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The adoption of no-till instead of reduced tillage does not improve some soil quality parameters in Argentinean Pampas

Anahí Domínguez*, José Camilo Bedano

CONICET—National Council for Scientific and Technical Research, Department of Geology, National University of Río Cuarto, Córdoba, Argentina

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ABSTRACT

No-till (NT) has been recognized worldwide as a more suitable system than tillage for enhancing soil quality. However, several concerns remain about its conservative nature, especially when it is performed either without cover crops or appropriate rotation schedules, and when it is accompanied by the usage of high amounts of agrochemicals. In this paper, we study some soil quality parameters when NT is adopted instead of reduced tillage, as well as the relevance of soil physical and chemical properties to explain the impact of management systems on soil macrofauna. We compared NT and reduced tillage (RT) systems, using natural grasslands (GR) as reference. We hypothesised that (1) soil quality will decline in both agricultural systems compared to the grassland but this declination will be less in no-till than in reduced tillage, and that (2) the changes in macrofauna community could be explained by changes in physical and chemical soil properties. Soil cover, organic matter, pH, moisture content, bulk density and mechanical resistance were assessed as indicators of soil physical and chemical quality. Soil macrofauna abundance and composition was determined by the TSBF method. We rejected our first hypotheses since from the assessed parameters only soil moisture content and spider abundance were favoured in NT compared to RT. Changes caused by both systems in the macrofauna composition (especially in soil inhabitants) were mainly explained by soil physical and chemical attributes. The ordination of sites according to canonical correspondence analyses clearly shows the influence of the management systems in the relationship between macrofauna assemblages and soil physical and chemical parameters; especially in the upper 30 cm of soil. GR had both a better soil physical and chemical quality and a higher abundance of the main macrofauna taxa (earthworms, beetles and ants) compared to agricultural systems. NT and RT were similar, sharing low earthworm and ant abundance and high potworm abundance. Our results show that adopting NT instead of RT does not favour assessed soil quality parameters. Thus, NT is questioned as a system which enhances soil quality, at least in the way it is performed by most farmers from Argentine Pampa.

1. Introduction

No-till has been recognized worldwide as a conservation farming practice, especially when practiced together with soil cover and crop rotations (FAO, 2008). In that case, no-till has been considered an effective practice to control soil erosion and runoff, increase water infiltration, enhance soil organic matter concentration, increase soil biological activity, and save energy (Lal, 2007).

However, there still are several concerns about these advantages of no-till. Some of them are: What happens if no-till is not conducted together with soil cover and crop rotation? To which extent can soil fauna engineering replace soil tillage to avoid soil compaction as a consequence of heavy machinery traffic? What are the consequences of the large increase in glyphosate usage? Some researchers have previously dealt with some of these issues. Paul et al. (2013) tested the interaction between two of the main principles of conservation agriculture – minimum tillage and crop residue management – and found that tillage and residue management alone did not influence soil carbon content. Other authors agree with the need of cover crop presence in no-till management to enhance soil quality (Aquino et al., 2008; Blanchart et al., 2006; Brévault et al., 2007; Ding et al., 2006; Sainju et al.,

* Corresponding author at: Ruta 36, Km. 601, X5804BYA, Río Cuarto, Córdoba, Argentina.
E-mail addresses: adominguez@exa.unrc.edu.ar, adominguez.unrc@gmail.com (A. Domínguez).

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2002). Regarding the consequences of no-till on soil structure, compaction of the topsoil under no-till systems has been described in several studies in the Pampas region. Díaz-Zorita et al. (2002) mention higher bulk density values in no-till compared to tillage systems. Moreover, lower crop yields have been attributed to higher bulk density values. In other regions, Filipovic et al. (2006), Franzluebbers et al. (1995) and Thomas et al. (2007) have also found higher soil bulk density values in no-till than in tilled systems. Regarding the possible impact of glyphosate on soil fauna, studies are still not conclusive. Casabé et al. (2007) did not find a negative effect on survival rate of *Eisenia fetida* but a negative effect on hatchability and viability of cocoons (at a concentration of 1440 g a.i.ha^{-1}). Buch et al. (2013) found no lethal effect but avoidance behaviour in two earthworm species (*Pontoscolex corethrurus* and *Eisenia andrei*, at a concentration of 47 mg a.i. kg^{-1}). However, glyphosate effect on Argentinean native earthworm species has not been assessed.

No-till has been widely promoted in Argentina by agronomists and agrifood companies and then widely adopted by most farmers. This technique is applied not only across all the Pampean region (the main agricultural region of Argentina) but also in regions previously not dedicated to agriculture, since no-till practices have allowed to extend agricultural boundaries. Nowadays, about 27 million ha are cropped under no-till, this system being applied in 78.5% of the cropped surface (AAPRESID, 2012), which emphasizes the need for deep soil quality assessment. Moreover, in most cases the no-till system has been restricted to the use of genetically modified crops, no-till-seeders and a chemical fallow during the winter season. Few cover crops and appropriate rotation schedules have been applied. No-till has also been accompanied by a huge increase in the use of some agrochemicals, mainly of glyphosate. In the period 1991–1992, 1 million l of glyphosate were sprayed while 20 years later the use of this herbicide reached 200 million l (Camino and Aparicio, 2010). There are also several studies which have linked soil physical, chemical and biological degradation with no-till practices performed in the study region (Arolfo et al., 2010; Bedano et al., 2006; Domínguez et al., 2010; Parra et al., 2011). Several aspects can be evaluated to analyse whether continuous no-till management is actually better for soil quality than other systems with tillage. Soil physical and chemical properties have always been considered as suitable indicators of soil quality (Cluzeau et al., 2012; Doran and Parkin, 1994). However, biological indicators have the potential to provide early warning because they capture subtle changes in soil quality as a result of their integrative nature that simultaneously reflect changes in physical, chemical and biological characteristics of the soil (Barrios, 2007). Within soil biota, the soil macrofauna (invertebrates with body diameter greater than 2 mm) has been highlighted as a useful indicator of soil quality. The assessment of macrofauna community provides evidence of the diversity and intensity of physical and chemical ecosystem engineering operated by invertebrates themselves and subsequent associated microbial activities, which contribute significantly to the production and delivery of soil ecosystem services in many ways (Lavelle et al., 2006; Velasquez et al., 2007). Therefore, the aims of this paper are to study whether assessed soil quality parameters are promoted by no-till system and the relevance of soil physical and chemical properties in explaining the impact of management systems on macrofauna. Thus, we compared no-till systems with reduced tillage systems, using natural grasslands as references. We hypothesise that (1) soil quality parameters will decline in both agricultural systems compared to the grassland but that decline will be less in no-till than in reduced tillage; (2) the changes in macrofauna community could be explained by changes in physical and chemical soil properties.

