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Morpho-structural evaluation of various soils subjected to different use intensity under no-tillage

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ABSTRACT

According to many evidences, in Argentina, no-tillage (NT) coupled with soybean monoculture leads to adverse soil structure features. While some farmers have simplified the production system through soybean monoculture others have intensified the land-use by increasing the number and diversity in the crop sequence. The effects of this intensification, in terms of soil structural quality, are contradictory, possibly caused by the increase of machinery traffic. In order to assess soil structural quality and the performance of selected morpho-structural variables with different levels of intensification, we analyzed plots under NT with high and low crop sequence intensification (Good –GAP- and Poor –PAP-, agricultural practices respectively) and reference plots in four soils (two Argiudolls, an Haplustoll and an Hapludert) of the Argentinian Pampean region. The morpho-structural variables assessed were Visual Evaluation of Soil Structure at field scale (VESS), visible porosity (Vp), roundness (Rd), eccentricity (Ecc) and 3-D aggregate features (faces, corners and edges). Plots with higher frequency of cereals in the sequence (GAP) presented on average higher VESS scores, higher Vp values and less rounded aggregates with more faces and corners, suggesting that crop sequence intensification induces favorable structural features. VESS, Vp, number of faces and corners were strongly correlated with aggregate stability tests mainly with the fast and fast$_{10s}$ test (r: −0.56, −0.74; 0.48, 0.52; 0.46, 0.49 and 0.42, 0.50, respectively) and with the more labile organic carbon fractions −POC$_c$ and POC$_f$- (r: −0.49, −0.5; 0.5, ns; 0.38, 0.48 and 0.31, 0.43, respectively). These observations suggest that the variables examined, concerning aggregates and pores were sensitive to changes in crop sequence and are useful soil quality indicators. However, the occurrence of platy structures also under GAP shows the need to adjust the VESS method to the NT system. Besides, the effect of agricultural intensification on soil morphology was modulated by soil type. In consequence, this last factor has also to be considered for the definition of a quality indicator to track the effect of crop sequences intensification under no-till management.

1. Introduction

No-tillage (NT) is an important management alternative for countries that produce agricultural commodities (Durán et al., 2011) and in Argentina more than 75% of cultivated area is managed in this way (AAPRESID, 2012). Among the benefits of this cropping system are the reductions in soil loss through erosion, the increase in water storage, as well as lower production costs (Derpsch et al., 2010; Kirkegaard and Hunt, 2010; Pierce et al., 1994). Numerous studies show that NT also produces an increase in number and diversity of soil fauna promotes organic carbon conservation and increases structural stability (Alvarez et al., 2012; Álvarez and Steinbach, 2009; Derpsch et al., 2010; González Chávez et al., 2010; Morrás et al., 2001), thus improving soil water availability for crops. However, some problems in soil physical fertility have been detected such as increase in bulk density, penetration resistance (Chagas et al., 1994; Mahboubi et al., 1993; Nesmith et al., 1987; Tebrügge and Düring, 1999) and formation of

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platy structures in the surface horizon (Ball and Robertson, 1994; Sasal et al., 2006; Morrás et al., 2012).

These problems can arise in many cases because the adoption of NT has not been accompanied with other appropriate agricultural practices (crop rotations, nutrient replacement and integrated pest management) so as to guarantee a sustainable production system (Austin et al., 2006). In Argentina, the spread of NT coincided with a marked increase in the area of soybean monoculture (*Glycine max* L. Merr.) (Novelli et al., 2011). This represents a risk for the sustainability of the production system, as soybean not only leaves very little stubble on the ground, but this stubble has a low C/N ratio and decomposes rapidly (Studdert and Echeverría, 2000). Soybean as the only crop in a year (full-season soybean) covers the soil only part of the year (Sanford, 1982; Bathke and Blake, 1984) favoring erosion processes.

In the Pampas region (the main crop area in Argentina), some farmers have simplified the production system through soybean monoculture (Viglizzo et al., 2011), while other farmers have intensified the crop sequence. Intensification occurs with the production of two crops per year, such as wheat/soybean or wheat/late corn (Caviglia and Andrade, 2010). As a result, in recent years various indices and relationships have been proposed to assess the effect of different crop sequences on soil properties, such as number of soybean crops in relation to the total number of crops (Novelli et al., 2013; Studdert and Echeverría, 2000) and the "intensification of the crop sequence index" (ISI), the number of months occupied by crops in a year (Novelli et al., 2011, 2013; Sasal et al., 2010). In addition, it has been shown that the number of years under NT is associated with changes in soil properties (Álvarez and Steinbach, 2009; Sasal, 2012).

Cropping intensification has shown many positive effects like a decrease in runoff (Sasal, 2012), an increase in soil organic carbon (Duval et al., 2014, 2016; Studdert and Echeverria, 2000) and in soil structural stability (Novelli et al., 2013; Sasal, 2012). This intensified land-use means greater root activity and a greater contribution of stubble throughout the year. However, Wilson et al. (2010) found that the benefits from crop intensification were not reflected in better soil quality due to soil deformation as a consequence of the increase in machinery traffic. Duval et al. (2015) found, in Pampas Argiudolls, higher values of bulk density and lower porosity values (pores >9 μm in diameter) compared to soils subjected to less intensification of the crop sequence. Kraemer (2015) found higher soil aggregates stability –which is considered a favorable property- in intensified plots, but also higher soil bulk density compared to less intensified plots.

One way to evaluate the effect of traffic and thus crop sequence intensification in soils under NT, is to analyze the physical response of soil aggregates through changes in their morphology (Morrás et al., 2012). Aggregates can be visually described by size, shape and porosity, which show important differences under different rotations and tillage systems, resulting in major changes in soil, air and water relationships (Carter, 2004). Thus, for example, Dexter (1985) proposed the use of aggregate morphology features for structure and soil quality evaluation. The presence of spherical aggregates of low roughness indicates an intensive land-use (Cremon et al., 2011; Morrás et al., 1999; Olszevski et al., 2004). Morrás et al. (1999) established, through analysis of aggregate morphology, changes in soil management which allowed a clearer interpretation of degradation processes in Ultisols under different management of *Ilex paraguariensis* plantations ("yerbatales"). Using the same method, Bonel et al. (2005) found in an Argiudoll, differences between soils of the natural environment under reduced tillage and under no-till. Similarly, Baver (1956) found that aggregate shape, especially a larger horizontal than vertical axis, is linked to structural degradation processes. Using Euler's polyhedral formula, Hartge et al. (1999) were able to differentiate aggregates of different depths from soils under no-till and conventional tilling through the description of their faces, edges and vertices, as pedoturbation processes caused by tilling practices destroy aggregate edges and vertices.

