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Assessment of soil biological degradation using mesofauna

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ABSTRACT

The aim of this work was to assess soil degradation by means of simple and relatively easy to measure biological indicators derived from mesofauna, and to provide criteria to derive threshold values from benchmark sites. We hypothesized (1) that simple biological attributes may be derived from soil mesofauna to be used as soil biological degradation indicators and (2) that this would be best attained by contrasting the deviation of the indicators from natural and managed benchmark sites. The study was conducted on Typic Hapludolls from Córdoba, Argentina. Soil biological degradation was assessed by comparing the deviation of one multivariate and two univariate indicators in intensively managed arable sites from benchmark sites. Three bioindicators were useful to assess soil biological degradation. Specifically, the OM/PA ([Oribatida + Mesostigmata]/[Prostigmata + Astigmata]) index and the multivariate indicator were effective in discriminating between the benchmark and the intensively managed sites and in distinguishing soil degradation levels among intensively managed sites; this finding confirmed our hypothesis. The indicators analyzed were robust and sensitive not only to tillage but also to a combination of management variables. The combined use of Principal Component Analysis and Minimum Spanning Trees techniques also proved to be an effective tool to evaluate the distance between intensively managed sites and between each intensively managed site and the three benchmarks. The bioindicators proposed are simple and easy to measure, and therefore suitable for assessing soil degradation. Validation of the proposed indicators for other soils, climates and land uses is recommended.

1. Introduction

The Argentine Pampas is a vast plain with over 52 million ha of lands suitable for cattle rearing and cropping (Viglizzo et al., 2001). An agricultural expansion process began in the 1960s with the shift from mixed systems (agriculture and cattle farming) to exclusively agricultural systems (SAGPYA, 2009). The most dramatic technological innovation in Argentine agriculture was the 1996 introduction of genetically modified glyphosate-tolerant soybean (Manuel-Navarrete et al., 2009) associated with no-till farming (SAGPYA, 2009). In the central-southern portion of Córdoba province, Argentina, intensive agricultural activity, specifically corn and soybean cropping, and increasing agrochemical use are rapidly leading to degradation of soil biological, chemical, and physical quality (Becker, 2006; Bedano et al., 2006a).

The use of organisms as indicators of soil quality has a relatively long history (Breure et al., 2005). Two general approaches are currently used to evaluate soil quality: the univariate and the multivariate approaches. The former involves the use of single parameters, called "bioindicators" or "metrics", or preferably the use of a "set of indicators" or a "battery of indicators" integrating different taxa that can be summarized or not in an index. Values of parameters from test sites are compared with those from reference sites. The multivariate approach is analogous to the water quality assessment methods: BEAST (Reynoldson et al., 2000), RIVPACS (Wright, 2000) and AusRivAS (Davies, 2000). In general, the system detects deviations between observed and expected communities of test and reference sites. Expected values are derived by different methods.

Several soil quality indicators including physical, chemical and biological parameters have been proposed (Doran and Parkin, 1994; Karlen et al., 1997). However, little effort has been made to determine threshold values or critical limits for the indicators proposed (Arshad and Martin, 2002). The need for threshold values has been stated for soil biota (Beylich et al., 2010) and specifically for biological indicators (e.g. Lobry de Bruyn, 1997) but has not been addressed practically in any case. The main reason is that threshold definition is one of the most critical steps in bioindication, as it occurs in water quality assessment (Stoddard et al., 2006), which has received much more attention than soil quality assessment. A critical threshold

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is the desirable range of values for a selected indicator that must be maintained to attain normal functioning of the soil system (Arshad and Martin, 2002).

Soil mesofauna is dominated by mites (Acari) and springtails (Collembola), which are among the most abundant and widespread soil arthropods in most soils. Because of their abundance and species richness and their almost ubiquitous presence in soils, mites and springtails have been proposed as soil quality indicators. Parameters range from species to more complex approaches, including all the community information. However, the ratio of data to theory is extremely low (McGeoch, 1998; Breure et al., 2004). Moreover, available bioindicators would not meet the demands of those institutions (mostly government agents) that need to use such indicators in practice (Büchs, 2003).

