in affecting the soil structure morphology, and on crop yield. For the conventional tillage system, the effect of crop residue retention (CONV + RES) was also compared to the conventional farmers’ practice (residues removed; CONV). CA resulted in four times higher earthworm abundance when compared to CONV. Residue retention per se (CONV + RES) did not favor earthworm abundance. In all cases the earthworm community was dominated by exotic species. CA increased total N and soil organic C concentrations relative to CONV, but only at 0–5 cm soil depth. Nevertheless, the more pronounced vertical stratification of soil organic carbon content under CA favored soil surface aggregation and aggregate stability as expressed by the aggregate mean weight diameter after dry sieving (MWDs) = 2.6 mm for CA and 1.6 mm for CONV) and wet sieving (MWDw = 0.9 mm and 0.6 mm, respectively). Also, CA improved topsoil water stable macroaggregation (WSA > 415 mg g⁻¹) when compared to CONV (251 mg g⁻¹). Residue retention within conventional tillage (CONV + RES) led to small increases in topsoil aggregate stability (i.e. MWDs, and WSA). Soil structural improvements were accompanied by a higher direct surface water infiltration. Micromorphological analysis of thin sections indicated a loose and highly biogenic soil microstructure in CA, whereas CONV was characterized by a physicogenic microstructure, despite similar soil bulk densities (SBD). SBD is thus a poor indicator of soil physical quality when comparing different tillage systems. Redundancy analysis illustrated that CA resulted in improvement in most parameters related to soil quality, especially at the soil surface, but significant yield increases were recorded only in 2004. CONV + RES lead to marginal improvements in soil quality with no yield increases.

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1. Introduction

Zero tillage coupled with crop residue mulching and crop rotation, which encompasses the basic principles for conservation agriculture (CA), has come forward as a sustainable management system that could revert physical soil degradation in resource-poor farms across very different agro-ecological conditions (FAO, 2008). In fact, such management has been a traditional practice in many parts of Latin America, including Mexico, where the coa or espeque (a wooden stick of about 50 cm) is used to plant, and residues are generally left on the surface (Hernández-Xolocotzi, 1985). Although CA is claimed to have many potential benefits, especially in semi-arid regions (Shaxson and Barber, 2003), there is a need to systematically evaluate and document which of these benefits can be realistically obtained by implementation of CA-based crop management practices under specific agro-ecological conditions (Giller et al., 2009).

In the semi-arid highlands of Central Mexico, conventional smallholder farming (CONV) is characterized by rainfed monoculture of maize (Zea mays L.), and to a lesser extent of wheat (Triticum aestivum L.), using mechanical tillage in combination with very limited returns of organic matter (i.e. crop residues are grazed by communal livestock, removed for fodder and/or burned). Under
these conditions, bare soils exposed to intense and erratic summer rain showers and winds, as well as high evapotranspiration levels result in slaking and crust formation, whereas intensive tillage causes the gradual loss of stable soil aggregates leading to soil erosion and compaction on the long term (Fischer et al., 2002; Govaerts et al., 2006). As an alternative, CA has been promoted to improve crop water availability through the presence (year-round) of a protective soil cover as well as by soil structural improvements (Govaerts et al., 2006; Six et al., 2004) achieved by increases in topsoil organic carbon (SOC) and reduced soil disturbance (Franzluebbers, 2002; Six et al., 2004; Tisdall and Oades, 1982). It is not clear to what extent residue retention under conventional tillage (CONV + RES), as practiced by some farmers in these semi-arid conditions, could lead to significant improvements in soil structure irrespective of soil tillage, as found in other regions (Zeleke et al., 2004).

Along with other soil macroinvertebrates (i.e. termites and ants), earthworms have been defined as ‘ecosystem engineers’ due to their role in soil structure formation and maintenance through the creation of continuous macro pores (Blanchart et al., 2004; Edwards and Shipitalo, 1998), stable macroaggregates (Blanchart et al., 2004; Six et al., 2004) and organo-mineral complexes (Marniissen and Dexter, 1990; Shipitalo and Protz, 1989; Six et al., 2004). Earthworm activity can be stimulated by reduced soil disturbance and/or crop residue retention and as such be an important determinant of soil structural characteristics under different crop management systems (Pulleman et al., 2003). Soil structural characteristics, and the specific role of different groups of soil fauna in soil structure formation, can be assessed through soil micromorphology which is based on identification of biogenic features in thin sections prepared from undisturbed blocks of soil (Kooistra and Brussaard, 1995; Kooistra and Pulleman, 2010). In the absence of other relevant soil macrofauna, we hypothesized that earthworms potentially play a key role in these semi-arid agro-ecosystems by enhancing physical soil functions (e.g. rainfall water infiltration) for crop production and should be considered as an important indicator in integrated soil quality assessments.

Given the climatic conditions (i.e. erratic and intense rainfalls), main production constraints (i.e. low rainfall use efficiency; susceptibility to soil erosion) and goals (i.e. sustained agricultural productivity for maize and wheat) (Govaerts et al., 2005; Masera et al., 1999), soil quality was defined in this specific case as the fitness of the soil to maximize rainfall productivity while minimizing negative impacts such as those related to soil erosion and soil C loss. Integrated evaluation of soil quality changes across management systems has been done using ordination techniques like factor analysis (Govaerts et al., 2006; Sena et al., 2002), although those studies have not included important biological parameters indicating the presence or activity of soil ecosystem engineers. CA management, as compared to the conventional farmers’ practice, was hypothesized to lead to increased soil organic C contents, soil structural stability and soil physical properties in the top soil layer. These improvements in soil quality parameters are often accompanied by larger numbers and biomass of earthworms, which have a distinct effect on soil structure morphology, and lead to higher and more stable crop yields. Retention of maize residues under the conventional farmers’ practices was expected to lead to intermediate improvement in soil quality parameters, earthworm abundance and crop yields.