There has been in recent years renewed interest in using visual structure in the field as a soil quality indicator. This interest has resulted in a recent special issue of the Journal of Soil and Tillage Research (Munkholm et al., 2013a). One of the most accepted methods, developed by combining several methodologies is by Ball et al. (2007). It proposed a "visual evaluation of soil structure in the field" (VESS), fast and easy to apply and not requiring trench construction (Peerlkamp, 1959; Shepherd, 2000, 2009). Using Ball's method, Liesch et al. (2011) determined that double cropping improved soil quality by 57%, while Imhoff et al. (2009) obtained promising results in the evaluation of different agricultural managements in the Argentinian Pampas. However there are still doubts about the use of VESS, due to its subjectivity and its application to soils with different moisture content (Ball et al., 2007), textures and mineralogy (Askari et al., 2013; Guimarães et al., 2013). Although for clay soil analysis, modifications of VESS in the Ball et al. (2007) method can be introduced, Guimarães et al. (2013) found that even different textures (clay and sandy-loam soils) did not cause different results with this methodology. On the other hand, Mueller et al. (2013), were able to make accurate assessments of soil quality in soils with >30% clay content using visual methods. However, in both Guimarães et al. (2013) and Mueller et al. (2013), the clays present were not expanding clays. Therefore more detailed studies, including soil types with contrasting mineralogy and managed differently, have to be carried out to assess the usefulness of the VESS for determining soil quality. Moreover, this methodology is also used to evaluate visible porosity (Vp). Due to its high degree of subjectivity, the method is currently modified to improve its efficiency (Guimarães et al., 2011). One of them consists in the use of image analysis, an efficient and accurate method to evaluate the effect of different agricultural management on soil quality (Olszevski et al., 2004).

Structure is a complex property related partially to the soil inherent characteristics (particle size, clay mineralogy, etc.) and also to anthropogenic influence (land management) (Ball et al., 2007). This complicates the assessment of structural soil quality through indicators in different soil types, climate and management systems (Schjønning et al., 2002). Taking these aspects into account, the combination of different morphological and structural variables seems useful to evaluate soil quality in a broad range of soil types and management systems. However, there are very few studies that use aggregate morphology as an indicator in NT systems, or compare soils with different textures and mineralogy. Moreover, studies including quantitative morphological evaluations of aggregates are almost nonexistent.

In this sense, and due to the effects of roots and biological activity, it is hypothesized that crop intensification will display better structural features compared to monoculture or less diversified crop sequences (PAP) regardless of higher machinery traffic. Moreover, it is expected that traditional and novel structural variables used here are adequate to monitor soil structural quality in plots subjected to different levels of crop intensification/simplification. The objective of this study was to assess the impact of crop sequence intensification under NT in different soils on morpho-structural variables. These variables were described and evaluated according to their interaction with soil type and their ability to discriminate the effects of crop intensification. To validate this approach the associations of these variables with physical, chemical and management variables were also quantified.

2. Materials and methods

2.1. Study sites and soil management

Soil sites and management were selected by scientists and farmers of the BIOSPAS consortium, an interdisciplinary project with the long term goal of defining ecological indicators of sustainability under no-till farming (Wall, 2011). Two agricultural practices were evaluated: good agricultural practices (GAP) and poor agricultural practices (PAP), both following the criteria of the AAPRESID program for Certification in Good Agricultural Practices (AAPRESID, 2013; http://www.aapresid.org.ar/ac/buenas-practicas-agricolas/) and the Good Agricultural Practice guidelines developed by the United Nations Food and Agricultural Organization (www.fao.org/prods/GAP/index_en.htm). GAP is characterized by intensive crop sequences (more crops during the year mainly due to the inclusion of winter crops), high stubble cover, good nutrient replacement and low use of agrochemicals, while PAP is distinguished by lower crop intensification and simplification of the crop sequence (low crop diversity), low nutrient replacement, high use of agrochemical and low yields. In addition, a reference system was designated as Natural Environment (NE), a natural grassland that had not been tilled for at least 30 years, located less than 5 km from the sampling area for GAP and PAP.

Because of the difficulty in establishing a strict replication of management practices in actual production fields, management treatments were further quantified in order to establish a management gradient that included the following variables: years under no-till, number of soybean or maize crops in relation to total crops (soybean/crops; maize/crops), number of soybean as the only crop in the year (soybean as only crop) and an intensification of the crop sequence index (ISI_{agr}) were calculated as the relationship between number of months occupied by a certain crop in a year and the total number of months cropped in that year (Table 1). When NE was also considered together with the agricultural treatments, the intensification of the crop sequence index was referred as ISI. Finally, an additional variable was included (PC1_management) to account for overall management variability, derived from a principal component analysis performed using all the variables mentioned above. This new variable reflects the score of the first principal component that accounted for 78.4% of total variability in the data.

The study was carried out in the top-soil (0–15 cm depth) corresponding to A horizons of four sites along a west-east transect in the northern Argentine Pampas: Bengolea (33° 01′ 31″ S; 63° 37′ 53″ W), Monte Buey (32° 58′ 14″ S; 62° 27′ 06″ W), Pergamino (33° 56′ 36″ S; 60° 33′ 57″ W) and Viale (31° 52′ 59,6″ S; 59° 40′ 07″ W). Mean annual precipitation and mean annual temperature decline towards the west from 1023 mm to 795 mm and from 18.0 °C to 16.3 °C, respectively (SMN, 2012, http://www.smn.gov.ar, November 2012). Precipitation varies with season and is concentrated during spring and summer. The soil in Bengolea, located in the Piedmont Pampa, is a sandy loam Entic Haplustoll that contains fluviate sands and silts with loessial sediments and a mostly ustic moisture regime. Monte Buey soils are in a flat area between the Piedmont and Rolling Pampas; it is a silty loam Typic Argiudoll with a moderately developed illuvial Bt horizon and a high proportion of silt. The soil at Pergamino is a silty loam Typic Argiudoll with deep and high clayey Bt horizon, representative of the gently undulating Rolling Pampa (slopes around 2–5%). This area has slightly higher annual rainfall than the previous location but has a well-developed drainage network. Soils in Viale are silty clay loam Hapluderts; this area has the highest precipitation of the study area, and also has a gently undulating landscape with well-drained soils. The clay mineralogy of soil surface horizons at Bengolea, Monte Buey and Pergamino is rather similar, 2:1 clays, mainly illites with a small proportion of irregular interstratified illite-smectite minerals and traces of kaolinite. By contrast, Viale soils are characterized by a high proportion of smectite and lower proportions of the other above mentioned clay minerals (Kraemer et al., 2012).

2.2. Soil structural assessment

A multiscalar approach was followed to determine the effect of soil management on morphological and structural soil features, which included field and laboratory measurements. The following analytical measurements were carried out.

2.2.1. Visual evaluation of soil structure (VESS)

VESS was evaluated using the methodology proposed by Ball et al. (2007). From each soil type-management combination, three undisturbed monoliths (15 × 15 × 15 cm) were obtained in three sampling subsites less than 50 m apart from each other, a total of nine replicates per treatment. This methodology consists of assessing the breakdown of monolith structure, identifying structural modifications in the soil layers and recognizing soil shape, size, color, visible porosity, presence of anaerobic zones

Table 1
Management characteristic of GAP (good agricultural practices) and PAP (poor agricultural practices) for the selected soils (Haplustoll-Bengolea, Argiudoll-Monte Buey, Argiudoll-Pergamino and Hapludert-Viale) for the 2004–2010 period.