2. Materials and methods

2.1. Site description

The study was conducted in the south of Córdoba province, Argentina (32°44′50″S, 63°54′48″W and 32°49′55″S, 63°45′05″W). Soil is a coarse loamy, illitic, thermic Typic Haplustoll (Soil Survey Staff, 2010). The climate is sub humid temperate with a marked dry season in winter; mean annual rainfall is 695 mm and mean annual temperature is 16 °C. Annual rainfall in the two sampled years was 744 mm and 614 mm.

2.2. Management description

Three systems were studied: two farming systems, no-tillage (NT) and reduced tillage (RT), and natural grassland as reference; each one with two replicates. The agricultural sampling sites were at least 100 ha in area and they were managed with similar agricultural practices for at least 8 years before sampling. They have the same Soil Series (according to Soil Taxonomy classifications) and they were also selected by having similar geomorphological characteristics in terms of slope (1–3%) and elevation (290–340 m a.s.l.). It can also be assumed that until 1900 all the sites had the same land-use history: they were natural grasslands. In 1900, land tenure was divided and a mixed production system of cattle rising and agriculture was applied in most farms (La Calle, 1977). Approximately since 1930 continuous agriculture under conventional tillage was spread in the region. Agrochemicals applied in all the sites during the sampled years were urea and phosphate (fertilizers); glyphosate and atrazine (herbicides) and chlorpyrifos (insecticide). In RT sites subtiller, disk harrow and roller were used. A soybean-corn crop rotation was applied in all the sites at least 5 years prior to sampling.

A third system was included in the study: natural grassland (GR), to be used as a reference. For that, two sites of about 2 ha were sampled. These natural sites had the same Soil Series and geomorphological characteristics as the managed sites, but they have been undisturbed and covered with natural pastures during the last 50 years. The plant community was dominated by *Stipa* sp. Plant cover was 100% and the litter layer was approximately 1 cm thick. These sites were not managed; they only had occasional cattle grazing.

2.3. Soil quality assessment

Soil sampling was conducted twice, in two consecutive springs. In each sampling time and in each field five sampling points were defined every 20 m along a transect with random starting point. In each sampling point we sampled all soil attributes. To assess soil macrofauna, a soil monolith of 25 × 25 × 30 cm was delimited, extracted and then separated into four layers: litter, 0–10 cm, 10–20 cm, and 20–30 cm in depth, according to the TSBF method (Anderson and Ingram, 1993). Altogether, 180 soil samples and 60 litter samples were collected and gently moved to the laboratory (3 systems × 2 fields × 5 monoliths × 4 layers × 2 years). We used the same frame of 25 × 25 cm to estimate the soil cover, measured as the percentage of soil covered by litter or crop residues. Next to each monolith, mechanical resistance was also measured with a hand penetrometer up to 30 cm depth (Bradford, 1986). Finally, 120 undisturbed soil cores (0–10 cm and 10–20 cm) were extracted to measure bulk density and moisture content.

In the laboratory, immediately after sampling, undisturbed soil cores sampled were weighed first to obtain moist weights, and then oven-dried up to a constant weight at 105 °C. Soil moisture percentage (gravimetric method) and soil bulk density were then calculated. Litter samples for soil macrofauna were also immediately hand-sorted after sampling. Soil samples were stored in dark and controlled conditions and randomly hand-sorted within no more than 10 days after sampling. All invertebrates larger than 2 mm were collected and counted; arthropods were preserved in 70% alcohol. Oligochaeta were fixed and preserved in 4% formaldehyde. Five high-range taxa were identified: earthworms (Oligochaeta: Haplotaxida: Lumbricina), potworms (Oligochaeta: Haplotaxida: Enchytraeina: Enchytraeidae), ants (Hexapoda: Insecta: Hymenoptera: Formicidae), beetles (Hexapoda: Insecta: Coleoptera), and spiders (Arachnida: Araneae). Ants and beetles were identified to morphospecies by using Bolton's (1994) and Palacio and Fernandez's (2003) keys for ants and Lawrence's et al. (2002) for beetles. From the remaining soil of each monolith, a soil subsample was used to measure organic matter and pH. Soil organic matter content was determined by the modified Walkley–Black method (Jackson, 1976). Soil pH was assessed by means of the potentiometric method, soil–water ratio 1:2.5.

2.4. Statistical analyses

2.4.1. Soil physical and chemical properties

A number of general linear mixed models (GLMM) were performed and Akaike's information criterion was used to determine the best predictive model. In the best-fit model, the fixed factors were management system and soil depth and the random factors were the sampling year, the field, and the monolith. Error variance structure was modelled using management system as grouping criteria and Var (Ident) of R's *nlme* library as variance function. A *posteriori* tests were performed by the DGC test (Di Rienzo et al., 2002). Significance levels of 10% for the GLMM and of 5% for a *posteriori* tests were used. InfoStat software was used for all analysis, as a friendly interpreter of R (Di Rienzo et al., 2012).

2.4.2. Soil macrofauna community

As macrofauna abundance did not have a normal error distribution a generalized linear mixed model was performed using Poisson error distribution and log link function (Ponce et al., 2011; Venables et al., 2011). Fixed and random factors of the model were the same as in Section 2.4.1. A *posteriori* tests were performed by DGC test (Di Rienzo et al., 2002). InfoStat software was used (Di Rienzo et al., 2012). In addition, a detrended correspondence analysis (DCA) (Hill, 1979; Hill and Gauch, 1980) was performed for the two groups with higher taxonomic resolution: Formicidae and Coleoptera. This indirect gradient analysis maximizes the separation between sites along ordination axes based on species composition, and has proven to be a powerful tool for detecting patterns in communities that reflect underlying environmental gradients (Hill and Gauch, 1980; Peet et al., 1988). It was conducted using CANOCO (ter Braak and Smilauer, 2004).

2.4.3. Relations between macrofauna abundance and environmental parameters

The relationship of each macrofauna taxa with respect to the environmental attributes was assessed by means of a canonical correspondence analysis (CCA) (ter Braak and Verdonschot, 1995) performed using CANOCO (ter Braak and Smilauer, 2004), with the ln transformation. The percentage of the variance in the weighted averages was calculated as: $100 \times (\text{Ev1} + \text{Ev2})/\sum \text{Ev}$; where Ev are the eigenvalues (ter Braak and Verdonschot, 1995).

3. Results and discussion

3.1. Soil environmental properties

As evidenced by the GLMM (Table 1), the soil cover, pH and bulk density were significantly influenced by the management system and the latter two also by the soil depth; soil mechanical resistance was influenced by the soil depth but not by the management system. Soil organic matter and moisture content were significantly affected by the interaction between depth and management.