Consequently, there is a need to provide cost- and time-effective soil quality parameters based on soil fauna to be included in soil quality assessment schemes. The aims of this paper were: (a) to assess soil degradation by means of simple biological attributes derived from soil mesofauna that are relatively easy to measure; and (b) to provide criteria to derive threshold values for each indicator from a benchmark site system. We hypothesized (1) that simple biological attributes may be derived from soil mesofauna to be used as soil biological degradation indicators and (2) that this would be better attained by contrasting the deviation of the indicators from natural and managed benchmark sites.

2. Methods

The study was conducted in La Colacha basin, Córdoba, Argentina (64°39′ and 64°50′W, and 32°54′ and 33°03′S). Soils formed in aeolian sediments and were classified as coarse-loamy, illitic, thermic Typic Hapludoll (Cantú, 1998) following the USDA classification (Soil Survey Staff, 1998). The climate is continental with annual rainfall of 800 mm and mean annual temperature of 16.5 °C.

Soil biological degradation was assessed by comparing the deviation of three indicators in intensively managed arable sites from benchmark sites. The former sites comprised 10 arable sites under different management practices: five no-till (NT) sites, two reduced tillage (RT) sites, and three conventional tillage (CT) sites (Table 1). The intensively managed sites had the same land use history as the benchmarks. All sites were natural grasslands until 60 years before this study. Since about 1950, land tenure was divided and cattle raising and agriculture were introduced in the area (Cantú, 1998). All the sites have the same Soil Series (according to Soil Taxonomy classifications). Slope (1–2%), elevation (640–710 m a.s.l.) and depth to the aquifer (more than 40 m) are also very similar in the four sites.

Three types of benchmarks located within the agroecosystem were selected: natural (NA), cattle-raising (CA), and mixed production system (MI) (cattle raising and agriculture). NA benchmark was represented by two natural grasslands covered with native grasses that had remained undisturbed for at least 50 years before the study. The plant community was dominated by *Stipa* sp. Plant cover was 100% and the litter layer was approximately 1 cm thick. The CA and MI benchmarks represent low input management practices, the most widely used until the introduction of genetically modified soybeans and no-till and the resulting agricultural expansion process. Each one was represented by one site, since there were no replicates available. The CA site had been devoted to cattle raising for 40 years. It was cultivated with alfalfa that had not been ploughed for four years before the study. The MI site was in a maize (*Zea mays* L.) – sunflower (*Helianthus annuus* L.) and pasture (alfalfa) rotation system (Table 1).

All benchmark sites were sampled three times (2000, 2001 and 2004), whereas the 10 intensively managed sites were sampled once in 2004. Samplings were conducted in all sites in early spring, before tillage operations. On each sampling date, six soil samples were taken from each site to extract soil mesofauna. Samples were obtained by means of a soil corer of 10 cm in diameter and 10 cm in depth. Mesofauna was extracted with a Berlese apparatus (Southwood, 1980) for 10 days and stored in 70% alcohol. Mites were sorted into the following suborders: Oribatida, Mesostigmata, Prostigmata, and Astigmata, and counted with a stereomicroscope.

To develop indicators, we used the uni- and the multivariate approaches. In the former approach, two parameters were used as indicators: *Oribatid mite density* and the index (Oribatida + Mesostigmata)/(Prostigmata + Astigmata), hereinafter *OM/PA index*.

Table 1
Land-use history, management practices and soil properties in the benchmark and the intensively managed arable sites at La Colacha basin, Córdoba, Argentina.