Soil treatment/ Rotation year	Haplustoll (Bengolea)		Argiudoll (Monte Buey)		Argiudoll (Pergamino)		Hapludert (Viale)	
	GAP	*PAP*	*GAP*	*PAP*	*GAP*	*PAP*	*GAP*	*PAP*
2004/2005	wheat/soybean	peanut	wheat/sorghum	soybean	soybean	soybean	wheat/soybean	maize
2005/2006	maize	wheat/soybean	maize	wheat/soybean	wheat/soybean	soybean	melilotus+ rye-grass/maize	soybean
2006/2007	wheat/soybean	soybean	wheat/soybean	maize	maize	soybean	soybean	wheat/soybean
2007/2008	vetch/maize	wheat/soybean	vetch/maize-soybean	soybean	soybean	soybean	wheat/soybean	maize
2008/2009	wheat/soybean	soybean	maize	soybean	wheat/soybean	soybean	maize	soybean
2009/2010	soybean	soybean	wheat/soybean	soybean	maize	soybean	soybean	soybean
ISI_{agr} [a]	0.67	0.53	0.64	0.49	0.56	0.42	0.59	0.50
Years under No-Till	13	5	28	10	6	5	13	9
Soybean/Crops ratio[b]	0.40	0.62	0.28	0.75	0.50	1.00	0.44	0.57
Maize/Crops ratio[b]	0.20	0.00	0.30	0.14	0.25	0.00	0.22	0.28
Soybean as only crop (%)[c]	17	50	00	66	33	00	33	50

[a] Crop sequence intensification index: relationship between number of months occupied by each crop and total number of months cropped during the study period.
[b] number of soybean or maize crops in relation to total crops during the study period.
[c] number of soybean as the only crop in the year.

and root distribution (inter and intra-aggregate). Using a chart with the description and a photo of each structural characteristic, a score was assigned to each monolith and a soil quality index (Sq) that ranges from 1 (good) to 5 (poor soil structure) was calculated. This index takes into account the number, type and thickness of each soil layer. Photographs of each monolith and other soil structural features were taken for further analysis in the laboratory.

2.2.2. Visible porosity (Vp), eccentricity (Ecc) and roundness (Rd)

To determinate Vp, Ecc and Rd, monoliths (near field capacity) were gently broken by hand along their weakness planes to obtain aggregates ranging from 3 to 5 cm in diameter. In each subsite, three aggregates were randomly selected and photographed with an incident light microscope (Wild MZ8 Leica photomicroscope). By combining seven to ten pictures, varying their focus and using Combine Z software (http://www.hadleyweb.pwp.blueyonder.co.uk/ CZP), a high quality image of each aggregate was composed ensuring good quality analysis of aggregate features. Vp was determined using *JMicrovision*^{r} software (http://www.jmicrovision.com/). Mean pore diameters greater than 50 μm were measured by placing a 1 cm^2 square section in the middle of each aggregate and measuring the diameter of the larger fifty pores. This corresponded to 60–80% of total visible pores within the section. Area and perimeter of aggregates were measured and their eccentricity (Ecc) and roundness (Rd) were calculated. Ecc was calculated using *JMicrovision*^{r} software (Eq. (1))

$$Ecc = (1 - b^2/a^2)^{(1/2)} \quad (1)$$

where, a: length of the semi-major axis, b: length of the semi-minor axis.

Ecc values range from 0 to ∞, with higher values meaning lower similarity between a conic section and a circle (a conic section of 0 is equal to a circle). Roundness (Rd) is a shape factor and depends on the roughness of the aggregate external surface; it ranges between 0 and 1, with higher values indicating greater roundness (Eq. (2)).

$$Rd = (4\pi A)/p \quad (2)$$

where, A: area of the polygon, p: perimeter of the polygon

2.2.3. Tridimensional aggregate morphology

Tridimensional features of soil aggregates (faces, edges and corners) were determined according to Hartge et al. (1999). Fifteen 3–5 cm aggregates from the ones described above, were randomly selected, air dried and the number of faces, edges and corners were counted under a microscope. Faces whose sizes were sensibly smaller (≈5 times smaller) than neighbour aggregates and faces and undefined edges and corners were not taken into account. To lower operator errors, each aggregate was assessed three times on different days.

2.3. Physical and chemical characteristics

Particle size distribution was determined by Robinson's pipette method for the clay (<2 μm) and silt fractions (2–50 μm) and by wet sieving for the sand fractions (>50 μm) (Soil Conservation Service, 1972). Clay mineralogy (homoionic to Mg^{+2}) was established by X-ray diffraction (Philips PW1050 with a θ/2θ goniometer set to 50 kV and 40 mA, 3–70° 2θ, step 0.02°) and a semiquantitative analysis was performed to obtain smectite and interstratified smectite/illite (S + S/I) content (Holtzapffel, 1985). Aggregate stability was determined with Le Bissonnais (1996) method (MWD_{fast}: Fast wetting; MWD_{stir}: stirred in water after ethanol submersion; MWD_{slow}: slow wetting and MDW_{mean}: Mean of previous three variables) and $MWD_{fast10s}$ (Mean weight diameter for fast 10 s wetting) was incorporated to asses early slaking processes (Kraemer, 2015; Kraemer et al., 2012). Detailed information can be found in Rosa et al. (2014). Finally, Atterbergs limits were determined: Ll (Liquid limit), Pl (Plastic limit), Pi (Plasticity index) (Means and Parcher, 1965), and CA (Clay activity): Pl/clay content (%).

The following variables were determined in crushed 2 mm sieved soil samples: pH (1:2.5 soil:water) using a potentiometer and electric conductivity (EC) using a conductimeter. Exchangeable ions and cation exchange capacity (CEC) were determined by the ammonium acetate 1N method and exchangeable Ca^{2+} was measured by atomic absorption spectrometry.

Soil organic carbon (SOC) was determined by dry combustion (LECO, St. Joseph, MI, USA). Soil carbon fractionation by particle size was performed using the method described by Duval et al. (2013). Samples were sieved through a pair of 53- and 105-μm diameter meshes. Three fractions were obtained: a coarse fraction (105–2000 μm) containing coarse particulate organic carbon (POC_c) and fine to coarse sands, a medium fraction (53–105 μm) with fine particulate organic carbon (POC_f) and very fine sands, and a fine fraction (<53 μm) containing mineral-associated organic carbon (MOC), as well as silt and clay. The C content of the particulate labile fractions was determined in the same way as the SOC. The difference between SOC and ($POC_c + POC_f$) was used to calculate the organic carbon content of the <53 μm (MOC).