In order to test these hypotheses we aimed: (i) to determine the effects of conservation agriculture (CA) vs. conventional tillage systems (CONV), as well as the effects of contrasting residue management (CONV vs. CONV + RES) within conventional farmers’ practices, on different soil quality parameters, including earthworm communities, (ii) to visually assess the impact of earthworms on soil structure through soil micromorphological analysis; and, (iii) to provide an integrated evaluation of soil quality changes due to CA vs. CONV management, and relate this to crop yields.

2. Materials and methods

2.1. Site characteristics and sampling

The study was conducted at the CIMMYT field station “El Batán”, situated in the semi-arid subtropical highlands of Central Mexico (19°31’N 98°50’W; 2,240 m asl). The average annual rainfall is 626 mm, with 87% of total rainfall falling between May and October, and the potential evapotranspiration is 1900 mm yr⁻¹ (Govaerts et al., 2005). One crop per year can be produced during summer, followed by a long dry winter, often with frost during the night. The research station is located in the area of the former lake of Texcoco. The soil is a fine, mixed, thermic, Cumulic Haplustoll according to the USDA soil taxonomy system (Soil Survey Staff, 1998) with a clayey loam texture (Govaerts et al., 2005) and a slope of <0.3% (Govaerts et al., 2007).

Before the establishment of the field experiment, the area had been under continuous maize cultivation with residue retention and zero tillage for 10 years (1988–1998). A field experiment comparing conventional and zero tillage treatments in three blocks was set up in 1998 for continuous maize cultivation. In 2001 the existing tillage treatments were split into two parts, resulting in a split plot design with 3 x 10 m plots (n = 3). The zero tillage treatments with residues left over the soil surface were converted to a maize–wheat rotation to represent a conservation agriculture (CA) system, with both phases of the rotation present each year. The conventional tillage treatments under continuous maize cultivation were split into two different residue treatments, with maize residues retained (CONV + RES), and with maize stubble removed from the soil before ploughing (CONV). This allowed for a comparison between the most common farmers’ practice in the region, maize monoculture with conventional tillage after maize residues have been removed (CONV), and the same practices but with residue retained (CONV + RES). The three CA plots that were in the wheat phase of the rotation at the time this study was carried out were only considered for yield analysis. Conventional tillage was done by a tractor-drawn disc plough to a depth of approximately 15 cm. Fertilization consisted of 120 kg urea-N ha⁻¹ applied at the first node stage for wheat and at the 4–6 leaf stage for maize for all treatments. Maize (hybrid) and wheat varieties were selected each year based on the best available variety and were identical for all treatments during the same year. Weeding and pest management operations were timely performed.

Soil and earthworm sampling took place in September 2005 and January 2006 (for time-to-pond measurements) in three replicate plots per treatment. Only CA plots that were under maize at the time of sampling were included. Undisturbed samples for soil micromorphological study were taken from two replicate plots only, as these analyses were intended to be qualitative. All samplings excluded a 1 m wide border area for each plot. Yield data were obtained from both maize and wheat plots according to Govaerts et al. (2005).

2.2. Earthworm abundance, biomass and species composition

Earthworm sampling was based on the TSBF methodology (Anderson and Ingram, 1993): two monoliths (30 × 30 wide and 30 cm deep) were extracted per replicate plot. The monoliths were then subdivided in two depth layers (0–15 and 15–30 cm). The soil was hand sorted to collect the earthworms. Fresh earthworms were weighed using a micro-balance, killed in 70% ethanol and preserved in diluted formaldehyde (10%). After 48 h, earthworms...
were transferred to flasks containing 50% ethanol to ensure their conservation. Taxonomic determination to species level was done for a representative subsample of the earthworms collected in each plot, including both adults and juveniles.

2.3. Chemical soil characteristics and C stocks

Composite samples consisting of five random soil cores (diam. 20 mm) per plot were taken from 0 to 5, 5 to 15 and 15 to 30 cm depth. Samples were air-dried and crushed to pass through a 2 mm sieve. Organic particles > 2 mm were discarded. Analysis for general soil characteristics including soil texture, pH (Salinity Laboratory Staff, 1945), total N (Bremner, 1960), soil organic carbon (SOC) (Wallden, 1947), extractable P (Bray and Kurtz, 1945), micronutrients (Wright and Lindsay, 1973) and cation exchange capacity (CEC) (Schollenberger and Simon, 1945) were done at the CIMMYT Soil and Plant Analysis Laboratory according standard procedures.

2.4. Soil aggregate distribution and stability

During hand sorting of monoliths, the soil material was gently broken up along natural planes of weakness into aggregates. A representative subsample was then passed through an 8 mm sieve, air-dried at room temperature and thoroughly mixed. Coarse plant residues, roots and few stones > 8 mm were removed. The two internal replicate monoliths were bulked to form one composite sample per depth layer that was used for dry and wet sieving. To determine dry aggregate size distribution, a sub-sample of 500 g was separated into six size fractions by mechanical sieving through a stack of sieves with openings of 6.3, 4, 2, 1 mm and 500 and 250 μm. They were shaken for 5 min at a frequency of 210 cycles min⁻¹. Soil remaining on each sieve was collected and weighed (Govaerts et al., 2006; Kemper and Rosenau, 1986). To determine the water-stable aggregate size distribution, 50 g of air-dried soil was fractionated by wet-sieving. Samples were submerged in demineralized water prior to wet sieving for 5 min to allow slaking (Le Bissonnais, 1996) and then manually sieved over a 2 mm mesh placed in demineralized water according to the method of Elliott (1986). The sieves were gently moved up and down 50 times for 2 min. The suspension with the soil material that passed the 2 mm sieve was transferred to a basin holding the 250 μm sieve and the procedure was repeated. Similarly, the procedure was repeated for the 53 μm sieves. All size fractions were oven dried at 75 °C and weighed. The <53 μm fraction was calculated by difference.

