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Multivariate evaluation by quality indicators of no-tillage system in Argiudolls of rolling pampa (Argentina)

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Abstract The purpose of this study was to develop operationally important soil quality indicators to evaluate long-term sustainability, at the farm scale, for no-tillage systems in Argiudolls of rolling pampa (Argentina). The soil was classified as series Arroyo Dulce (Typic Argiudoll), a fertile dark, deep and well-drained soil of the hills. Three situations were considered: pristine soil with grass vegetation, grassland soil (also considered as a reference situation); and 15 years no-tillage soils from four production plots. Physical, physico-chemical, chemical and biochemical indicators were considered. Data were analyzed by principal components analysis (PCA) with canonical discriminant analysis (CDA). The first three components explained 90% of the overall variation. For pristine undisturbed soil, the main variables selected by PCA were particulate C, pH, respiration and total organic C, and in the case of grassland they were C stock (mass of C in the 0–10 cm soil horizon), water-soluble C, and % silt. The no-tillage area was separated in different plots according to the degree of erosion with different depths of the A horizon. Clay content and bulk density were the main variables in the less degraded no tillage plots. Cluster analysis was applied to construct an average linkage distance dendrogram.

Keywords Soil quality · Indicators · No tillage

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Introduction

Traditionally, the quality of a soil has been solely associated with its productivity, and only recently, soil quality has been defined in terms of sustainability (Trasar-Cepeda et al. 1998). As soil quality concerns the functioning of a complex system, its assessment requires the measurement of many biological, chemical and physical parameters of soil. It is obvious that it is not possible to measure everything and a selection is needed. Multivariate statistical approaches may be a first step toward soil quality assessment. They provide an objective mean to extract and weight information and to identify relevant parameters (Wander and Bollero 1999). Principal component analysis was used by Schipper and Sparling (2000) to identify and group different land-use situations.

Quantitative estimates of soil quality in areas with contrasting agricultural management regimes are generally based on properties such as C, N and P content (Ellert and Bettany 1995). Other soil quality indicators have stable characteristics, e.g., mineralogical composition and texture (Gregorich et al. 1994), whereas others respond rapidly to changing environmental conditions, e.g., biological indicators (Wardle and Ghani 1995). Bending et al. (2004) suggested that a variety of biochemical and microbial analyses should be used when considering the impact of management on soil quality.

Soils in humid regimes are more sensitive to degradation from repeated tillage due to erosion and loss of soil organic matter, so agricultural management has moved towards the use of conservation-based forms of tillage and residue management. It is well known that no-till practices increase soil organic matter content in the surface layer, improve soil aggregation, and preserve the soil resources better than conventional till practices (Yang and Kay 2001). Under no-tillage conditions, it was also observed that the rate of macroaggregate formation and degradation leads to a formation of stable microaggregates in which C is stabilized and sequestered in the long term (Six et al. 2000). No tillage thus represents a soil C sequestering practice with a reduction in CO_2 emissions from soil. (Sperow et al. 2003).

The effect of soil no tillage systems on soil biochemical and microbiological practices has been studied by monitoring the following: respiratory activity (Buchanan and King 1992); ammonifiers, nitrifiers, cellulolytic and total microflora, protease and urease activities (Palma et al. 2000); humic fractions, CO_2 evolution and arginine ammonification (Gonzalez et al. 2003); changes in C and N fractions (Doyle et al. 2004); soil microbial biomass C and N, and composition of soil microbial communities by phospholipids fatty acid contents (Feng et al. 2003; Spedding et al. 2004).

The purpose of this study was to develop operationally important soil quality indicators, which can be used to evaluate long-term sustainability, at the farm scale, for no tillage systems in Argiudolls of rolling pampa (Argentina). We used multivariate statistical methods to separate relevant factors.

Materials and methods

The study was conducted on an agriculture–cattle field (latitude 34°01′S, longitude 60°20′W) in Arrecifes, Buenos Aires province, Argentina. It is a representative field of rolling pampa soils with typical management practices for this region. A decision was made to compare 15 years no-tillage production plots with reference situations.