Carbohydrates (CH) determination was performed following Puget et al. (1999). Total carbohydrate (CH_t) extraction was done by acid hydrolysis: a 1 g soil sample was treated with 10 mL H_2SO_4 0.5 M and heated to 80 °C during 24 h. To determine soluble carbohydrate (CH_s) content, 1 g of soil was suspended in 10 mL of distilled water and heated to 80 °C during 24 h. After extraction, each suspension was centrifuged at 4000 rpm for 15 min (Puget et al., 1999). Carbohydrate contents were determined using the phenol–sulphuric acid spectrophotometric method with a glucose standard curve (Dubois et al., 1956).

2.4. Statistical analysis

To test the effect of management treatments (NE, GAP and PAP) and soils (Haplustoll, Argiudoll –Monte Buey, Argiudoll – Pergamino and Hapludert) on the different variables (Sq –VESS-, Vp, Ecc, Rd, n° faces, corners and edges) mixed linear models were built for each dependent variable. These models had soils, management treatment and their interactions as fixed effects and aggregate nesting within soil type and sub-sites within sites as the random factors of the model. Identification (id) for each aggregate was assigned for Vp, Ecc and Rd. This id is a nesting factor and was considered as a random component within the mixed model. The models were compared against simpler ones that had only fixed effects. If differences between both models were non-significant (P > 0.05) the analysis was continued with the simple model. Vp was log10 transformed to obtain a normal distribution. Decimal numbers were assigned for the different Sq (VESS) categories (Sq 1–5), allowing Sq to be treated as a continuous variable (Munkholm et al., 2013b). Variance component analysis was used to determine the proportion of the variance due to management or soil type. This discrimination helped to understand the dynamic or inherent behavior of each structural variable according to Karlen et al. (2001). To assess association between soil structural variables and soil characteristics and management variables, Pearson correlation was calculated. Statistical analyses were performed using R software (R Development Core Team, 2011) except Pearson correlations that were calculated using Infostat/P v1.1 (2002).

3. Results

3.1. Soil structure

3.1.1. Haplustoll (Bengolea)

Monoliths from the natural environment (NE) showed notorious vertical isotropy up to a depth of 15 cm. This soil is characterized by a fine, very weak granular structure with single grains (Fig. 1a). Soil consistence was friable and no densified or hardened layers were observed. When extracted, monoliths showed a tendency to cohere, basically due to the presence of a dense root framework inside and between peds. Numerous fine roots inside and covering 1–5 cm peds were found (Figs. 2 a and 3 a).

GAP monoliths were characterized by three clearly differing layers (Fig. 1b). The surface layer (0–5 cm depth) showed weak granular structure and single grains with numerous roots in its upper part and thin, discontinuous, platy peds in the lower part. At 5–10 cm depth, a compacted layer appeared, broken into coarse moderately developed subangular blocks, with scarce roots. At 10–15 cm depth, smaller and very weak subangular blocks were found, while roots were similarly distributed and scarce in number. Although visible porosity appeared in peds from the three layers, its proportion was less than in the NE treatment (Figs. 2 b and 3 b).

Monoliths from the PAP treatment showed a weakness plane at 3–5 cm depth (Fig. 1c). The surface layer was weakly structured, very friable and with scarce aggregates. Below the fissure, subangular aggregates of different size and grade were found. Platy peds were also observed, though they were weaker and more discontinuous than those in GAP. Roots, mostly small, appeared uniformly distributed within the monolith and visible porosity was low (Figs. 2 c and 3 c). No relevant differences were found between subsites in any of the treatments.

3.1.2. Argiudoll (Monte Buey)

In the NE treatment, monoliths had a granular structure close to the surface (0–5 cm) and moderately developed subangular blocks below that depth (Fig. 1d). Roots were abundant in the first 5 cm, and then decreased abruptly. Monoliths from the GAP treatment presented a very significant vertical anisotropy (Fig. 1e) and their extraction did not present difficulties. The upper 5 cm had a well-developed granular structure with a significant presence of biogenic aggregates and abundant roots throughout this layer. By contrast, a compacted layer of weak platy peds juxtaposed to moderate subangular blocks and a decrease of root density, was noted at 5–10 cm depths (Fig. 1e). At greater depths, those emerging platy peds disappeared and the structure was characterized by large subangular blocks. Visible porosity at depths 0–