The aggregate size distribution after dry and wet sieving was expressed as the mean weight diameter (MWD₆₅ and MWD₆₅, respectively) calculated as the sum of the proportion of each size fraction’s weight multiplied by the mean diameter of that fraction (van Bavel, 1949):

\[ MWD = \sum_{i=1}^{n} d_i w_i \]

where \( d \) is the mean diameter of each size fraction \( i \), \( w \) is the proportion of total sample weight occurring in the size fraction \( i \) and \( n \) is the number of size fractions. Water stable aggregation (WSA) was presented as the percentage of total macroaggregates (>250 μm) after wet sieving.

2.5. Soil bulk density

For soil bulk density (SBD), two samples per replicate plot were collected at 5, 15 and 25 cm soil depth using a metal ring of known volume (i.e. 100 cm³). Soil was oven-dried for 48 h at 105 °C and weighed before calculating the bulk density (Blake and Hartge, 1986).

2.6. Time-to-pond

Time-to-pond (TTP) was determined as a measure of direct surface water infiltration vs. susceptibility to runoff using a metal ring placed on the ground to demarcate a circular area (296 cm²) without impeding water flow out of this area. The area was watered using a watering pot with outflow of 0.151 s⁻¹ from a height of 75 cm, and the time and water volume added until the water began to run out of the circular area were recorded (Govaerts et al., 2006). Time-to-pond was measured twice, once during the crop cycle (TTP₆₅) at the time of soil and earthworm sampling (early September), and once after tillage (TTP₆₅) (mid-January), and at six different locations within each replicate plot.

2.7. Soil structure morphology

Undisturbed soil samples from two replicate plots per treatment were collected from the wall of the 30 cm deep pits that remained after monolith extraction. Per depth profile, three 8 × 6 cm metal tins were cut vertically into the soil at 0–8, 9–17 and 18–26 cm soil depths. The sample location was 15 cm from the stem of the maize plant (row spacing = 75 cm). The samples were kept refrigerated and were fumigated before transport to the Netherlands for thin section preparation to avoid post-sampling disturbance of the samples by soil biota. At destination the samples were air-dried at stable room temperature and impregnated with a colorless unsaturated polyester resin. After evaporation of the largest part of the acetone from this solution, samples were hardened by gamma radiation. The thin sections, with a thickness of 25 μm, were made from the core of the hardened block following the procedure developed by Jongerius and Heintzberger (1975). Qualitative description of soil structural characteristics was done through microscopic observations and following the terminology of Bullock et al. (1985) with two classes of groundmass: physicogenic (angular blocky ped further subdivided into pure, slaked material and organic particles) and biogenic (granular to subangular blocky macroaggregation, further subdivided into macrofauna and mesofauna-worked groundmass); and, with three classes of voids: physicogenic (pure or modified), biogenic (macro- and mesovoids) and infillings (biogenic void infilled by soil material or shapeless excreta) (Kooistra and Brussaard, 1995; Kooistra and Pulleman, 2010).

2.8. Data analysis

Data were analyzed using the SPSS 17.0 package and divided into two different datasets to test separately for the effect of management system (CA vs. CONV) and for the effect of residue management under conventional tillage (CONV vs. CONV + RES). Two separate ANOVAs were performed given the trial was set up in 1998 to compare zero tillage and conventional tillage systems. Residue management was only established as a split plot treatment within CONV in 2001. Data distributions were tested through both the Kolmogorov–Smirnov and Shapiro–Wilk tests. Transformation attempts of non-normal data were unsuccessful. Non-parametric data were: total nitrogen (mg kg⁻¹), SOC (mg kg⁻¹), earthworm total abundance (individuals m⁻²) and time-to-pond (s). Mean comparisons were performed with one-way ANOVA for parametric data, and Mann–Whitney and Kruskal–Wallis tests for non-parametric data. Significance of difference between treatment means was examined by a LSD range test procedure at *P < 0.05.
Relations between soil parameters and management were analyzed through a direct multivariate ordination analysis in which dependent variables (soil parameters: calcium (Ca$^{2+}$), cation exchange capacity (CEC), earthworm abundance (WRM), extractable phosphorus (P), magnesium (Mg$^{2+}$), mean weight diameter of dry-sieved samples (MWDd), mean weight diameter of wet-sieved samples (MWDMw), pH: potassium (K), sodium (Na$^{+}$), soil bulk density (SBD), soil organic carbon (SOC), time-to-pond during the crop cycle (TTPc), time-to-pond after harvest and tillage of the conventionally tilled treatments (TTP), total nitrogen (N) and water stable aggregation (WSA)) were arranged on axes linearly constrained by the independent variables (management parameters: CONV, CONV + RES, and CA) using CANOCO 4.5 software package (ter Braak and Smilauer, 2002). Detrended correspondence analysis (DCA) using detrending-by-segments indicated that the gradient length (expressed on standard deviations units of dependent variables turnover) was <4 which allows the use of both principal component analysis (PCA) and redundancy analysis (RDA) due to predominantly linear responses along the ordination gradient. While unconstrained (indirect) ordination methods such as PCA (e.g. Govaerts et al., 2006; Sena et al., 2002) provide an indication of the variation in the dependent variables, a constrained (direct) ordination method such as RDA was preferred given it allows to specifically analyze the variation in the dependent variables in relation to the environmental variables, in this case management treatments (Jongmans et al., 1995; ter Braak and Smilauer, 2002). Soil chemical, biological and physical parameters were centered and standardized (to zero mean and unit variance) and significance of the first and all ordination axes was calculated by a Monte Carlo significance test (200 permutations). Only key parameters (i.e. loadings > 0.20) were included in the RDA interpretation, which was illustrated through a biplot. Finally, Pearson’s (parametric) and Spearman’s correlations (non-parametric) were used to evaluate relationships between selected parameters.