3.1.1. Soil cover

As expected, soil cover was of 100% in GR and was significantly higher than in NT and RT (Table 2). Soil cover also showed a trend to be higher in NT than in RT, but it was not significantly different. The high variance explained by the field (25.95, Table 1) indicates that this property had different values between the sites of the same management system. This is likely because in one NT field a winter crop (wheat) was seeded, showing that the improvement of soil cover by NT is highly dependent on the presence of a cover (or winter) crop. This result also shows that the use in RT of shallow tools enables to keep a substantial proportion of crop residues covering the soil. The failure of the main annual crop to produce enough residues to keep a significant soil cover implies a potential problem in most Argentinean humid pampa farms, because the use of cover crops in the winter season has been little adopted. Thus, the benefits of a substantial cover crop for soil organisms, either epigeic or edaphic, such as increase of spatial heterogeneity, suitable habitat availability, food resources availability, etcetera, are lost or diminished (Cobb et al., 1999; Lobry de Bruyn, 1999). Benefits of soil cover on soil physical and chemical quality conservation, by decreasing hydric and wind erosion and by increasing soil organic matter and crop yield (Díaz-Zorita et al., 2002) could also be absent.

3.1.2. Soil organic matter

At 0–10 cm soil depth, SOM content was significantly higher in GR than in both farming systems (Table 2). Differences among depths were only observed in GR where SOM was higher in 0–10 cm than in 10–30 cm. Such concentration of SOM in the upper layer was expected considering the original characteristics of the

Table 1
Parameter estimates from the General Linear Mixed Model with management (grassland, no-till and reduced tillage), depth (0–10 cm, 10–20 cm and 20–30 cm) and the interaction between them as fixed factors and with year, field and monolith as random factors affecting soil properties.

	Fixed parameters (p value)			Random parameters (variance)		
Properties	Management (M)	Depth (D)	M × D	Year	Field	Monolith
Cover	0.0622	–	–	0.0031	25.95	
Organic matter	0.2351	<0.0001	0.0007	0.42	0.55	0.000039
Moisture	0.8556	0.0351	0.0975	4	3.68	0.00016
pH	0.0803	<0.0001	0.4818	0.000022	0.16	0.00000031
Mechanical resistance	0.4496	<0.0001	0.2371	2.69	3.19	1.46
Bulk density	0.0234	<0.0001	0.3906	0.04	0.04	0.00000049

GLMM; for fixed parameters$p$ value < 0.10.

Table 2
Effect of the management system (grassland, no-till and reduced tillage) and the soil depth (0–10 cm, 10–20 cm and 20–30 cm) on soil physical and chemical properties.

	Depth	Management	Media
Cover (%)	–	GR	100.00 a
		NT	64.40b
		RT	45.33b
Organic matter (%)	0–10 cm	GR	4.78 a
		NT	3.36b
		RT	3.33b
	10–20 cm	GR	3.17b
		NT	2.92b
		RT	2.67b
	20–30 cm	GR	2.59b
		NT	2.73b
		RT	2.28b
Moisture (%)	0–10 cm	GR	16.58a
		NT	17.36a
		RT	14.62b
	10–20 cm	GR	14.47b
		NT	15.88b
		RT	15.69b
pH	Management	GR	6.38a
		NT	6.08b
		RT	6.08b
	Depth	0–10 cm	6.01a
		10–20 cm	6.14b
		20–30 cm	6.39c
Mechanical resistance (MPa)	Management	GR	8.09a
		NT	7.08a
		RT	5.02a
	Depth	0–10 cm	5.23a
		10–20 cm	7.74b
		20–30 cm	7.23b
Bulk density (g/cm^3)	Management	GR	1.24a
		NT	1.35b
		RT	1.30b
	Depth	0–10 cm	1.20a
		10–20 cm	1.40b

GR: grassland; NT: no-till; RT: reduced tillage. Different letters for each property indicate significant differences between different managements and/or depth. Test DGC p value < 0.05.

soil. On the other hand, NT and RT had similar SOM content throughout the soil profile (Table 2). Random factors also had a low impact on SOM content (Table 1). These results do not support the generalized idea that NT maintains and even increases SOM in the first 10 cm of the soil (Lal et al., 2007; Thomas et al., 2007). There are also previous reports indicating that RT has an effect on SOM more similar to that of no-till rather than that of conventional tillage. For example, Duiker and Beegle (2006) observed higher SOM at 0–5 cm in NT than in RT, but lower at 5–15 cm. On the other hand, the lack of a continuous use of cover/winter crops could also explain the ineffectiveness of NT in increasing SOM (Ding et al., 2006). It is well-known that SOM accumulation enhances soil biota development, improves other physical and chemical properties and increases crop yield as well (Thomas et al., 2007). SOM reduction in both farming systems compared to reference system warns about the possibility that those benefits might not be achieved.

3.1.3. Soil moisture

At the top 10 cm of soil, moisture content was significantly higher in the GR and NT than in RT, showing no-till success in maintaining the soil water content. This was observed for the upper soil layer, whereas at 10–20 cm depth differences between NT and RT were not observed. The sampling year explained an important part of the variance of this property (Table 1), as expected owing to its relation with annual climatic variations. These results support part of our hypothesis, since NT enhances water retention capacity, in agreement with Lal et al. (2007) and other authors. This high moisture content in NT is expected to have a positive effect on soil fauna development (Edwards and Bohlen, 1996; Lal et al., 2007; Lavelle and Spain, 2003).

3.1.4. Soil pH

The GR had higher soil pH than NT and RT, but there were no differences between both farming systems (Table 2). Regardless of the management, the pH was significantly higher when increasing soil depth (Table 2). These results were not expected, because previous reports have found a significant interaction between soil depth and management system. Soils under NT are frequently more acidic in shallow layers than those under tillage, but less acidic in deeper layers (Logan et al., 1991). However, our results agree with Thomas et al. (2007) who did not find a significant effect of reduced tillage on soil pH. These results are closely related to those of SOM, since both properties are strongly related, as an increase in SOM and associated organic acids changes the proportions of cations and anions, increasing the soil pH (Thomas et al., 2007). High fertilization rates have also been related to soil acidification in agricultural lands compared with natural grasslands in the study region (Musso et al., 2004; Cabrera et al., 2012) and in other regions (Riley and Barber, 1971; Thomas et al., 2007). Similar soil pH values between both managements are likely related to similar SOM values and fertilization levels among NT and RT.

3.1.5. Soil mechanical resistance

There were no significant differences in soil mechanical resistance (MR) due to the management system (Table 2). In the three systems MR was lower at 0–10 cm depth than at 10–30 cm (Table 2). As MR is highly dependent on moisture content (Gupta and Allmaras, 1987; Taboada et al., 1998), its high values are probably related to sampling in a period of the year where moisture contents were especially low. Indeed, a high proportion

Table 3
Parameter estimates from the Generalized Linear Mixed Model with management (grassland, no-till and reduced tillage), depth (0–10 cm, 10–20 cm and 20–30 cm) and the interaction between them as fixed factors affecting soil properties, and with year, field and monolith as random factors affecting soil properties.