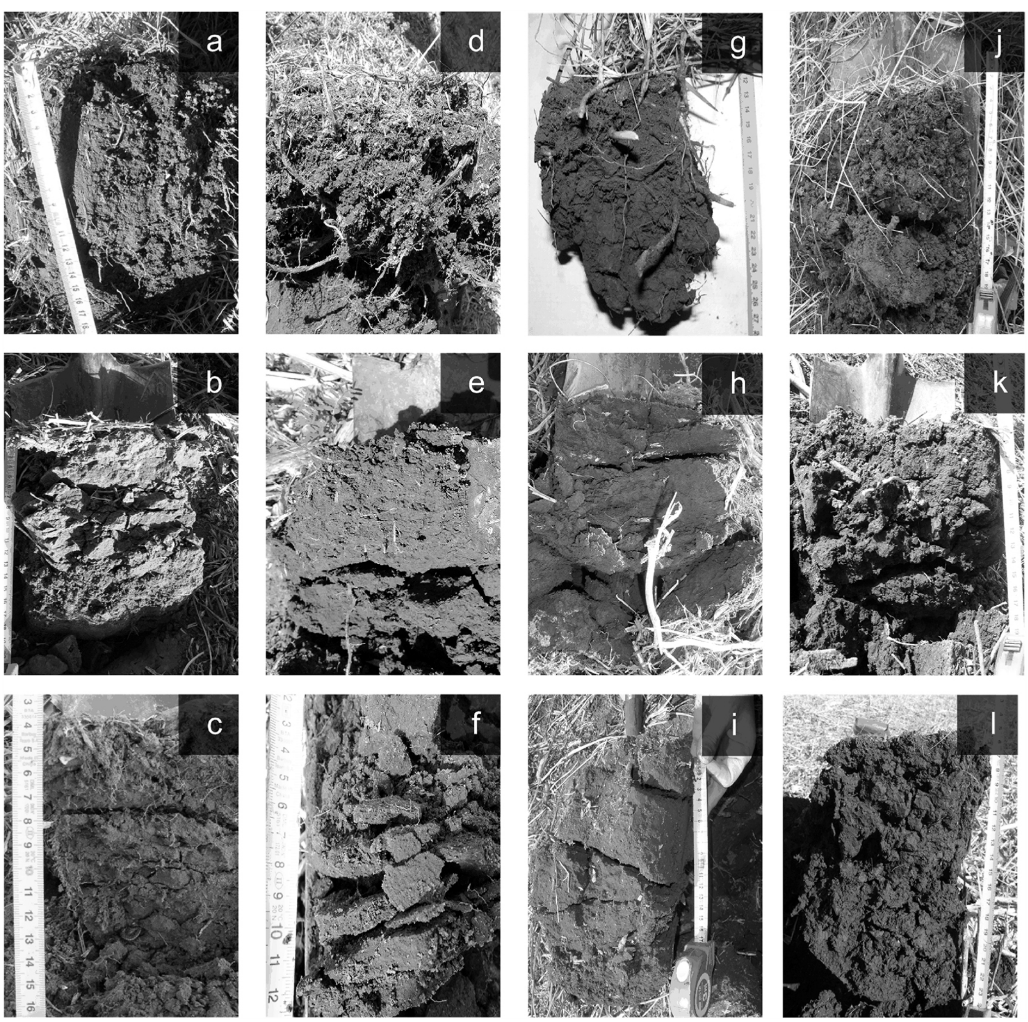

Fig. 1. Monoliths from soil type-management treatment combinations (natural environment –NE-; good agricultural practices –GAP- and poor agricultural practices –PAP-). Haplustoll (Bengolea)-NE, GAP and PAP: a–c, respectively; Argiudoll (Monte Buey)-NE, GAP and PAP: d–f, respectively; Argiudoll (Pergamino)-NE, GAP and PAP: g–i, respectively; and Hapludert (Viale)-NE, GAP and PAP j–l, respectively.

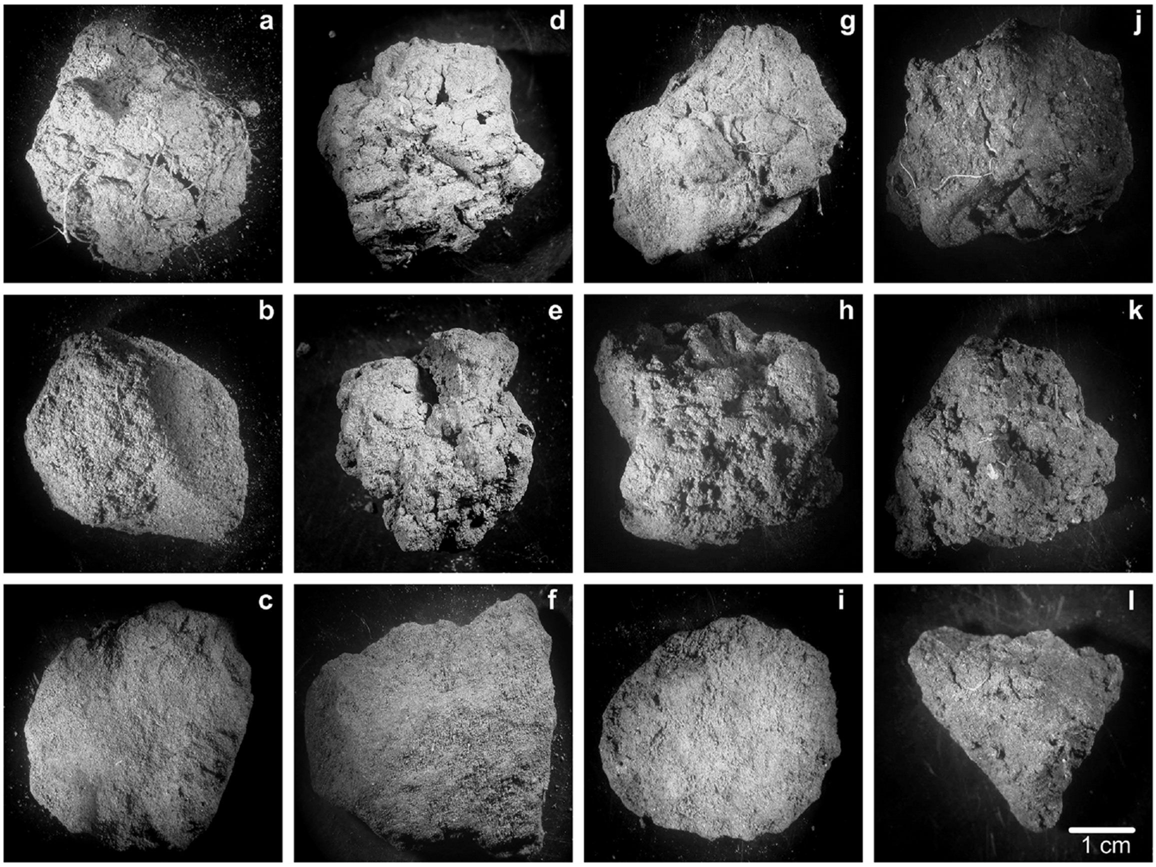

Fig. 2. Soil aggregates (1–5 cm) from soil-management treatment combinations (natural environment –NE-; good agricultural practices –GAP- and poor agricultural practices –PAP-). Haplustoll (Bengolea)-NE, GAP and PAP: a–c, respectively; Argiudoll (Monte Buey)-NE, GAP and PAP: d–f, respectively; Argiudoll (Pergamino)-NE, GAP and PAP: g–i, respectively; and Hapludert (Viale)-NE, GAP and PAP j–l, respectively.

15 cm was high, while root presence was not as abundant as expected (Figs. 2 e and 3 e).

Monoliths under PAP had a very thin surface layer (~1–2 cm) with loose grains, light colors (value ~4–5) and moderate root presence (Fig. 1f). Between 2–15 cm depth, soil structure was characterized by coarse subangular aggregates, more conspicuous at about 5 cm depth, which easily broke horizontally into thick platy peds (Fig. 1f). Visible porosity in aggregates was very low (Figs. 2 f and 3 f); roots were scarce and restricted to interpedal voids (Figs. 2 f and 3 f). As in the Haplustoll, soil structure was also quite similar between treatment subsites.

3.1.3. Argiudoll (Pergamino)

In the NE, monoliths were highly coherent and remained intact when removed (Fig. 1g). A mixture of granular structures with fine, moderately developed subangular blocks was found in this treatment, the latter increasing its proportion with depth (Fig. 1g). In subsite 2 the soil was more cohesive and aggregates were larger in the surface layer. In this treatment, aggregates showed a significant porosity, roots developed inside and between peds with size and frequency decreasing with depth.

The soil under GAP presented two distinct layers. Up to a depth of 4–5 cm, a mixture of granular structure and fine, moderately developed subangular blocks was characteristic. Platy peds, varying in size and grade, appeared usually at the lower limit of this layer. This type of structure was frequently observed at the edge of the field where machinery traffic was more intense (subsite 1). Below 5 cm, subangular aggregates were larger and more distinct, and platy peds became less frequent. Root abundance was intermediate to low all across the monolith (Figs. 1 h and 2 h).

The monoliths under PAP were easy to extract, presenting a very fine and weak granular structure at the surface. Below a depth of 4–5 cm, the soil showed some compaction and the structure was of fine and weak subangular blocks (Fig. 1i). Platy peds were scarce, weakly developed and discontinuous, aggregate porosity was very low (Fig. 2i). Root abundance was similar to GAP.