The soil, classified as series Arroyo Dulce (Typic Argiudoll), is a dark, deep and well-drained soil of the hills, with good fertility conditions. Sampling was performed in May 2004. Each plot had a representative area with uniform management of 0.5 ha and each area was divided into three sub-areas (20×80 m). Three soil cores were sampled from each 0- to 10-cm soil layer. Cores from each sub-area were pooled and sieved (less than 2 mm) and kept at 4°C prior to microbiological analysis (for chemical and physical analysis, samples were kept at room temperature).

Three different situations were considered: (1) pristine undisturbed soil, with grass vegetation; (2) grassland, also considered as a reference situation, a degraded pasture planted in 1998, with dominance of *Festuca arundinacea* and *Paspalum dilatatum*; (3) No-tillage situation since 1990. The no-tillage area included different situations according to the degree of erosion. These situations were classified as: (1) plot 30 with an A horizon of 25 cm; (2) plot 33 with an A horizon of 23 cm indicating a low erosion; (3) and (4) corresponding to plots 42 and 45 with 19 and 6 cm of A horizon, respectively, both with higher erosion.

Soil dry bulk density was determined using the core method and considering the 0- to 10-cm soil layer (Lahlou 1999). Particle size analysis was carried out using the sedimentation procedure as approached by Bouyoucus (1927). Structural stability was determined by sieving moist soil through an 8-mm sieve and gently breaking; then soil was air-dried and sieved so as to obtain the 4.76-, 3.36- and 2.00-mm aggregate fractions (De Leenheer and de Boodt 1958). This sieving was done with a mechanical shaker at 1,440 vibrations min^{-1} for 5 min. These fractions were then wetted until holding capacity, incubated for 24 h, and wet-sieved through a set of sieves with 4.76-, 3.36-, 2.00-, 1.00-, 0.50- and 0.30-mm openings. Sieving frequency was 35 oscillations min^{-1} during 5 min. Then, each fraction was dried at 50°C for 24 h. The sum of products between the weights of each aggregate fraction and the mean diameter of the fraction is called the mean weight diameter (MWD). The change in MWD from dry sieving to wet sieving is a number inversely related to soil aggregate stability.

Soil pH was measured in a 1:2.5 soil/distilled water suspension using a pre-calibrated glass electrode (Thomas 1996); electrical conductivity of saturated soil paste was determined as reported by Rhoades (1996).

Extractable P was determined as reported by Bray and Kurtz (1945). Soil samples were shaken with 10 ml of 0.03 N NH_4F–0.025 N HCl extracting solution for 5 min at 100 oscillations min^{-1}. Then the soil suspension was filtered and the filtrate (1 ml) was treated with 8 ml of ascorbic acid molybdate solution and the optical density read at 650 nm.

The organic C content of soil was evaluated using the wet oxidation method of Walkley and Black (Nelson and Sommers 1982). Particulate C was measured using the method described by Cambardella and Elliot (1992), which involves the dispersion of soil in sodium hexametaphosphate (5 g l^{-1}) and the successive sieving of the soil suspension through a 53-μm sieve to isolate the particulate organic matter fraction. Water-soluble C (Mazzarino et al. 1993) was obtained by stirring samples of soil with distilled water (solid phase/solution 1:50) for 24 h at room temperature. The suspension was centrifuged at 19,500 × *g* for 10 min and the supernatant passed through a 0.4-μm glass fiber container under vacuum. Particulate and water-soluble C were determined by the dichromate oxidation titration technique of Walkley and Black as previously noted. Stock C was calculated by total C content and bulk density and expressed in mg C ha^{-1} (Ellert and Bettany 1995).

Respiration was measured as proposed by Jenkinson and Powlson (1976), by incubating soil samples (30 g) for 7 days with NaOH 1 N. Then $BaCl_2$ solution was added to precipitate CO_3^{2-} and the residual NaOH was titrated with 0.5 N HCl.

A multivariate analysis of variance (MANOVA) was first performed in order to detect differences among the considered situations. Next, a principal component analysis (PCA) including canonical discriminant analysis (CDA) was carried out to construct new variables that allowed reduction of the dimension of the data and to determine which of the original variables were mainly responsible for the mean differences between management situations. Finally, a joining tree clustering was performed to determine the relative multivariate distance among groups. Data were processed using the Infostat statistics program (2002).