	Fixed parameters (p value)			Random parameters (variance)		
High range taxa	Management (M)	Depth (D)	M × D	Year	Field	Monolith
Earthworms	0.0226	<0.0001	<0.0001	0.46	0.00	7.68
Ants	0.0003	<0.0001	<0.0001	0.06	0.00	10.36
Beetles	0.0269	<0.0001	<0.0001	0.33	0.14	4.81
Spiders	0.0270	<0.0001	<0.0001	0.01	<0.0001	3.11
Potworms	0.0423	<0.0001	<0.0001	0.69	3.0E − 08	3.37

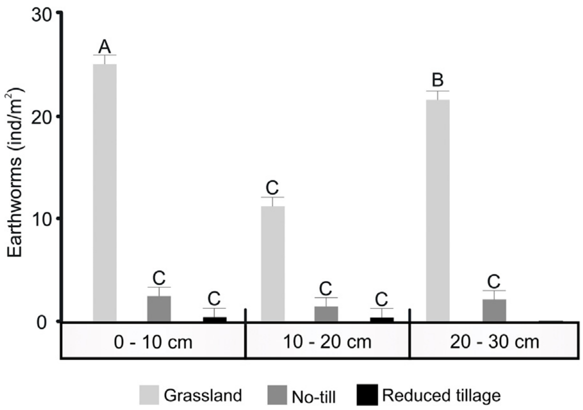

Fig. 1. Earthworm abundance in the different management systems and soil depths. Different letters indicate significant differences between abundances of the different managements and/or depths. Test DGC p value < 0.05.

of MR variance was explained by the year (random factors, Table 1), likely because annual climatic variations produced changes in soil moisture content and therefore in MR.

3.1.6. Soil bulk density

GR had significantly lower bulk density (BD) values than NT and RT and a not significant trend of a higher BD in NT than in RT was also observed. Bulk density was higher at 10–20 cm than at 0–10 cm, showing that, regardless of the management system, soil compaction increased with depth. Random factors did not have a strong effect on this property. The trend of a higher BD on NT compared with RT agrees with results from previous researches (Filipovic et al., 2006; Parra et al., 2011; Thomas et al., 2007). Our results suggest that there is a non-significant trend to soil compaction in NT. It may be a consequence of heavy machinery traffic, absence of tillage and a soil biota activity not sufficient to counteract the compaction process. If this increase in soil compaction were a persistent consequence of no-till, and if it were increased over time, this effect would be a critical factor for crop productivity (Díaz-Zorita et al., 2002).

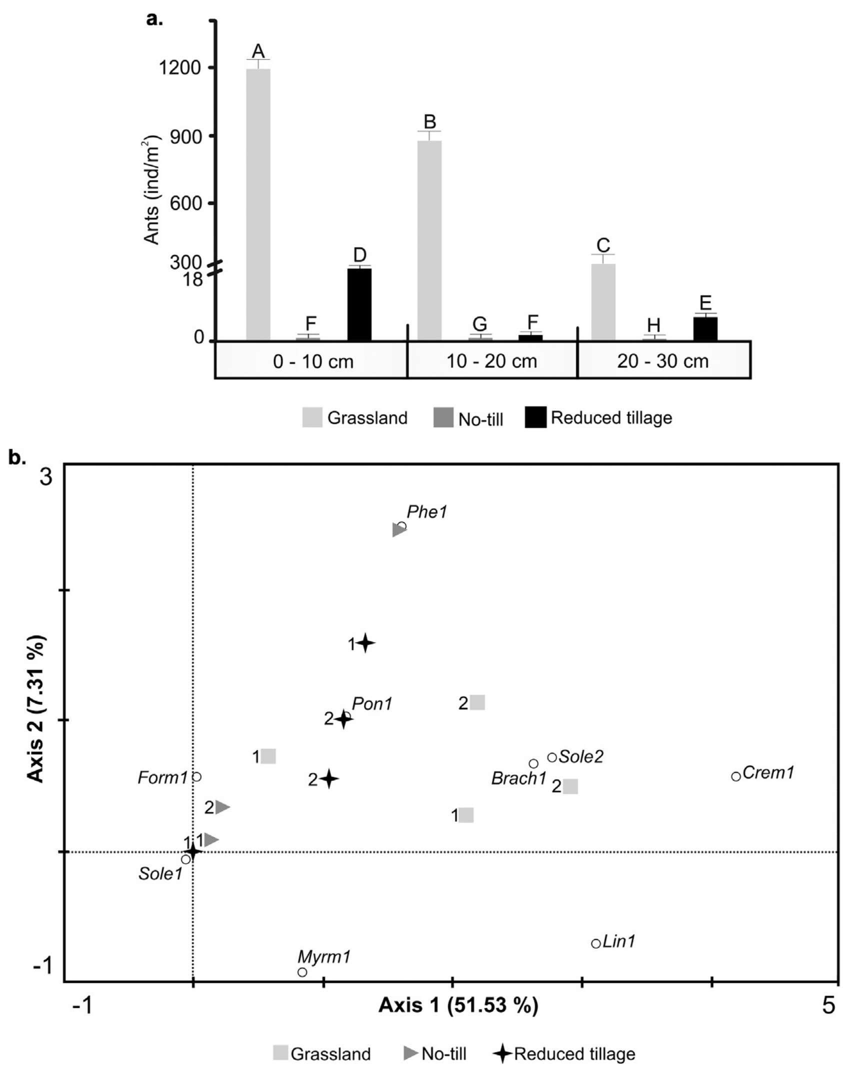

Fig. 2. (a) Ant abundance in the different management systems and soil depths. Different letters indicate significant differences between abundances of the different managements and/or depths. Test DGC p value < 0.05. (b) Ordination of the sites according to the first two axes of the detrended correspondence analysis conducted using the ant species abundance data in 0–10 cm. Number before system label indicates first (1) or second (2) sampling date. Total inertia: 1.176; eigenvalue first axis: 0.606; second axis 0.086. Species code: *Brach1*: *Brachymyrmex* sp. 1; *Crem1*: *Crematogaster* sp. 1; *Form1*: *Formicinae* sp. 1; *Lin1*: *Linepithema* sp. 1; *Myrm1*: *Myrmicinae* sp. 1; *Phe1*: *Pheidole* sp. 1; *Pon1*: *Ponerinae* sp. 1; *Sole1*: *Solenopsis* sp. 1; *Sole2*: *Solenopsis* sp. 2.

3.2. Soil macrofauna community

The impact of the management systems on the abundance of all the high-range taxa (earthworms, ants, beetles, spiders and potworms) significantly varied with soil depth. This is shown by the GLMM, where the interaction between the management system and the soil depth was statistically significant for all the groups (Table 3).