3.1.4. Hapludert (Viale)

A typical grumosolic structure, characterized by angular and subangular blocks throughout the monoliths, was observed in all treatments (Fig. 1j–l). However, some particularities in ped size differentiated the treatments. NE and GAP treatments showed smaller sized aggregates in the upper five centimeters than in PAP. In turn, larger blocks with some hydromorphic features appeared around a depth of 10–15 cm in NE, which were not observed in the other treatments. In general, visible porosity and amount of roots was higher in NE and GAP than in PAP (Figs. 2 j–l and 3 j–l).

3.2. Structural variables

To assess the effect of management and soil type, a set of structural variables were measured. They are described together with their statistical significance in Table 2. Almost all structural variables were statistically significant and were affected by soil types and management interaction (Table 2).

3.2.1. Visual assessment of soil structure

Soil quality index (Sq) presented an interaction between management and soil type (Table 2). The Hapludert and the Argiudolls presented high Sq values for both GAP and PAP,

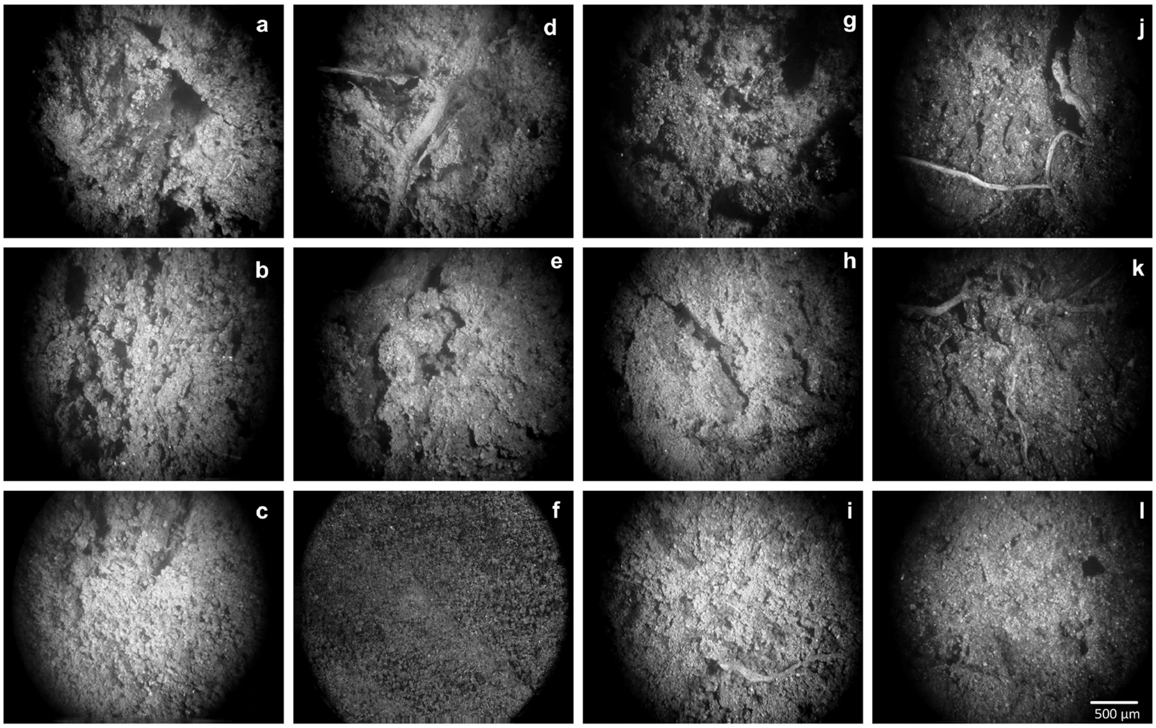

Fig. 3. Soil aggregates (1–5 cm) ×5 magnification from soil-management treatment combinations (natural environment –NE-; good agricultural practices –GAP- and poor agricultural practices –PAP-). Haplustoll (Bengolea)-NE, GAP and PAP: a–c, respectively; Argiudoll (Monte Buey)-NE, GAP and PAP: d–f, respectively; Argiudoll (Pergamino)-NE, GAP and PAP: g–i, respectively; and Hapludert (Viale)-NE, GAP and PAP j–l, respectively.

Table 2
Effects of management and soil type on morphostructural variables and comparisons between models (fixed vs. mixed with random effects –soil type) of the F values are shown for each term in the model.

Morphostructural variables	Management	Soil type	Management x Soil type	Difference between models (P value)
Visual evaluation of soil structure (Ball et al., 2007)				
VESS (Sq)	28.447***	17.287***	5.363**	0.66
Image aggregate evaluation				
Roundness (Rd)	9.048***	10.913***	4.688***	0.99
Eccentricity (Ecc)	1.6466	0.6171	0.7132	0.94
Visual Porosity (Vp)	210.29***	1.82	8.02	0.0001
Tridimensional soil aggregates evaluation (Hartge et al., 1999)				
Faces	14.665***	12.445***	1.231	0.99
Corners	21.615***	2.351	3.316**	0.0029
Edges	1.675	33.224***	7.53***	0.4057

** $P < 0.01$.
*** $P < 0.001$.

indicating poor structure (Fig. 4) while, in general, Sq values were lower in the Haplustoll. The lowest value for this soil type was found in NE differing significantly from GAP and PAP. On the other hand, the Argiudoll (Monte Buey) under PAP treatment showed the highest statistically significant Sq value of all soils (Fig. 4), with the following trend: NE < GAP < PAP. In the Argiudoll (Pergamino), GAP showed the highest Sq value, significantly different to those from NE and PAP. No differences were detected between the other two managements. In the Hapludert, PAP was significantly higher than GAP with no differences between the other management treatments.

In all soils and particularly in NE and under GAP treatments, Sq increased with depth, with less effect in the Hapludert (data not shown). Furthermore, in the Argiudolls and Haplustoll, high Sq values (approx. 4) under GAP and PAP at a depth of 5–10 cm were associated with the presence of laminar structures (continuous, discontinuous, weak or strong).