Results and discussion

Means and standard deviations for all the studied variables for each group are shown in Table 1. Clay, structural sta-

Table 1 Means and standard deviations of measured variables

	CLAY	SAND	SILT	MWD	BD	pH	EC	PBRAY	CT	CSOL	CPART	CSTOCK	RESP
Means													
UND	26.67	15.00	58.33	91.22	1.06	6.21	0.61	20.99	2.22	173.10	1.10	23.76	0.35
GRASS	27.50	11.67	60.83	96.26	1.28	6.60	0.66	7.87	1.89	217.43	0.68	24.26	0.34
NT 30	35.00	8.33	56.67	130.43	1.33	5.57	0.48	15.28	1.71	153.60	0.67	22.90	0.18
NT 33	33.33	9.17	57.50	109.81	1.32	5.73	0.45	8.60	1.58	154.10	0.39	20.96	0.02
NT 42	33.33	17.50	49.17	139.39	1.34	6.11	0.46	21.49	1.58	114.60	0.67	21.17	0.08
NT 45	30.83	13.33	55.83	208.86	1.31	5.97	0.41	22.43	1.38	110.10	0.32	18.30	0.16
Standard deviations													
UND	2.89	4.33	6.29	5.49	0.06	0.04	0.10	4.79	0.33	11.63	0.42	4.96	0.05
GRASS	0.00	1.44	1.44	15.32	0.03	1.08	0.49	4.32	0.47	33.53	0.34	6.39	0.10
NT 30	2.50	3.82	5.77	19.99	0.09	0.35	0.18	7.69	0.27	17.20	0.22	4.96	0.10
NT 33	1.44	1.44	0.00	20.85	0.09	0.21	0.08	6.58	0.15	29.00	0.26	3.42	0.01
NT 42	3.82	5.00	5.20	75.33	0.07	0.58	0.05	13.10	0.37	14.47	0.44	4.46	0.03
NT 45	3.82	2.89	1.44	65.81	0.18	0.09	0.12	8.36	0.23	11.30	0.15	4.66	0.04

CLAY, SAND and SILT are expressed as g per 100 g of dry weight soil

MWD Mean weight diameter (mm), *BD* bulk density (g cm^{-3} dry weight soil), *EC* electrical conductivity (mmhos cm^{-1}), *PBRAY* extractable P (μg g^{-1} dry weight soil), *CT* total organic C content (g per 100 g dry weight soil), *CSOL* soluble C (μg g^{-1} dry weight soil), *CPART* particulate C (g per 100 g dry weight soil), *CSTOCK* stock C (mg C ha^{-1} soil), *RESP* soil respiration (μg CO_2 per g dry weight soil per hour), *UND* undisturbed soil, *GRASS* grassland soil, *NT 30* no tillage plot 30, *NT 33* no tillage plot 33, *NT 42* no tillage plot 42, *NT 45* no tillage plot 45

bility and bulk density increased from the undisturbed and grassland situation to the no-tillage situations, while sand, silt, pH, electrical conductivity, and all the C variables (total organic C, water-soluble C and particulate C), soil stock C and respiration decreased.

In order to assess the sensitivity of different variables to agriculture effects, pH, total organic C content, bulk density, extractable P content and respiration mean values of no tillage, undisturbed and grassland systems were compared. Both total organic C content and respiration were more sensitive than bulk density and pH, for separating the no tillage from the other two situations (Fig. 1). Soil cultivation is known to decrease soil organic matter content, soil pH and nutrient content, whereas variables such as extractable P may depend on fertilization history (Zubillaga and Giuffré 1999).

Multivariate analysis of variance showed that there were significant differences between the six groups mean vectors (Pillai–Bartlett trace, $p<0.0030$). In Fig. 2, grassland and undisturbed situations were linked together, whereas all no-tillage situations could be grouped differently into two subgroups, according to unweighted pair group method using an arithmetic average (UPGMA) rule for Euclidean distances in cluster analysis. The two subgroups have an approximate linkage distance of 1.10, ranked according to the degradation of the plots, whereas the linkage distance of both undisturbed and grassland from the no-tillage soil is 1.70. Analysis was carried out using all variables.

The main variables selected by PCA were particulate C, pH, respiration and total organic C for the undisturbed soil, whereas electrical conductivity, stock C, water-soluble C, and silt were selected for the grassland situation (Fig. 3).