3.2.1. Earthworms

Both farming systems had a strong negative effect on earthworm abundance for all depths compared to the GR (Fig. 1). There was a trend to higher abundance in NT compared to RT, but differences were not significant. This trend agrees with previous findings where mechanical tillage is one of the main management practices that negatively affects earthworms (Chan, 2001; Kladivko et al., 1997). Chlorpyrifos use in RT (700 g a.i.ha^{-1}) is likely to explain the low earthworm abundance. Indeed, a similar dose (600 g a.i.ha^{-1}) has been previously demonstrated as causing a negative effect on earthworm abundance (De Silva et al., 2010).

The provision of soil ecosystem services is sustained by chemical, physical and biological processes in which earthworms (as ecosystem engineers) have a main role (Lavelle et al., 2006). Some of those processes in which they directly partake or indirectly mediate are the comminution and incorporation of litter into soil, the building and maintenance of structural porosity and aggregation in soils through burrowing, casting and nesting activities, the control of microbial communities and activities, plant protection against some pests and diseases, and acceleration of plant succession (Lavelle et al., 2006). Therefore, the likely consequences on the soil functioning of the negative impact of NT and RT on earthworms cannot be overlooked. Furthermore, it is possible that soil and crops could be more affected by low earthworm abundance under NT than under RT. Indeed,

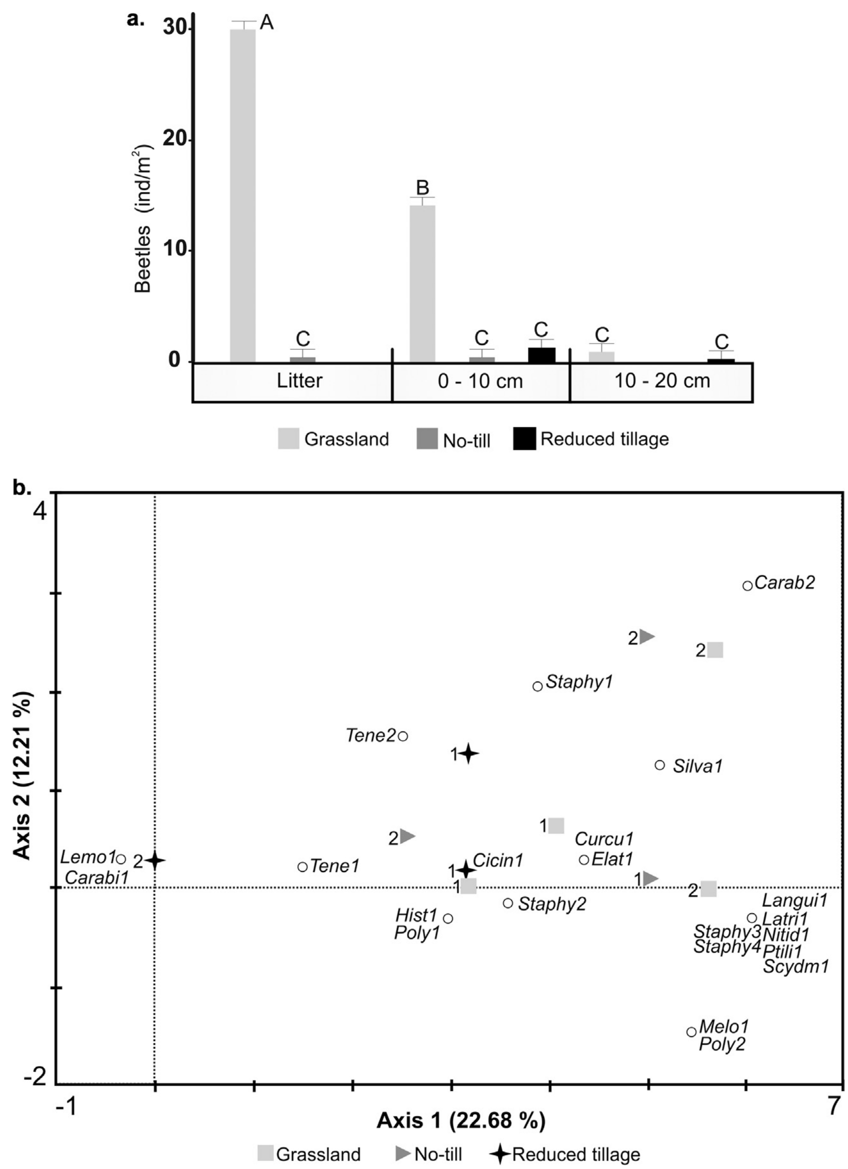

Fig. 3. (a) Beetle abundance in the different management systems and soil depths. Different letters indicate significant differences between abundances of the different managements and/or depths. Test DGC p value < 0.05. (b) Ordination of the sites according to the first two axes of the detrended correspondence analysis conducted using the beetle species abundance data in 0–10 cm. Number before label indicates first (1) or second (2) sampling date. Total inertia: 3.725; eigenvalue first axis: 0.845; second axis: 0.455. Species code: *Carabi*: *Carabidae* sp. 1; *Carab2*: *Carabidae* sp. 2; *Cicin1*: *Cicindelidae* sp. 1; *Curcu1*: *Curculionidae* sp. 1; *Elat1*: *Elateridae* sp. 1; *Hist1*: *Histeridae* sp. 1; *Langui1*: *Languidae* sp. 1; *Latri1*: *Latridiinae* sp. 1; *Lemo1*: *Lemodinae* sp. 1; *Melo1*: *Meloidae* sp. 1; *Nitid1*: *Nitidulidae* sp. 1; *Poly1*: *Polyphaga* sp. 1; *Poly2*: *Polyphaga* sp. 2; *Ptili1*: *Ptilidae* sp. 1; *Scydm1*: *Scydmaenidae* sp. 1; *Silva1*: *Silvanidae* sp. 1; *Staphy1*: *Staphylinidae* sp. 1; *Staphy2*: *Staphylinidae* sp. 2; *Staphy3*: *Staphylinidae* sp. 3; *Staphy4*: *Staphylinidae* sp. 4; *Tene1*: *Tenebrionidae* sp. 1; *Tene2*: *Tenebrionidae* sp. 2.

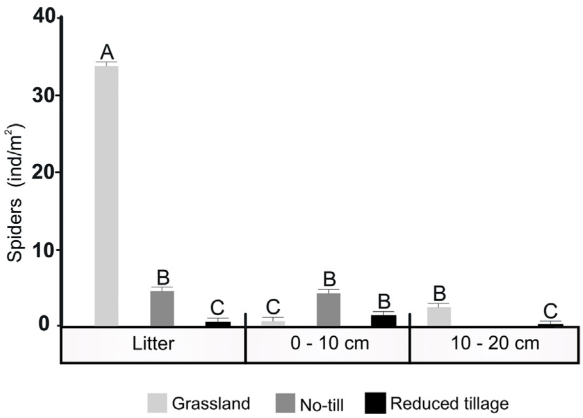

Fig. 4. Spider abundance in the different management systems and soil depths. Different letters indicate significant differences between abundances of the different managements and/or depths. Test DGC p value < 0.05.

mechanical tillage can replace, at least partially, some of the benefits that earthworms provide to soil, such as soil compaction reduction and crop residues incorporation (Hobbs et al., 2008).