3.2.2. Visible porosity, roundness and eccentricity

Visible porosity (Vp) was analyzed using a mixed model, while roundness (Rd) could be modeled with a simpler fixed effects model. For both variables, the management × soil type interaction was statistically significant ($P < 0.001$, Table 2). Neither soil type nor management affected eccentricity ($P > 0.05$) and in consequence no comments are offered for this variable. For three of the four soils studied, Vp varied with agricultural management (GAP – PAP) ($P < 0.001$) (Fig. 5a, original units), Vp being greater in GAP. No differences between NE and GAP were detected (Figs. 2 and 3). In the Haplustoll no significant differences between management

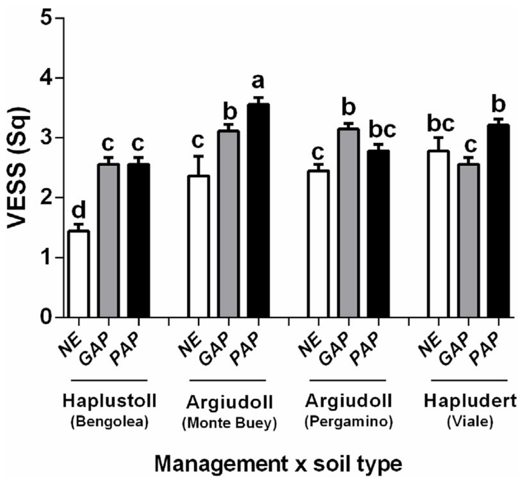

Fig. 4. Visual evaluation of soil structure (VESS) as soil quality index (Sq) for the Haplustoll (Bengolea), Argiudoll (Monte Buey), Argiudoll (Pergamino) and Hapludert (Viale) for three management treatments: natural environment (NE), good agricultural practices (GAP) and poor agricultural practices (PAP). Lower values indicate better structural quality. Different letters above bars indicate significant differences among soil type × management interaction (LSD, $P < 0.05$).

practices were found, although NE and PAP showed the highest Vp values in this soil type.

Mollisols presented higher Rd under PAP while in the Hapludert no significant differences were found (Fig. 5b). No significant differences between management treatments were found in the Argiudoll (Pergamino). The Argiudoll (Monte Buey) under PAP showed significant differences with NE and GAP. In the Haplustoll, Rd presented significant differences between GAP and NE but no differences were detected between NE and GAP (Fig. 5b). No differences among managements were found in the Hapludert and overall it showed the lowest Rd values (Figs. 5 b and 2 k–l). In conclusion Rd presented differences mainly in Mollisols towards an increase in Rd under PAP (Figs. 2a–i)

3.2.3. Tridimensional aggregate morphology

The number of faces and edges was modeled with fixed effect models, while the number of corners required a full mixed model (Table 2).

The number of faces followed a NE > GAP > PAP pattern, with significant differences only between GAP and PAP ($P < 0.0001$) (Fig. 6a). Soil type had also a strong effect on the number of faces, with the Hapludert showing the highest values followed by the Haplustoll. Both Argiudolls presented low number of faces with significant differences only with the Hapludert (Fig. 6b). No interaction between soil type and management treatment was detected.

The number of corners showed a significant interaction between soil type and management ($P < 0.001$, Table 2). In all Mollisols, the NE treatment showed higher number of corners. This difference was significant when compared with all agricultural managements of the Argiudoll (Monte Buey) and with the PAP in the Argiudoll (Pergamino) (Fig. 6c). In general, aggregates in soils under GAP presented a higher number of corners than under PAP except in the Argiudoll (Monte Buey) (Fig. 6c). In contrast, the number of edges had an irregular behavior for both, soil type and management. It is worth mentioning that the Hapludert and the Haplustoll presented a higher number of edges than both Argiudolls.

The 3-D variables measured presented a standard deviation of 0.62, 1.59 and 1.40 with a variation coefficient of 14.8, 22.2, 24.0 for number of faces, corners and edges, respectively. PAP treatments showed lower variation coefficients suggesting that this type of management induces a homogenization of structural features.

3.3. Dynamic and inherent behavior of the morphostructural variables

To rank morphostructural variables according to their tendency to follow changes in agricultural practices, a variance component analysis was performed. VESS (Sq) and Vp were the variables that explained best variations among management treatments across soil types (Table 3). However, Vp had a large unexplained residual component. Regarding the 3-D variables, the number of faces and corners had larger variance components associated with management treatment than those associated with soil type. For Rd, the contribution of the different factors to the total variance was relatively balanced, with somewhat higher values for management treatment. The number of corners showed a low variance contribution due to sites, combined with a large residual component.

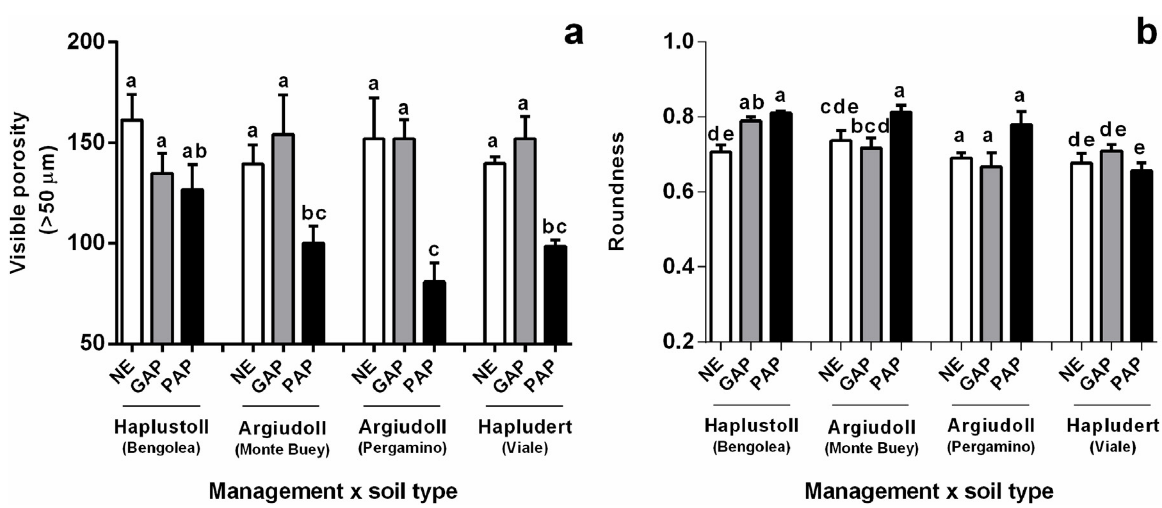

Fig. 5. a) Aggregate visible porosity expressed as mean pore diameter (µm) and (b) roundness in the various soil types under different managements. NE: natural environment, GAP: good agricultural practices, PAP: poor agricultural practices. Different letters above bars indicate significant differences among soil × management treatment interaction (LSD, $P < 0.05$).