3. Results

3.1. Effects of management on biological, chemical and physical soil parameters

3.1.1. Earthworm abundance and species composition

Earthworm abundance was significantly higher under CA (194 ind. m$^{-2}$) compared to CONV (Fig. 1). No significant differences in earthworm abundance were found between tilled plots with residue (CONV + RES; 52 ind. m$^{-2}$) and without residue retention (CONV; 46 ind. m$^{-2}$). The same trend was found for biomass with the following results: 117.6 (CA), 34.0 (CONV + RES) and 29.1 (CONV) g m$^{-2}$ (data not shown). Earthworm communities comprised the species Aporrectodea longa (Ude, 1896), Aporrectodea tuberculata (Eisen, 1874) and Bimastos parvus (Eisen, 1874), with only few Phoenicodrilus taste (Eisen, 1895) specimens under CONV. No differences in earthworm species composition were observed between the management treatments. On average, A. longa was the predominant species (47%), followed by A. tuberculata (32%) and B. parvus (19%) (data not shown).

3.1.2. Chemical soil parameters

CA plots had significantly (*P < 0.05) higher total N and SOC concentrations when compared to the CONV treatment, but only in the top 5 cm (1.53 g N kg$^{-1}$ versus 1.04 g N kg$^{-1}$ and 15.43 g C kg$^{-1}$ versus 9.40 g C kg$^{-1}$ for CA and CONV, respectively) (Table 1). Other chemical soil parameters such as pH, P-Bray, K$^+$, Mg$^{2+}$, CEC, Ca$^{2+}$, Na$^{+}$ as well as micronutrients (i.e. Fe, Mn, Zn and Cu; data not shown) did not differ between tillage systems. No differences in any soil chemical characteristic were found between CONV and CONV + RES.

3.1.3. Physical soil parameters

Both alternatives to the CONV treatment resulted in higher mean weight diameter for dry-sieved soil aggregates (MWDd) at 0–15 cm depth (Table 2). But significant differences in aggregate stability, as expressed in MWD after wet-sieving (MWDws), were only found between CA and CONV. At 0–15 cm depth CA resulted in a significantly (**P < 0.01) greater MWDws when compared to CONV (0.9 mm vs. 6.6 mm, respectively). The top 15 cm of the soil under CA contained 415 mg g$^{-1}$ of water stable macroaggregates (>250 μm; WSA), a significantly higher amount than in the CONV treatment (251 mg g$^{-1}$). Residue retention in tilled plots also increased WSA (333 mg g$^{-1}$) when compared to plots where residues were harvested (251 mg g$^{-1}$).

Differences in time-to-pond between management systems were only found during the crop cycle (TTPt). Direct surface water infiltration was particularly high for CA (15.8 s). Residue incorporation under conventional tillage (CONV + RES) also led to a significant increase in TTPt (7.4 s) when compared to CONV (6.1 s) (Fig. 2). After harvest and tillage of the conventional tillage treatments, TTP values were similar across treatments. Soil bulk density (SBD) did not differ significantly according to management system or residue treatment and average values across treatments ranged from 1.37 g cm$^{-3}$ at 0–5 cm to 1.45 g cm$^{-3}$ at 5–15 cm and 1.35 g cm$^{-3}$ at 15–30 cm depth (cf. Table 1).
Table 1

Chemical and physical soil properties for three soil layer depths (0–5, 5–15 and 15–30 cm). Soil bulk density values correspond to 5, 15, and 25 cm depths. Mean values followed by different letters are significantly different between the two treatments compared (*P < 0.05). The standard error is given between parentheses. Treatments compared were: conventional tillage (CONV) vs. conventional tillage with residue incorporation (CONV + RES); and conventional tillage (CONV) vs. conservation agriculture (CA).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Treatment</th>
<th>pH-H₂O</th>
<th>N (kg⁻¹)</th>
<th>P-Bray (mg kg⁻¹)</th>
<th>Ca²⁺ (mg kg⁻¹)</th>
<th>Na⁺ (mg kg⁻¹)</th>
<th>SOC (mg kg⁻¹)</th>
<th>CEC (mequiv. 100 g⁻¹)</th>
<th>SBD (g cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>CONV</td>
<td>6.6 (0.3)</td>
<td>1.04 (0.08) A</td>
<td>48.7 (15.6)</td>
<td>1544 (79)</td>
<td>604 (36)</td>
<td>9.40 (0.76) A</td>
<td>13.7 (0.71)</td>
<td>1.39 (0.04)</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>6.3 (0.1)</td>
<td>1.53 (0.05) B</td>
<td>58.5 (12.2)</td>
<td>1625 (23)</td>
<td>626 (11)</td>
<td>15.43 (0.43) B</td>
<td>14.9 (0.23)</td>
<td>1.40 (0.03)</td>
</tr>
<tr>
<td></td>
<td>CONV</td>
<td>6.6 (0.3)</td>
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<td>1544 (79)</td>
<td>604 (36)</td>
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<td>13.7 (0.71)</td>
<td>1.39 (0.04)</td>
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<tr>
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<td>CONV + RES</td>
<td>6.5 (0.1)</td>
<td>1.19 (0.05)</td>
<td>55.9 (15.9)</td>
<td>1497 (38)</td>
<td>608 (17)</td>
<td>10.53 (0.37)</td>
<td>13.7 (0.34)</td>
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<td>5–15</td>
<td>CONV</td>
<td>6.9 (0.2)</td>
<td>1.02 (0.07)</td>
<td>43.1 (13.1)</td>
<td>1692 (49)</td>
<td>646 (35)</td>
<td>8.53 (0.87)</td>
<td>14.8 (0.63)</td>
<td>1.43 (0.01)</td>
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<tr>
<td></td>
<td>CA</td>
<td>6.8 (0.1)</td>
<td>1.07 (0.08)</td>
<td>48.9 (13.8)</td>
<td>1916 (78)</td>
<td>703 (17)</td>
<td>10.17 (0.99)</td>
<td>16.7 (0.66)</td>
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<td>1692 (49)</td>
<td>646 (35)</td>
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<td>14.8 (0.63)</td>
<td>1.43 (0.01)</td>
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<tr>
<td></td>
<td>CONV + RES</td>
<td>6.9 (0.1)</td>
<td>1.08 (0.03)</td>
<td>37.9 (13.7)</td>
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<td>692 (23)</td>
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<td>7.1 (0.2)</td>
<td>0.96 (0.07)</td>
<td>34.6 (13.0)</td>
<td>1863 (28)</td>
<td>708 (21)</td>
<td>8.50 (0.70)</td>
<td>16.2 (0.42)</td>
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<td>38.3 (10.6)</td>
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<td>16.2 (0.42)</td>
<td>1.31 (0.01)</td>
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<td>30.7 (11.5)</td>
<td>1926 (12)</td>
<td>749 (48)</td>
<td>8.61 (0.42)</td>
<td>16.9 (0.98)</td>
<td>1.36 (0.00)</td>
</tr>
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</table>