Earthworm abundance in GR was significantly higher according to the following depth gradient: 0–10 cm > 20–30 cm > 10–20 cm, whereas earthworm depth distribution in the agricultural systems was very homogenous. Spatial distribution in each field was rather variable, as shown by the high variance due to monolith in the random component of the model (Table 3). Thus, plot scale spatial variations in the soil properties influenced earthworm abundance. However, mean abundances were not modified, since there were no important differences between the fields in each system.

3.2.2. Ants

Mean ant abundance was significantly higher in GR than in both agricultural systems, in all soil depths (Fig. 2a). Abundance ranges in agricultural systems were notably lower than in GR; and higher in RT than in NT. As expected for a gregarious taxon, the monolith random factor was the main source of variance in the random component of the statistical model (Table 3). The species composition of ant community was also different among systems (Fig. 2b). Higher number of species was associated to GR. *Ponerinae* sp. was associated to RT system. This species is probably more resistant to mechanical disturbance and therefore account for the higher ant abundance observed in RT. Negative effects of tillage as well as positive effects of no-till on ants are rather well documented (Lobry de Bruyn, 1999). However, results presented here do not agree with those findings, being more related to those of Aquino et al. (2008) who found similar ant abundance on NT and RT. As already mentioned, some particular traits of *Ponerinae* species may explain our results. Low ant abundance can have negative consequences on soil functioning in both agricultural systems, because of ecosystem engineering role of ants.

3.2.3. Beetles

Beetles are the most diverse and abundant constituent of the litter dwellers functional guild. Their abundances were significantly lower in both farming systems compared to GR at litter and 0–10 cm layer (Fig. 3a). Both systems had a similar negative impact on beetle abundance since no differences between NT and RT were observed. Beetle abundance was higher at shallow depths in GR, whereas in NT and RT it was homogeneously low. Differences in soil habitat among monoliths explained part of the variance in beetle abundance (Table 3), but less than in the case of earthworms and ants. No clear pattern of the fields according to the management systems was observed in the DCA ordination for beetle species (Fig. 3b). No well defined groups of beetle species for each system were found, except for a higher number of species associated to GR1.

Our results agree with previous reports of decreasing beetle abundance caused by farming (Aquino et al., 2008). Differences in the management impact on different taxonomic groups of beetles have also been found (Hatten et al., 2007; Teodorescu and Cogalniceanu, 2005). Low beetle abundance found on both farming systems indicates that NT does not create more suitable conditions than RT for litter and soil beetles. Important ecosystem functions which depend on them may not be accomplished. For example, a negative effect on processes like litter decomposition – by diminution of saprophagous abundance – and also in biological pest control – by diminution of predator abundance – (Lavelle and Spain, 2003; Padmavathy and Poyyamoli, 2011) is expected.

3.2.4. Spiders

Spider abundance was significantly higher in GR than in both farming systems in both the litter and 10–20 cm layer (Fig. 4). The abundance was also significantly higher in NT than in RT in the litter layer and the same trend but not statistically significant, was observed in 0–10 cm. The spatial distribution inside each field partly explained the variance of the random component of the model (Table 3). Lietti et al. (2008) also observed higher spider abundance in NT compared with RT. These results are probably related to the fact that they prefer an architecturally complex environment and more stable soil conditions (Holland, 2004). Moreover, as this group had high mobility and thus high recolonization ability, it may be less affected by agrochemical sprayings. As well as in the case of predator beetles, low abundance in NT but especially in RT, could be related to a lower ability of the whole agroecosystem to achieve biological pest control (Padmavathy and Poyyamoli, 2011).

3.2.5. Potworms

Mean potworm density was significantly higher in RT than in GR and NT in all depths (Fig. 5). In the 10–20 cm depth and 20–30 cm depth there was a trend to higher abundance in NT than in GR but differences were not statistically significant. High potworm abundance in agriculture systems has been observed before (Nowak, 2004); especially when management practices have changed the edaphic environment and caused a diminution of earthworm abundance. Potworms seem to be more resistant than earthworms to that kind of changes, and to have a greater ability to recover quickly from disturbance (Wardle, 1995). On the other hand, they are weak competitors, and thus their competitive elimination from habitats suitable for other detritophages like

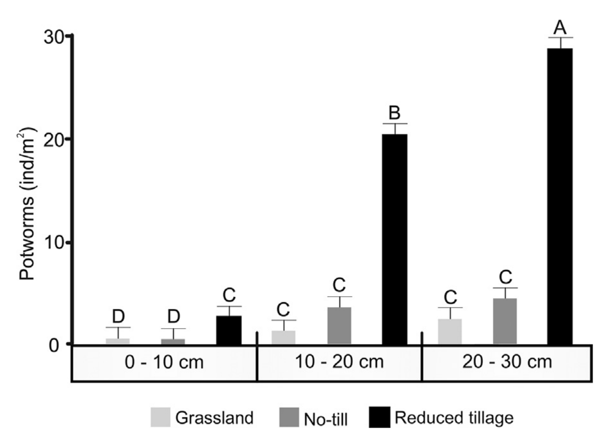

Fig. 5. Potworm abundance in the different management systems and soil depths. Different letters indicate significant differences between abundances of the different managements and/or depths. Test DGC p value < 0.05.

earthworms has been documented (Nowak, 2004) and agree with our observations in GR. Higher abundance in RT than in NT can be explained partly by a lower competition with earthworms (that were less abundant in RT) and partly by an increase in food supply caused by residue incorporation into the soil by tillage (Cochran et al., 1994). Potworms usually feed on slightly to strongly decomposed remains of plants and microorganisms (Didden et al., 1994). Through feeding activity of potworms, the soil assumes a fine-grained crumb structure with stability often higher than that of bulk soil (Jänsch et al., 2005). They also possess a