Site	Management system	Plot size (ha)	Crop rotations in the last 4–6 years	Tillage equipment	Soil properties			
					Texture	BD	OM	pH
NA 1	Natural grassland	5	–	–	Sandy loam	0.95	6.39	5.66
NA 2	Natural grassland	12	–	–	Sandy loam	0.97	3.39	6.35
CA	Cattle-raising	70	Alfalfa–Alfalfa–Alfalfa–Alfalfa	Not ploughed during last four years	Sandy loam	1.34	3.26	6.38
MI	Mixed system	40	Maize–Sunflower–Alfalfa–Alfalfa–Maize–Maize	Mouldboard plow and chisel plow	Sandy loam	1.16	1.93	6.26
NT1	No-till	44	Wheat–Soybean–Soybean–Soybean	No-till planter	Sandy loam	1.21	2.75	5.80
NT 2	No-till	41	Soybean–Soybean–Soybean–Soybean–Soybean	No-till planter	Sandy loam	1.23	2.46	6.05
NT 3	No-till	27	Maize–Wheat–Soybean–Maize	No-till planter	Sandy loam	1.31	2.53	6.31
NT 4	No-till	44	Soybean–Soybean–Soybean–Soybean	No-till planter	Sandy loam	1.29	1.72	6.40
NT 5	No-till	25	Soybean–Wheat–Soybean–Soybean	No-till planter	Sandy loam	1.31	1.89	6.05
RT1	Reduced tillage	24	Soybean–Soybean–Maize–Maize	Chisel plow and disk harrow	Sandy loam	1.43	1.60	6.31
RT 2	Reduced tillage	15	Soybean–Soybean–Maize–Maize	Chisel plow and disk harrow	Sandy loam	1.25	1.48	6.59
CT1	Conventional tillage	5	Alfalfa–Soybean–Maize–Soybean–Maize	Mouldboard plow, chisel plow and double action disk harrow	Sandy loam	1.40	1.82	6.19
CT 2	Conventional tillage	22	Soybean–Maize–Soybean–Maize–Soybean–Maize	Mouldboard plow, chisel plow and double action disk harrow	Sandy loam	1.41	1.49	6.58
CT 3	Conventional tillage	40	Peanut–Peanut–Peanut–Maize–Sunflower–Maize	Disk plow	Sandy loam	1.31	1.54	6.39

BD, bulk density (g cm^{-3}); OM, organic matter content (%). Bulk density was measured with the core method (Blake and Hartge, 1986); OM was determined by the modified Walkley–Black method (Jackson, 1976) and pH by the potentiometric method, soil–water ratio 1:2.5. OM and pH values are the average of three samples composed of five subsamples each one; BD values are the average of three replicates.

Among mites, oribatids are considered good indicators of soil conditions. The effect of cultivation on oribatid mites has been shown to be negative, since they are particularly vulnerable to disturbances (Behan-Pelletier, 1999; Bedano et al., 2006a). Their vulnerability is due to the generally low metabolic rates, slow development, and low fecundity of oribatid mites, which cannot respond rapidly to access resource flushes caused by pulses of primary productivity (Behan-Pelletier, 1999).

The relative proportion of mite suborders in the soil has been suggested as an indicator in previous works. For example, the Oribatida/Astigmata ratio has been proposed as an indicator in Germany and Argentina (Karg, 1963; Hermosilla and Rubio, 1974). The OM/PA index proposed here is based on the differential response of the four soil mite suborders to agricultural practices (Bedano et al., 2006a), which has been attributed to their contrasting sensitivity to cultivation associated with their life-history traits (Norton, 1994; Skubala, 1995; Behan-Pelletier, 1999).

Three thresholds for each univariate bioindicator were defined by means of the data distribution of each benchmark site. The 25th percentile of the data distribution of the benchmark sites was used to set thresholds. The 25th percentile is a relatively conservative value and reflects the idea that data below that value of benchmark site data distribution should not be used as reference. Biological soil degradation of each intensively managed site can therefore be estimated based on one of the three thresholds proposed. If the index value of an intensively managed site is below a threshold, then the site will be considered biologically degraded.

For the multivariate approach, Principal Component Analysis (PCA) combined with Minimum Spanning Trees (MST) (Gower and Ross, 1969) was used. The variables included in the multivariate analysis were abundance of Oribatida, Mesostigmata, Prostigmata, Astigmata, and Collembola. Collembolans were included in the multivariate bioindicator because they are sensitive to agricultural practices (Neave and Fox, 1998; Fox et al., 1999). Specifically, it has been shown that in the study region their density is reduced by high-input management systems (Bedano et al., 2006b). The abundance data were not transformed before the analysis. Both approaches were statistically analyzed using InfoStat software (Di Rienzo et al., 2009).

3. Results

The parameter Oribatid mite density showed higher values in the NA and CA benchmark sites than in the intensively managed sites (Fig. 1). The mixed production system showed intermediate values, but differences from the intensively managed sites were not clear. All intensively managed sites except two were below the conservative threshold of the 25th percentile of the NA and CA benchmarks, which were similar to each other.