3.1.4. Impact of management and earthworms on soil structure morphology

Micromorphological analysis of undisturbed soil samples confirmed the clayey loam texture. The groundmass contained fine silt grains up to sand size mineral grains and very few rock fragments (up to 100 mm in diameter), predominantly of volcanic origin, including alkaline feldspars. The smallest grains were partly weathered; the larger minerals were angular and fresh to slightly altered. There was no sedimentary layering visible.

The occurrence of surface crusting depended on treatment (Table 3). Soil crusts were virtually absent under CA and the soil surface consisted of a layer of worm casts and elongated worm channels (either open or filled with cast material) (Fig. 3). Plots under CONV were characterized by greater presence of slaked material with semi-horizontal pressure-induced cracks. In CONV + RES, surface crusts were discontinuous and the soil surface was locally characterized by a loose and open structure. At 2–14 cm depth, soils under conventional tillage had a subangular blocky structure interrupted only by physicogenenic voids, such as planar voids, created by tillage (cf. Table 3). Within conventionally tilled plots, residue removal resulted in a more massive soil structure with less evidence of biological activity. In contrast, under CA the soil microstructure was loose and highly biogenic with intact earthworm casts ranging from 2 to 4 mm in diameter. At 15 cm soil depth, a compacted soil layer was present across all treatments. While this plough pan was clearly identifiable within the conventionally tilled treatments, especially at CONV, 17 years of no tillage (including four years of CA) left a remnant plough pan extensively reworked by soil macrofauna. Soil structure changed below the plough pan in conventional tillage plots as a result of an increase in biological activity, particularly in CONV + RES. A subangular blocky structure was found, although weaker and looser in CONV + RES when compared to CONV, with many earthworm channels of 1 mm in diameter along with cracks due to shrinkage and swelling. In CA, the structure was highly biogenic (as in the upper soil layer) with evidence of macrofauna activity, often modified by mesofauna and infilled with loosely accumulated small excrements.

3.2. Integrated analysis of soil quality parameters through RDA

Constrained (by management) multivariate regression explained 40.2% of the variance of measured soil parameters (F = 2.017, P = 0.004, n = 200). The resulting RDA biplot indicated that RDA axis 1 was particularly important in explaining the variance (i.e. 35.1%) in soil parameters related to soil quality, and corresponded to the difference between CA and conventional tillage treatments (Fig. 4). CA was associated with higher earthworm abundance (0–15 cm and 15–30 cm), nitrogen concentration (0–5 cm), SOC (0–5 cm), MWDds (0–15 cm), MWDws (0–15 cm and 15–30 cm), WSA (0–15 cm) and TTPa, but a relatively low Na⁺ concentration. Both earthworm abundance (0–15 cm) and SOC (0–5 cm) were significantly correlated to MWDws (r = 0.68; *P < 0.05 and r = 0.72, **P < 0.05, respectively) in the 0–15 cm soil layer. Soil organic carbon at 5–15 cm depth was statistically correlated to both WSA (r = 0.48, *P < 0.05) and MWDds (r = 0.76, **P < 0.01) (data not shown). Compared to CA and CONV, CONV + RES had lower WSA (15–30 cm), SBD (5 cm) and Ca²⁺ (5 cm). The conventionally tilled treatment had a lower TTP after tillage than CA and CONV + RES. CA had higher maize yields in