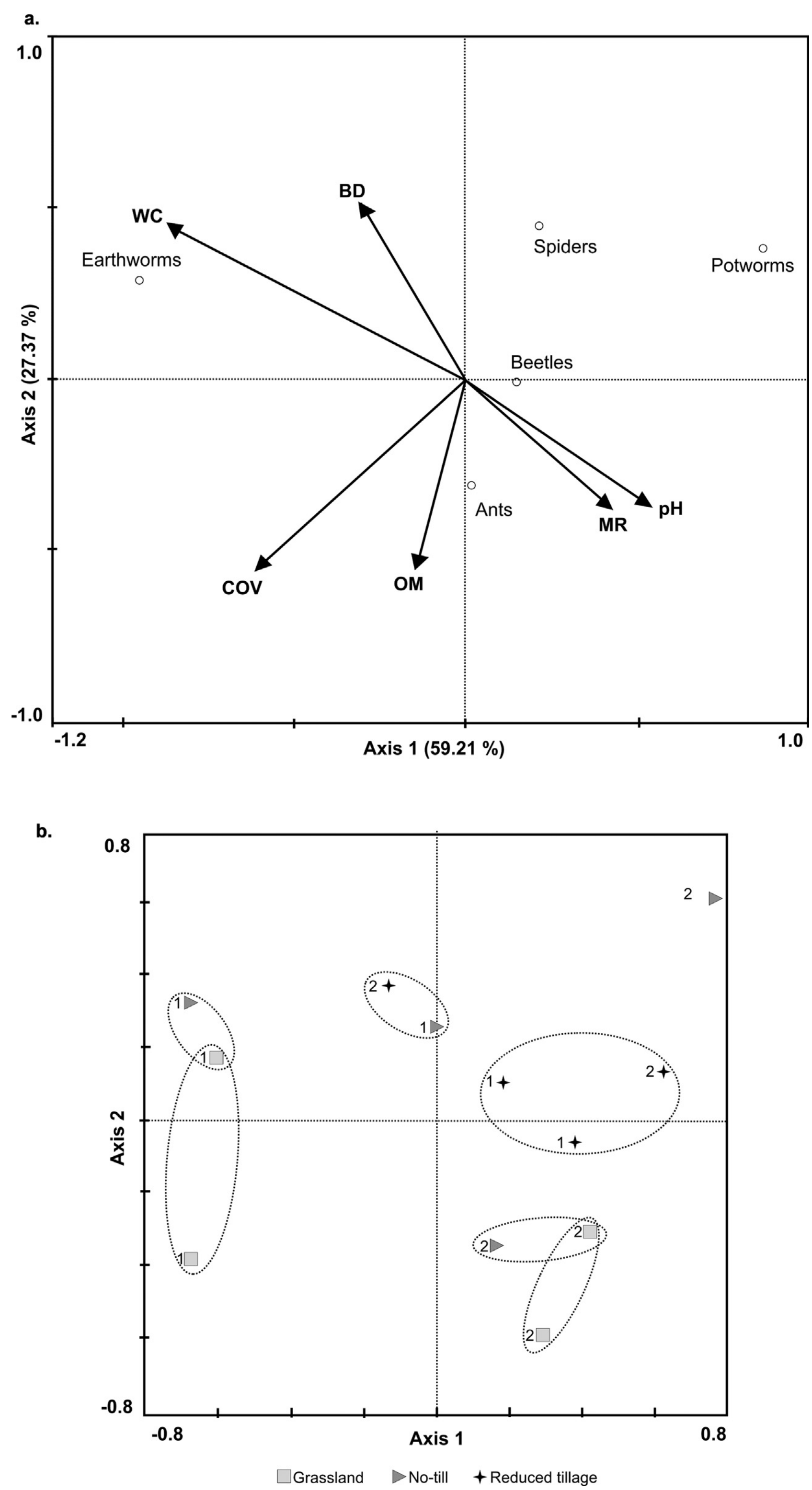

Fig. 6. Canonical correspondence analysis ordination diagram based on soil macrofauna high-range taxa with respect to six environmental variables: soil cover (COV), soil organic matter (OM), moisture (WC), pH, bulk density (BD) and mechanical resistance (MR) at 0–10 cm depth in two sampling times. (a) Ordination of environmental variables and macrofauna. (b) Ordination of sites (number before label indicates first (1) or second (2) sampling date). Environmental variables are represented by arrows and high-range taxa by empty circles. Total inertia: 0.583; cumulative percentage variance explained by both axes = 86.58%; eigenvalues first axis = 0.225, second axis = 0.104.

certain digging ability (small compared with most earthworms) and thus may improve the small-scale water and air management of the soil (Jänsch et al., 2005). The high abundance found in NT and RT may play a key role in processes such as decomposition of organic matter and nutrient cycling in cropped soils.

3.3. Relations between macrofauna and environmental properties

Comparisons between NT and other management systems showing NT benefits have been often conducted at shallow soil depths, usually until 5 or 10 cm. So, for a better result comparison, we have separately analysed the relationship between soil properties and macrofauna for both the 0–10 cm depth and the total soil depth considered in this study.

In the first 10 cm of soil (Fig. 6) the eigenvalues of axes 1 (0.225) and 2 (0.104) of the canonical correspondence analysis (CCA) explained 86.58% of the variance in the weighted averages. Earthworms had the highest abundance weighed averages at sites with soil moisture content, cover, bulk density – and to a lesser extent organic matter – values higher than their average values (Fig. 6a). These results agree with numerous previous reports which show that soil moisture status is a major limitation to earthworm activities and distribution (Edwards and Bohlen, 1996; Lavelle and Spain, 2003). Furthermore, our results indicate that with water levels near to those observed here, earthworms are more resistant than expected to relatively high bulk density values, despite the proved negative effect of soil compaction on earthworms (Chan, 2001; Edwards and Bohlen, 1996). Unexpectedly, the