The OM/PA index (Fig. 2) response was more consistent with the land use explanation than the indicator Oribatid mite density. The highest index value was observed in the NA benchmark, followed by CA and MI sites. The OM/PA index in all the intensively managed sites was below the NA threshold and only three sites were above the CA benchmark site. The difference between the NA and CA thresholds is clearer than in the previous indicator.

Both bioindicators were useful to show differences between experimental sites other than the tillage method. No pattern of tillage influence on site assessment was observed. However, in both cases the two reduced tillage sites showed the lowest values. The OM/PA index was better for distinguishing sites with the same tillage method.

The multivariate approach was also useful to discriminate sites according to land use. The plot (Fig. 3) showed an ordination compatible with land use explanation, and differentiated and ordered sites in relation to their distance from the benchmarks. Sites NT4, NT1 and NT2 had the faunal communities that were most different from those of the benchmarks; therefore, in terms of their biological communities they can be assessed as the most degraded sites.

The location of sites in the PCA plot is determined by their values on the first two principal ordination axes. The use of the bidimensional space produces loss of information; hence, the distances between sites on the plane may not correspond with the distances in the original (multivariate) space. This can therefore lead to misinterpretation of the true distances between benchmark and intensively managed sites. The MST technique yields a set of lines that connect all the sites, where the line length represents the dissimilarity between them. Thus, it provides information about the relationships between sites according to the distances in the original space, whose dimension is equal to the number of variables under study. Hence, MST tends to connect closely related sites and can be used to gain understanding of site ordering along a gradient. Our results show that there is not a clear agreement between the bidimensional space arrangement of sites and that in the original distance matrix. NT2 can be assessed as close to the condition of RT1 in terms of bidimensional distance, but the multivariate distance shows a greater distance between them.

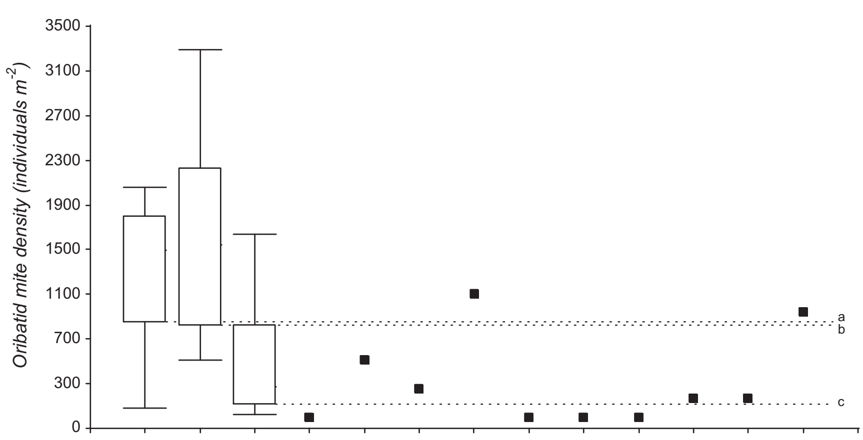

Fig. 1. Indicator Oribatid mite density (individuals m^{-2}) in the natural (NA), cattle-raising (CA) and mixed (MI) benchmark sites and in the intensively managed sites. NT, no-till sites; RT, reduced tillage sites; CT, conventional tillage sites. The boxes indicate the 25th percentile, median, and 75th percentile; whiskers extend from the 5th to the 95th percentile values. a, NA benchmark; b, CA benchmark; c, MI benchmark.