Table 2

Mean weight diameter (MWD) after dry and wet sieving, and contents of total water stable aggregates (WSA; 250 μm–8 mm). Mean values followed by different letters are significantly different between the two treatments compared (*P < 0.05) and with a star for highly significant differences (**P < 0.01). The standard error is given between parentheses. See Table 1 for treatment abbreviations.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Treatment</th>
<th>MWD</th>
<th>WSA (mg g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry sieving (mm)</td>
<td>Wet sieving (mm)</td>
</tr>
<tr>
<td>0–15</td>
<td>CONV</td>
<td>1.61 (0.19) A</td>
<td>0.59 (0.05) A</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>2.62 (0.15) A</td>
<td>0.86 (0.09) B</td>
</tr>
<tr>
<td></td>
<td>CONV</td>
<td>1.61 (0.19) A</td>
<td>0.59 (0.05) A</td>
</tr>
<tr>
<td></td>
<td>CONV + RES</td>
<td>2.25 (0.08) B</td>
<td>0.69 (0.07)</td>
</tr>
<tr>
<td>15–30</td>
<td>CONV</td>
<td>2.06 (0.40)</td>
<td>0.64 (0.05)</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>2.31 (0.11)</td>
<td>0.88 (0.05)</td>
</tr>
<tr>
<td></td>
<td>CONV</td>
<td>2.06 (0.40)</td>
<td>0.64 (0.05)</td>
</tr>
<tr>
<td></td>
<td>CONV + RES</td>
<td>1.97 (0.08)</td>
<td>0.50 (0.04)</td>
</tr>
</tbody>
</table>
Table 3
Description of macrostructure morphology of soil thin sections. See Table 1 for treatment abbreviations. Ø stands for diameter.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Description of macrostructure morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONV</td>
<td>0–2</td>
<td>Slaked material, probably caused by traffic, reworked by soil fauna.</td>
</tr>
<tr>
<td></td>
<td>2–14</td>
<td>2–6 cm. Tilled groundmass consisting of mechanically reworked soil and with remnants of compacted material (up to 10 mm Ø). 7–14 cm. Few visible organic fragments and soil material somewhat looser with infillings containing worm casts. Porosity mainly based on irregular voids (tillage and root voids).</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Compact layer with pressure-induced cracks (plough pan), reworked by soil meso- and macrofauna.</td>
</tr>
<tr>
<td></td>
<td>18–26</td>
<td>Subangular blocky structure (from weakly to well developed, cracks and 2–3 cm Ø ped.). Macrofauna casts and fauna channels partly filled with mesofauna excrements and used by roots.</td>
</tr>
<tr>
<td>CONV + RES</td>
<td>0–2</td>
<td>Surface crust, but including areas with a loose and open structure due to decomposing roots and residues that attract soil biota.</td>
</tr>
<tr>
<td></td>
<td>2–14</td>
<td>Tilled groundmass constituted by mechanically reworked soil with fragments of slaked material (up to 10 mm Ø). More worm channels than in CONV, but many burrows disturbed by tillage.</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Plough pan but less distinct that in CONV and modified by meso-, macrofauna and roots.</td>
</tr>
<tr>
<td></td>
<td>18–26</td>
<td>Weak and loose subangular blocky structure with casts of 1–2 mm Ø. Many pores of earthworms (circa 1 mm Ø).</td>
</tr>
<tr>
<td>CA</td>
<td>0–2</td>
<td>Topsoil constituted mainly by excrements (worm casts as well as enchytraeid and insect larvae excrements) containing fragmented organic residues, biological channels and packing voids between the casts.</td>
</tr>
<tr>
<td></td>
<td>2–14</td>
<td>Loose and highly biogenic structure with worm casts of 2 to 4 mm. Big worm channels sized 2–5 mm Ø partially filled with excrements and that constitute a pore system with vertical and horizontal pores between 2 and 5 cm.</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Slightly compacted layer with pressure-induced cracks, possibly remnant of a plough pan, but less densely packed and discontinuous due to soil biological activity (i.e. earthworms and roots). Presence of some earthworm channels covered by a clay coating, and casts reingested by mesofauna.</td>
</tr>
<tr>
<td></td>
<td>18–26</td>
<td>Extremely biogenic structure with larger macrofauna activity. Casts of 1–2 mm Ø, with low quantity of organic matter, and wide worm channels (up to 4 mm Ø) are prevalent. Diapause and hatching chambers were also present (up to 2 cm wide). Voids are commonly modified by mesofauna.</td>
</tr>
</tbody>
</table>

2004 and 2005 when compared to CONV, but the yield difference was only significant (*P < 0.05) in 2004 (Table 4). Within conventional tillage, yields did not significantly differ between the two residue management options.

4. Discussion

4.1. Management effects on biological, chemical and physical soil parameters

Conservation agriculture (CA) resulted in an evident increase of earthworm abundance when compared to conventional tillage (CONV). Earthworm biomass under CA (117.6 g m⁻²) was particularly high and even superior to values from some Mexican tropical pastures (i.e. 73.2 g m⁻² on average; Fragoso et al., 1999). Increased earthworm abundance and biomass under CA is in line with previous research results (Chan, 2001; Kladivko, 2001). This is probably explained by the absence of tillage which strongly reduced direct physical damage to earthworms, as well as habitat disturbance (Chan, 2001; Kladivko, 2001; Lavelle et al., 2001). Although aboveground crop residues constitute a major food source (along with soil organic matter and root residues) for most earthworm species (Lavelle et al., 2001), residue retention per se did not favor earthworm proliferation when incorporated into the soil by conventional tillage (CONV + RES). Increased biomass returns to the soil through crop rotations have also been considered beneficial for earthworm proliferation, but evidence has been generally inconclusive (e.g. Govaerts et al., 2006; Hubbard et al., 1999; Rovira et al., 1987). Regarding species composition, earthworms found belonged predominantly to the Lumbricidae family but included the

![Fig. 2](image-url) Time-to-pond measured during the crop cycle and after harvest and tillage of the conventionally tilled treatments. Treatments compared were: conventional tillage (CONV) vs. conventional tillage with residue incorporation (CONV + RES) (left); conventional tillage (CONV) vs. conservation agriculture (CA) (right). Mean values followed by an asterisk are significantly different between the two treatments compared (*P < 0.05). Error bars indicate the standard error.
American *Bimastos parvus*. As reported for other agro-ecosystems (Fragoso et al., 1999; Ortiz-Ceballos and Fragoso, 2004), the earthworm community was mainly composed of exotic species given their adaptability to intensive agricultural management (Fragoso, 2001; Grosso et al., 2006). *B. parvus* presence under CONV is particularly surprising. This is an epigecic species feeding at and immediately below the soil surface and thus considered highly sensitive to conventional tillage (Chan, 2001; Kladivko, 2001). Both *Aporrectodea tuberculata* (endo-anecic) and *Aporrectodea longa* (anecic) generally persist in tilled soils (Berry and Karlen, 1993; Ernst and Emmerling, 2009), although they are new to maize and wheat habitats in Mexico (E. Huerta, personal communication, 2011). In contrast to epigecic species, endo-anecic and anecic species can have a large impact on soil porosity.