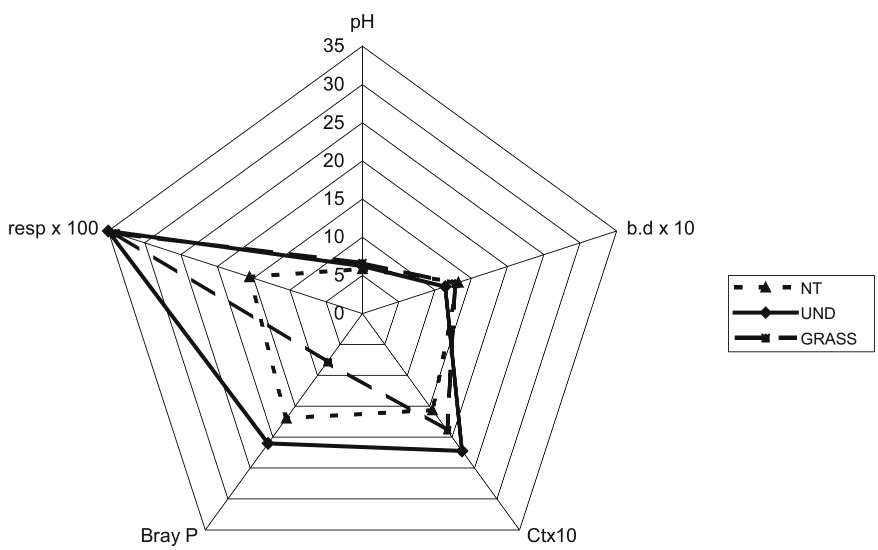

Fig. 1 Mean values of extractable P (Bray P), pH, soil respiration × 100 (resp × 100), total organic C content × 10 (Ctx10) and bulk density × 10 (b.d. × 10) in no tillage plots (NT), pristine soil (UND) and grassland soil (GRASS) situations

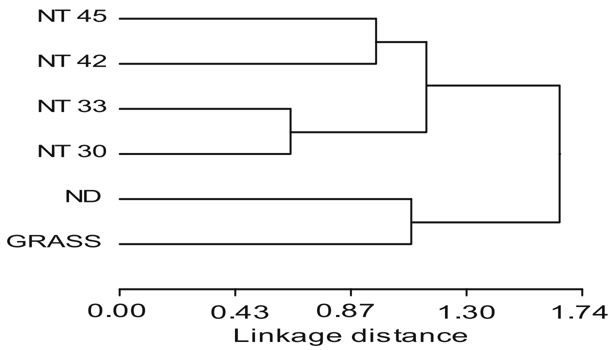

Fig. 2 Euclidean distances for undisturbed soil (UND), grassland soil (GRASS), no tillage plot 30 (NT 30), no tillage plot 33 (NT 33), no tillage plot 42 (NT 42) and no tillage plot 45 (NT)

The no-tillage plots were separated from the control situations, being structure (estimated as MWD), the main variable for no-tillage 42 and 45 plots, and clay and bulk density, the main variables for no tillage 30 and 33 plots. Thus soil structure stability can be a sensitive indicator, related to infiltration and water holding capacity, porosity, bulk density and resistance to root penetration, and here physical degradation can be related to soil compaction. Schipper and Sparling (2000) also found lower organic C content and respiration, and increased bulk density in cropped soils.

The first three canonical variables (c.v.) explained 90% of the total variation (Table 2). The first c.v. explained 57% of the overall variance and mainly comprised positive values of electrical conductivity, total organic C, water-soluble C, stock C, and respiration values, confirming the trend of Table 1, with the undisturbed and grassland situations showing the highest values of these variables. The second c.v., explained 22% of the variance and the main components were high and positive values of sand and extractable P, which separated no-tillage 30 and 33 plots from