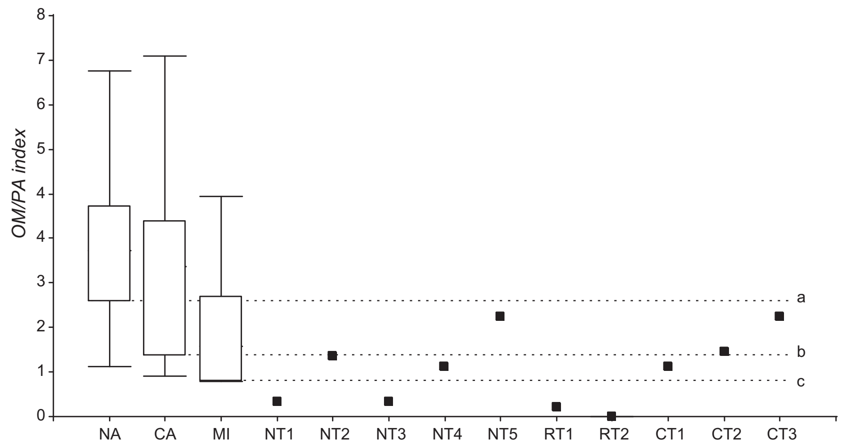

Fig. 2. Indicator (Oribatida + Mesostigmata)/(Prostigmata + Astigmata) index in the natural (NA), cattle-raising (CA) and mixed (MI) benchmark sites and in the intensively managed sites. NT, no-till sites; RT, reduced tillage sites; CT, conventional tillage sites. The boxes indicate the 25th percentile, median, and 75th percentile; whiskers extend from the 5th to the 95th percentile values. a, NA benchmark; b, CA benchmark; c, MI benchmark.

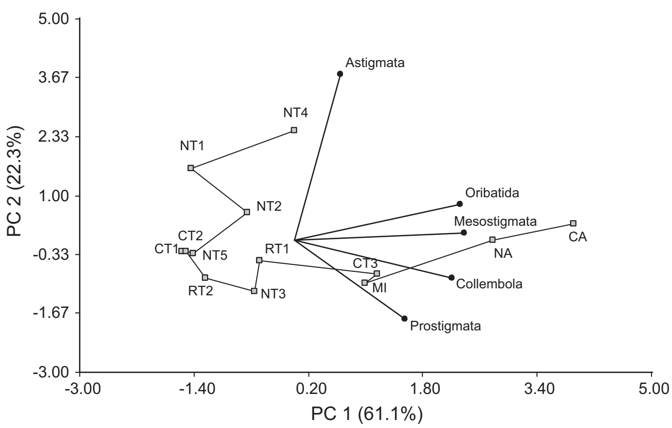

Fig. 3. Principal component analysis combined with minimum spanning trees for soil mesofauna parameters in the natural (NA), cattle-raising (CA) and mixed (MI) benchmark sites and in the intensively managed sites. NT, no-till sites; RT, reduced tillage sites, CT, conventional tillage sites.

4. Discussion

The conceptual–methodological focus of this paper implies that soil conditions in the benchmark sites, where soil functions are best performed, are defined as the goal for soil protection, and are therefore the reference soil conditions. Different intensively managed sites that had the same soil type were assessed by contrasting the deviation from the benchmark sites considering one multivariate and two univariate bioindicators. The greater the distance from the benchmark, the more biologically degraded the site.

The univariate indicator Oribatid mite density and the OM/PA index showed that the intensively managed sites are degraded in relation to the NA and CA benchmarks. This seems rather obvious, but it is the first condition that confers robustness to the system. Values of both indicators were lower for most intensively managed sites than for the three benchmark sites. Among the intensively managed sites, different soil biological degradation levels were observed. In general, both indicators showed that the sites with greatest differences from the benchmark conditions are the two reduced tillage sites and the NT1 site. The OM/PA index performed better than Oribatid mite density indicator. It had the strongest discriminatory power and therefore would be the most reliable in assessing biological condition of intensively managed sites. Because this index integrates the information about four taxa, it is more likely to reflect the diverse responses of soil mesofauna to soil management. It has been suggested that for a biological classification of arable lands, the evaluation of mesofauna species density can determine a poorer separation of sites because density values are less stable than other parameters of the community (Ruf and Beck, 2005; Bedano and Ruf, 2007). This also agrees with observations from aquatic bioindication, where indices generally discriminate better than individual metrics (Barbour et al., 1999).

Threshold definition is a crucial step and a poorly developed aspect in soil biological quality indication. In this paper, we developed a threshold derivation method and propose three different thresholds derived from three benchmark soil conditions, which confirms our hypothesis that thresholds values may be obtained from benchmark sites. Land users or policy makers might select one according to their goals and interests and then assess whether intensively managed sites attain the designated benchmark. The sites that perform below the threshold of the selected benchmark should be considered biologically degraded. However, the benchmarks are specific for a given soil and biological combination – in this case the Argentinean pampas.