Our study showed that 4 years of contrasting management was not sufficient to lead to significant differences in soil C sequestration relative to CONV, even after a history of no-tillage (1988–1998). Calculation of SOC stocks for the whole 0–30 cm layer, using bulk density data and soil organic C concentrations, did not show significant differences (8.1 Mg ha\(^{-1}\) in CA vs. 6.1 Mg ha\(^{-1}\) in CONV). Some authors claim that differences in soil C storage can take many years to develop (Gál et al., 2007; Six et al., 2000), while a review by Govaerts et al. (2009) comparing long-term soil C sequestration in tillage treatments found that differences were not verified in 24% of cases reviewed. More precise understanding of the conditions in which CA has potential for soil C increases throughout the soil profile when compared to conventional tillage is needed. In any case, CA led to a pattern of SOC and total N stratification in which C concentrations were significantly higher at 0–5 cm depth (cf. Table 1). Lower macroaggregate turnover under CA has been found to favor topsoil C accumulation as fine (53–250 µm) intra-aggregate particulate organic carbon (iPOC C) into microaggregates (Angers et al., 1997; Six et al., 2000). Topsoil SOC accumulation under CA

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**Fig. 3.** Soil structure morphology (0–30 cm depth) for conventional tillage (CONV), conventional tillage with residue incorporation (CONV + RES) and conservation agriculture (CA). Images are scans of the thin sections without optical multiplication. Arrows indicate: (a) soil crust; (b) compaction; (c) reworked slaked material; (d) physicogenic groundmass; (e) earthworm burrow; (f) bow-like infillings indicating earthworm-worked groundmass.
has been identified as a key in promoting progressive restoration of physical soil functions through increased resistance to slaking and to wind erosion (Franzluebbers, 2002; Govaerts et al., 2006; Le Bissonnais, 1996). In the absence of tillage, carbon inputs into the soil surface increase the formation of additional intermolecular bonds upon drying (Six et al., 2000) and reduce the wettability of soil aggregates (Caron et al., 1996). This explains increased soil surface aggregate formation and stabilization as reflected by greater dry- and wet-sieved aggregate sizes when compared to CONV at 0–15 cm depth (cf. Table 2). The role of crop rotation is probably minimal on this regard given analogous wheat and maize yields (see Section 3.2). In a very similar experiment, Govaerts et al. (2006) did not find any effect on soil quality from maize–wheat rotations (vs. maize monoculture) (Govaerts et al., 2005). The aim of the present study was to compare management systems as found in the region, rather than between individual

management components. While research needs to address if proposed alternatives do provide sufficient medium-term improvement that justify farmers’ adoption, we would like to emphasize that a full factorial evaluation of the role of individual CA management components (residue, tillage, crop rotation) would allow for a better mechanistic understanding and is therefore an important additional research priority.

Improved soil structural stability, especially at the topsoil, has been related to increased rainfall infiltration (Barthès and Roose, 2002) and reduced runoff (Kemper and Rosenau, 1986). This, along with increased water infiltration through ponding as caused by crop residue mulching (Gilley and Kotzwit, 1994), explains higher time-to-pond values found in CA when compared to CONV during the crop cycle. While similar direct surface water infiltration rates are found in CONV short after tillage, this is only achieved temporarily through mechanical made soil macroporosity (Carter, 1988). Low macroaggregate stability on CONV, as reflected in thin sections by aggregate collapse into soil cruts and slaked layers, during the crop cycle (i.e. a critical period for water use efficiency) results in lower water infiltration (Carter, 1988; Kay, 1990).

Previous research has indicated how soil bulk density (SBD) values might not differ when comparing different tillage systems (Al-Kaisi et al., 2005; Logsdon and Karlen, 2004), especially in trials less than 15 years old (Verhulst et al., 2010). However, in our study similar SBD values across crop management systems corresponded to very different structural morphologies as found through thin section analysis. Under CONV, a SBD of 1.43 g cm⁻³ corresponded to the existence of a massive plough pan (cf. Fig. 3), while a SBD of 1.46 g cm⁻³ under CA referred to a remnant plough pan with denser biogenic structure, which does not likely imply reduced hydraulic conductivity due to the presence of considerable porosity (formed by soil macrofauna and decayed plant roots) (Edwards and Shipitalo, 1998). In conventionally tilled plots evidence of soil biological activity mainly consisted of small sized macrofauna and soil mesofauna with less profound effects on soil structure. Given different soil structural morphologies, SBD values were a poor indicator of soil compaction.