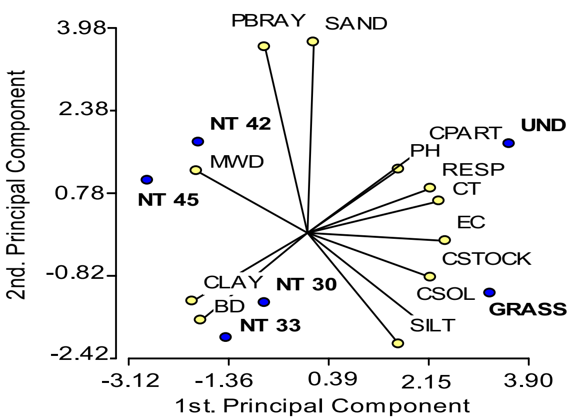

Fig. 3 Bi-Plot of principal components. Extractable P (PBRAY), pH (PH), electrical conductivity (EC), soil respiration (RESP), total organic C content (CT), soluble C (CSOL), particulate C (CPART), stock C (CSTOCK), bulk density (BD), mean weight diameter (MWD), % silt (SILT), % sand (SAND), and % clay (CLAY) in undisturbed soil (UND), grassland soil (GRASS), no tillage plot 30 (NT 30), no tillage plot 33 (NT 33), no tillage plot 42 (NT 42) and no tillage plot 45 (NT 45)

Table 2 Eigenvectors corresponding to the first three principal components (PC) including proportion of variance explained and eigenvalues of measured variables

Variable	PC		
	First	Second	Third
CLAY	−0.29	−0.19	−0.40
SAND	+0.02	+0.54	+0.05
SILT	+0.24	−0.31	+0.30
MWD	−0.28	+0.18	+0.37
BD	−0.27	−0.25	+0.10
pH	+0.24	+0.18	+0.46
EC	+0.36	−0.02	+0.08
PBRAY	−0.11	+0.53	−0.10
COX	+0.34	+0.09	−0.26
CSOL	+0.32	−0.27	+0.10
CPART	+0.29	+0.23	−0.41
CSTOCK	+0.32	−0.13	−0.30
RESP	+0.32	+0.13	+0.19
Eigenvalue	7.46	2.90	1.31
Cumulative proportion	57%	80%	90%

CLAY, SAND and SILT are expressed as g per 100 g dry weight soil
MWD Mean weight diameter (mm), *BD* bulk density (g cm^{-3} dry weight soil), *EC* electrical conductivity (mmhos cm^{-1}), *PBRAY* extractable P (μg g^{-1} dry weight soil), *CT* total organic C content (g per 100 g dry weight soil), *CSOL* soluble C (μg g^{-1} dry weight soil), *CPART* particulate C (g per 100 g dry weight soil), *CSTOCK* stock C (mg C ha^{-1} soil), *RESP* soil respiration (μg CO_2 per g dry weight soil per hour)

no-tillage 40 and 42 plots, thus confirming the trend of Table 1. The third c.v. explained 10% of the variance and the principal variables were clay, pH and particulate C. The incidence of C variables in the first (and most important) c. v. supports the importance of organic C content for soil quality.

Changes brought about by cultivation of pristine soil and grassland were evident in this study. Statistical analysis clearly distinguished no-tillage from pristine and grassland plots, associated to chemical and biochemical variables. It also separated no-tillage plots, associated with intrinsic physical properties such as structure stability, from degraded plots, where lower organic matter has a direct influence on soil structure. On the other hand, clay content and bulk density appeared to be the main variables in less-degraded no-tillage plots, where structure stability does not appear to be a limiting factor.

This study also provides evidence of microbial response to management practices, and biochemical and molecular tools can be relevant in the assessment of microbial functioning, which is sensitive to management and may also provide information on the status and activity of the microbial communities as well as the resilience of the microbial communities to stress (Bending et al. 2004). However, some of these parameters can be expensive.

For the selected scale of study (field), economical and practical issues must be taken into consideration to allow farmers to make their own observations between monitoring periods. Relative value of the indicators will also depend on their feasibility to provide sensitive information along a time scale and to provide suitable information on sustainability trends.

In conclusion, the indicators used in this experiment were simple and sensitive for the purpose of differentiating no-tillage systems from pristine and grassland soils. Physical indicators were shown to be sensitive in distinguishing no-tillage situations; chemical indicators (e.g., C fractions) and biochemical indicators (e.g., respiration) were relevant factors in distinguishing pristine and grassland from cultivated plots. Moreover, multivariate analysis was a very useful tool in identifying plot-associated variables.

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