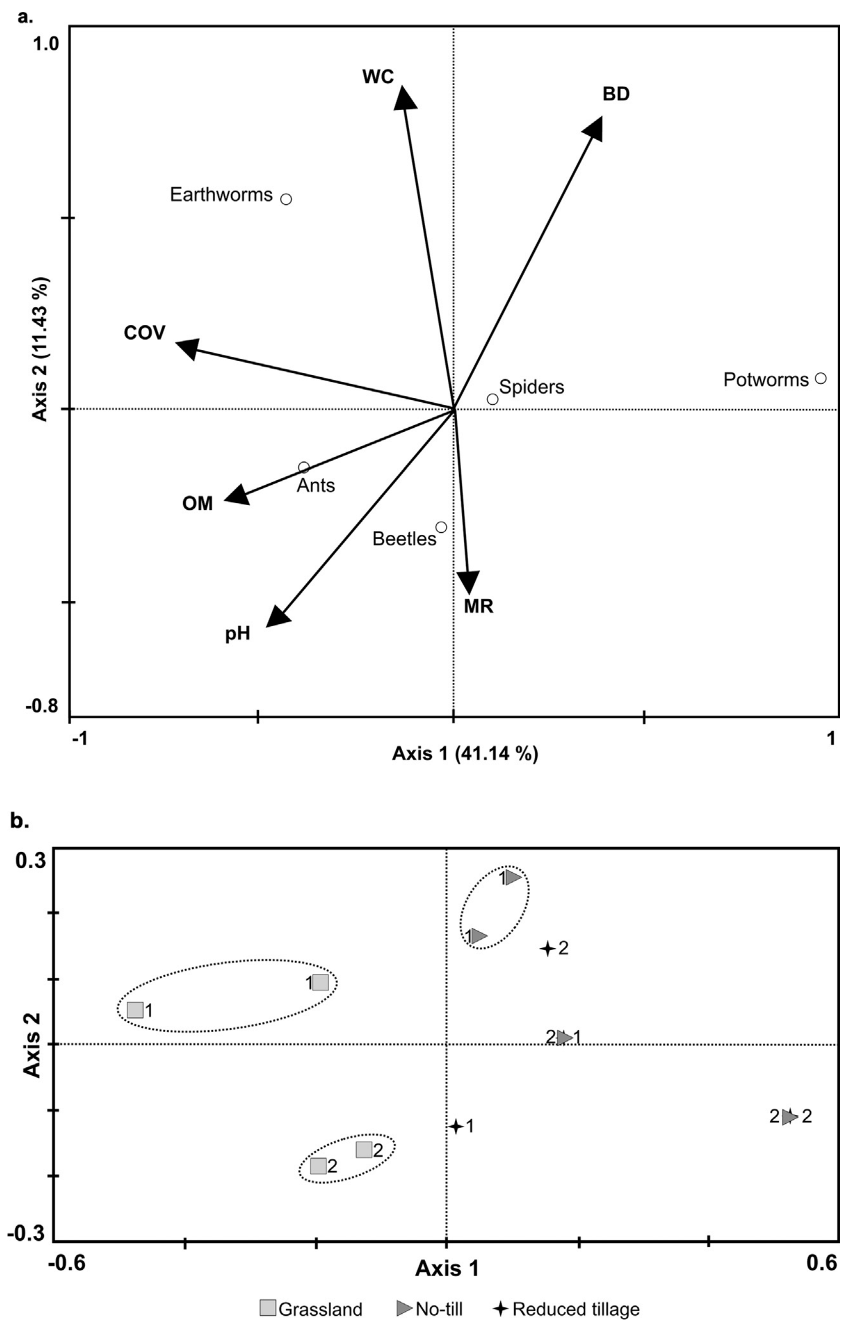

Fig. 7. Canonical correspondence analysis ordination diagram based on soil macrofauna high-range taxa with respect to six environmental variables: soil cover (COV), soil organic matter (OM), moisture (WC), pH, bulk density (BD) and mechanical resistance (MR) at 0–30 cm depth in two sampling times. (a) Ordination of environmental variables and macrofauna. (b) Ordination of sites (number before label indicates first (1) or second (2) sampling date). Environmental variables are represented by arrows and high-range taxa by empty circles. Total inertia: 0.175; cumulative percentage variance explained by both axes = 85.98%; eigenvalues first axis = 0.072, second axis = 0.020.

relation between earthworm abundance and organic matter was less pronounced in spite of the fact that SOM has been widely recognized in development and maintenance of earthworm communities (Ayuke et al., 2011; Edwards and Bohlen, 1996). As the effect of SOM is different for different species (Li et al., 2009) predominant species here may be less sensitive to lower SOM values, at least in the common ranges of the region.

Ants had the highest abundance weighed averages at sites with soil cover, organic matter, mechanical resistance and pH values higher than the average. There is previous evidence that ant communities are enhanced by high SOM and soil cover (Ali et al., 1986; Lobry de Bruyn, 1999). However, Jacquemin et al. (2012) found that chemical and physical soil quality weakly explained ant diversity and distribution. They also emphasize the scarce available information about subterranean ant response to soil physical and chemical properties. That effect is also likely highly species-specific, since ants select microhabitats with specific physical and chemical conditions according to the species preferences and life strategies (Johnson, 2000).

Beetle abundance was higher at sites with values of the soil physical and chemical attributes near to the average; therefore no clear relation between beetles and soil quality can be stressed. This can reflect the diversity of life history strategies inside this taxon.

Spiders and potworms had the highest abundance at sites with soil physical and chemical properties markedly different to the sites at which the other taxa were more abundant. Potworms adaptation to soils with low chemical and physical quality has been suggested as a consequence of their weak ability to compete. This strategy allows them to have high abundance in soils where their detritivorous competitors are negatively affected (Nowak, 2004).

Soil moisture content and bulk density showed a positive correlation, this was likely related to good moisture conservation in no-till where high compaction was also found, as indicated by BD. As expected, soil cover and SOM were positively correlated.

In Fig. 6b, the ordination diagram of sites, which are plotted in base of linear combinations of environmental variables (ter Braak and Verdonschot, 1995), is presented. This diagram allows us to analyse if sites from different management systems are separated and thus differ in their macrofauna composition, based in high-range taxa. An important effect of sampling time was observed, and this overshadows to some extent the effect of the management system on the ordination diagram. To a certain extent, the relation between macrofaunal high-range taxa and soil physical and chemical attributes at 0–10 cm depth is highly influenced by the temporal factor, which can overshadow the management system effect. Although it was possible to observe that both GR and the NT1 had in the first sampling time high earthworm abundance, while in the second sampling time there was high ant abundance. On the other hand, NT2 and both RT in both sampling times had low abundance of both ecosystem engineers.

The same analysis but considering a depth of 0–30 cm of soil, showed a rather different pattern (Fig. 7). The eigenvalues of axes 1 (0.072) and 2 (0.020) of the CCA explained 85.98% of the variance in the weighted averages. Mean abundance of earthworms and ants were associated to soils with good chemical and physical quality. That is, soils with high cover, organic matter and pH values and in the case of earthworms also soils with higher moisture content (Fig. 7a). On the other hand, spiders and chiefly potworms had higher abundance in soils with opposite characteristics than previous ones. Unlike at 0–10 cm depth, the relationship between biological and environmental properties here was related to site ordination explained by management system (Fig. 7b). Therefore, in the whole depth the effect of the management system clearly prevailed on the site ordination, and the effect of sampling time was notoriously lower. Although there were differences in the community according to sampling times, with a predominance of earthworms in the first sampling year and beetles and ants in the second, grassland was related to a better soil physical and chemical quality together with higher abundance of the main macrofauna taxa. Moreover, NT and RT sites were not ordered separately from one another and they shared low earthworm and ant abundance but high potworms abundance.

4. Conclusions

Soil quality declined in both NT and RT compared to GR. Moreover, soil quality deterioration was similar in both management systems: from the assessed soil quality parameters only soil moisture content and spider abundance were favoured in NT compared to RT. The negative impact of agriculture on soil physical and chemical attributes is suggested to explain the observed changes in soil macrofauna compared to GR. Earthworms, ants and beetles showed a great decrease in their abundances in both agricultural systems compared to GR. As they are key organisms in soil ecosystem functioning, the question whether studied soils maintain their capability to achieve ecosystem functions arises.

We conclude that NT, in the way that is applied by most farmers of the study region, does not constitute a more suitable system for soil macrofauna than those with low tillage input. NT is more dependent on soil fauna activity than tilled systems, because crop residue incorporation and soil porosity generation rely only on soil biota activity. Consequences in long term soil quality and also in crop yields would be expected. The compacting effect as a consequence of heavy machinery traffic, the increase of soil erosion when cover crops are not used, and the increase in agrochemical use may be factors related to soil quality decline in NT. Further research on these issues is needed.

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