### 4.2. Soil quality changes

As hypothesized, earthworms played a key role in enhancing physical soil functions. When conditions were conducive to their proliferation, as in CA, earthworm activity was a major factor affecting soil structural morphology as confirmed by micromorphological analysis and the positive correlation of earthworm abundance to MWDws (r = 0.68; *P* < 0.05). These organisms significantly contributed to soil macroaggregation (>250 μm) and biogenic macroporosity (≥1 mm) through their casting and burrowing activities (Pulleman et al., 2005; Shipitalo and Protz, 1989). At the same time, the tight correlation between SOC and both MWDds (r = 0.76, **P** < 0.01) and MWDws (r = 0.72, *P* < 0.05) in the topsoil suggests that soil organic matter content is a major factor explaining differences in stable aggregation in the soils under study. These results are consistent with earlier studies in a

![Fig. 4. Ordination diagram of the redundancy analysis (RDA) of the agricultural management (triangles: CONV, CONV + RES, and CA) displaying 40.2% of the variances in the soil parameters (dashed arrows). Only soil parameters of which more than 20% of their variance is accounted for by the diagram are shown. Eigenvalues of the two canonical axes are 0.331 (F = 2.251, *P* = 0.01, n = 200) and 0.051 (F = 2.017, *P* = 0.004, n = 200). Treatments were: conventional tillage (CONV), conventional tillage with residue incorporation (CONV + RES) and conservation agriculture (CA). Abbreviations indicate the following soil parameters: CA: calcium concentration (mg kg⁻¹); CEC: cation exchange capacity (mequiv. 100 g⁻¹); Na: sodium concentration (mg kg⁻¹); N: total nitrogen (g kg⁻¹); MWDds: mean weight diameter of dry-sieved samples (mm); MWDws: mean weight diameter of wet-sieved samples (mm); SBD: soil bulk density (g cm⁻³); SOC: soil organic carbon (g kg⁻¹); TTPah: time-to-pond during the crop cycle (s); TTPai: time-to-pond after harvest and tillage of the conventionally tilled treatments (s); WRM: earthworm abundance (ind. m⁻²); WSA: water stable macroaggregation (mg g⁻¹). Numbers following parameters referred to sampling depth.](image-url)

Table 4

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Maize yields (kg ha⁻¹)</th>
<th>Wheat yields (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONV</td>
<td>4809(183)</td>
<td>2862(247)</td>
</tr>
<tr>
<td>CA</td>
<td>4414(827)</td>
<td>3224(272)</td>
</tr>
<tr>
<td>CONV + RES</td>
<td>4809(183)</td>
<td>2862(247)</td>
</tr>
<tr>
<td></td>
<td>4927(389)</td>
<td>3441(317)</td>
</tr>
</tbody>
</table>
wide range of soil types (Tisdall and Oades, 1982; Six et al., 2004). While earthworms are not always the major agent contributing to soil structure formation and maintenance (Oades, 1993; Six et al., 2004), in this study these organisms, along with sustained carbon inputs and low macroaggregate turnover, can be considered key to the formation of a loose and highly biogenic soil microstructure. These comprehensive changes were well illustrated by the multivariate analysis which showed how CA resulted in improved overall soil quality with increases in all parameters related to soil physical properties (i.e. topsoil MWD_d0, MWD_w, and WSA). Enhanced dynamics between soil biota, carbon inputs and soil aggregation as a result of minimum soil disturbance and sustained crop residue returns under CA favored soil’s water infiltration capacity while reducing susceptibility to losses through runoff and wind erosion (Barthès and Roose, 2002; Govaerts et al., 2006; Six et al., 2004). The conventional farmers’ practice (CONV) was characterized by significant positive loadings only for Na⁺. Even after a decade of zero tillage (1988–1998), conventional tillage without residue retention (CONV) led rapidly to a massive physiogenic soil profile characterized by subangular blocky peds with slight evidence of soil biological activity below the plough pan. Changes brought to conventional tillage through crop residue retention are well illustrated by the RDA biplot. Marginal soil improvements in the form of increased WSA at 0–15 cm depth when compared to CONV were sufficient to lead to sustained direct surface water infiltration rates.

Although conservation agriculture did lead to significant improvements in key soil parameters related to physical soil quality, particularly important in semi-arid conditions, as compared to conventional management, these improvements were not (immediately) translated into consistent yield differences (cf. Table 4). However maize yields under CA were higher in 2004 and 2005, although not significantly in 2005, when compared to CONV plots under equal N fertilization rates which may indicate a trend in time as a transition period normally exist between changes in tillage management and yield improvements (Govaerts et al., 2005). Further research is needed to understand how soil quality changes contribute to yield increases in both the short and long-term. Alternative management practices improving soil quality, such as CA, would be hardly adopted by farmers if these are not characterized by clear short-term comparative advantages (Giller et al., 2009; Hellin and Scharader, 2003), especially under realistic farm conditions (i.e. partial crop residue returns given competitive uses) (Giller et al., 2009). Implementation and research in long-term trials considering farmers available resources seem thus necessary to support the implementation of more sustainable crop management systems.

5. Conclusions

Studied crop management systems lead in a relative short-time span (i.e. 4 years) to distinct soil microstructure morphologies with important implications in these semi-arid conditions. Conservation agriculture led to the formation of loose and highly biogenic topsoils as a result of increased earthworm activity and sustained carbon inputs into these soils. Enhanced dynamics between soil biota, especially earthworms, carbon inputs and soil aggregation contributed to higher direct surface water infiltration when compared to conventional practices. Whereas tillage prevented earthworm proliferation and topsoil organic carbon accumulation. Poor aggregate stability under CONV resulted in soil crusts formation and slaked soil layers which required continuous tillage to improved water infiltration into these soils. While crop residue retention under conventional tillage (CONV + RES) did not prevent soil crusts formation, direct surface water infiltration was significantly increased. Our results confirmed how soil quality changes at the topsoil are specially key for soil functioning (Franzluebbers, 2002). However, comprehensive soil quality changes under CA were not translated into consistent yield increases under the time-frame considered. While major changes occurred at the soil surface, soil micromorphologies also diverged in the rest of the sampled soil profile. Nevertheless, SBD values were similar across treatments pointing to the inadequacy of this indicator for comparisons between tillage systems.

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