It has been suggested that the most promising approach to soil quality indication is analyzing the information of the community as a whole by means of a multivariate statistical procedure (Ruf et al., 2003). In this paper, the multivariate indicator and univariate parameters, specifically the OM/PA index, yielded a similar assessment pattern. The benchmark sites were plotted on one extreme of the gradient, and the intensively managed sites were ordered according to the deviation of their communities from the benchmarks. PCA combined with MST technique is an effective tool for better understanding the relationships between benchmarks and intensively managed sites and among intensively managed sites. One advantage is that using the MST technique the connection of each site with the most similar one, including the benchmarks, is readily visualized in the graph. For the purpose of soil quality indication, this is very useful because an evaluation of each intensively managed site is made, considering the relationship between several intensively managed sites and benchmarks sites at the same time.

The soil degradation assessment provided by the three bioindicators does not fit well with the tillage explanation. For example, sites under the same tillage systems were assessed differently: one was defined as degraded and the other as close to the benchmark. The lack of a strong influence of tillage on assessment results is a robust characteristic of the bioindicator system, because it suggests that parameters respond not only to tillage but also to a combination of all management variables. The OM/PA index and the multivariate indicator showed that the CT3 site exhibits the most similar biological condition to the reference sites of all sites. This can be explained in terms of a combined effect of high rotation rate (four different crops – excluding soybean – in the last 4 years) and less intensive tillage and lower soil compaction than in the other CT sites. Among NT sites, there are some differences between the assessments provided by both indicators. Considering the community as a whole (multivariate indicator) crop rotation seems to have a strong influence, since the three sites assessed as more degraded (NT4, NT1 and NT2) were under soybean monoculture for the last years. The OM/PA index assessment agrees to some extent, but shows lower values in the two RT sites, being therefore more sensitive to tillage than to rotation (both sites have had maize in the last 2 years).

No-till has been recognized as an alternative management strategy with lower environmental impact than other techniques, such as plow tillage. However, our data suggests that this is not true for all the NT sites. Soil biological degradation in NT sites is not lower than in the tilled plots; rather, in some sites it is higher. This can be in part because in most cases no-till system does not include a crop rotation scheme and also does not use cover crops, two management practices that are considered key in the system (Díaz-Zorita et al., 2002; Lal, 2007).

Taxonomic identification of soil invertebrates is considered a bottleneck to the adoption of these organisms in soil monitoring programmes (Gardi et al., 2009). However, it has been demonstrated that the use of higher taxonomic level groups of macro (Nahmani et al., 2006) and mesofauna (Bedano and Ruf, 2010) can provide relevant information on soil status. By means of the approach proposed in the present work the difficulties related to taxonomic classification are overcome since indicators are calculated using high-level taxa. Indicators calculated on the basis of data at a lower taxonomic level are expected to be more sensitive than the indicators proposed in this paper. However lower taxonomic resolution indicators would be more time and resources consuming and would also require more taxonomic expertise. This would make the bioindicator system more unsuitable for application. In our opinion, the indicators proposed in this contribution are appropriate for meeting the intended objective. If the aim is to increase sensitivity in detecting differences among managements, then lower taxonomic resolution indicators should be employed. For example, the effect of experimental manipulation is better demonstrated by using species-level indicators (Bedano and Ruf, 2010).

As we hypothesized, the univariate indicator OM/PA index and the multivariate indicator were effective in discriminating between the benchmark and the intensively managed sites and in distinguishing soil degradation levels among intensively managed sites. One limitation to this approach is the spatial validity of the bioindicators proposed. Consequently, the extent to which these indicators can be extrapolated to other soils, climates and land uses needs to be confirmed. However, adopting the present conceptual–methodological approach, including benchmark sites definitions, threshold derivation and multivariate methods, can be useful in other regions. One advantage in Argentine agroecosystems is that, at least so far, there are natural or semi-natural soils that can be taken as a benchmark. However, with the rapid advance of agriculture in the region there is a need to protect these natural areas for use as permanent plots for long-term soil degradation monitoring.

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