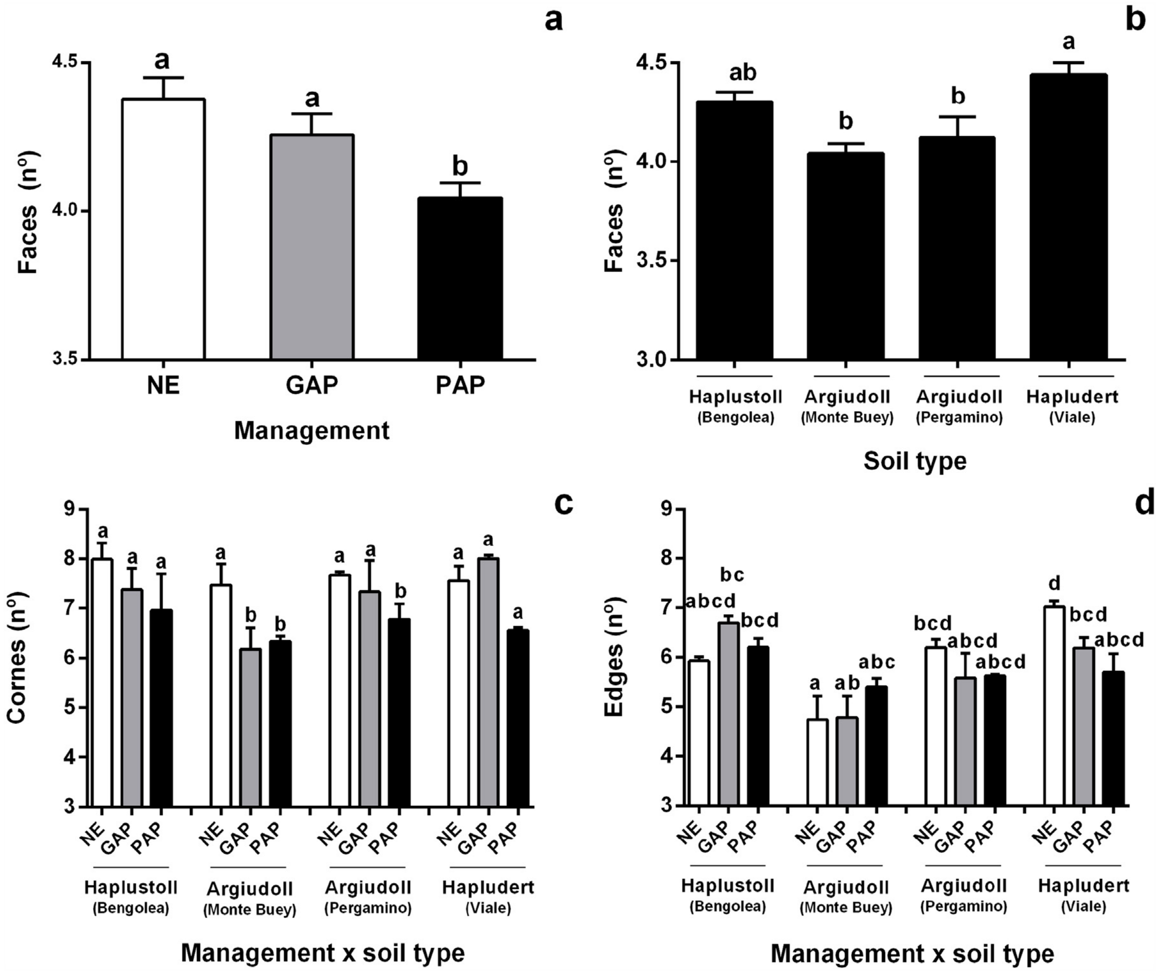

Fig. 6. a) Mean number of faces per aggregate for each management treatment b) Mean number of faces for each soil type, c) Mean number of corners and d) Mean number of edges corresponding to management × soil type interaction. NE: natural environment; GAP: good agricultural practices; PAP: poor agricultural practices. For a and b, different letters above bars indicate significant differences between management treatments and soil type respectively. For c and d, different letters above bars indicate significant differences for the soil × management interaction (LSD, $P < 0.05$).

3.4. Effect of management characteristics on morphostructural variables

All morphostructural variables analyzed, except aggregate eccentricity, were correlated with management related variables. In general, ISI and ISI_{agr} were the management variables that associated more strongly with morphological and structural changes in the soils (Table 4). Sq, Vp and number of faces showed high correlations with ISI and ISI_{agr}. This result indicates that an intensification of soil use (longer periods of living roots occupancy and higher biological activity) improves the visible soil structure, increases visible porosity and number of faces in aggregates. When only ISI is considered, Rd and number of corners also showed significant correlations, which implies a decrease in roundness and an increase in the number of corners associated to higher ISI values. Morphological variables that were more strongly associated with management practices were Vp and number of faces. It must be noted that these two variables also correlated significantly with the PC1_management, which summarizes the contribution of all variables related with management. The negative correlation between this variable and Vp and number of faces suggests that more balanced practices, which include the use of legumes and grasses and longer plot occupancy, would probably increase Vp and aggregates with more faces. Finally, all variables related to soybean preponderance in the rotation had an opposite effect to those associated with corn cultivation. This fact highlights the influential effect of crop type on soil structural development (Table 4). Rotations with a higher share of soybean generated more rounded aggregates with lower number of faces and less visible porosity compared to rotations with higher share of corn.

Table 3
Components of variance analysis expressed as percentages for management treatments, soil types and unexplained residual.

Morphoestructural variables	Variance components (%)		
	Management	Soil type	Residual
Visual evaluation of soil structure (Ball et al., 2007)			
VESS (Sq)	97.2	0.0	2.8
Image aggregate evaluation			
Roundness (Rd)	35.6	19.9	44.5
Eccentricity (Ecc)	1.9	0.0	98.1
Visual Porosity (Vp)	62.3	0.0	37.7
Tridimensional soil aggregates evaluation (Hartge et al., 1999)			
Faces	36.2	27.7	36.1
Corners	33.2	0.20	66.6
Edges	19.0	45.9	35.1

Table 4
Pearson correlations between morphostructural and management variables for all soil types. ns: no significant.

Morphostructural variables	PC1_ management	ISI	ISI_{agr}	Years under NT	Soybean/Crops	Maize/Crops	Soybean only crop
Visual evaluation of soil structure (Ball et al., 2007)							
VESS (Sq)	ns	−0.64***	−0.63***	ns	ns	ns	ns
Image aggregate evaluation							
Roundness (Rd)	ns	−0.32*	ns	ns	ns	−0.65**	ns
Eccentricity (Ecc)	ns	ns	ns	ns	ns	ns	ns
Visual Porosity (Vp)	−0.74***	0.53**	0.68***	0.47*	−0.78***	0.52*	−0.78***
Tridimensional soil aggregates evaluation (Hartge et al., 1999)							
Faces	−0.45*	0.52**	0.48*	ns	−0.54**	ns	−0.48*
Corners	ns	0.46**	ns	ns	ns	ns	ns
Edges	ns	ns	ns	ns	ns	ns	ns

PC1_management: management characteristics that contribute to Principal Component 1 of multivariate analyses; ISI: crop sequence intensification index; ISI_{agr}: crop sequence intensification index for commercial crops; Years under No-Till; Soybean/Crops: ratio of the number of total soybean crops to total crops; Maize/Crops: ratio of the number of total maize crops to total crops; Soybean only crop: number of years of soybean as only crop in the agriculture sequence.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

3.5. Effect of physical and chemical variables on morphostructural variables

Although morphostructrural variables were mainly affected by management practices (Table 3), some soil physical and chemical variables control their behavior. Thus, Sq correlated positively with silt content, and negatively with sand content (Table 5). Rd correlated with multiple intrinsic variables and the three-dimensional morphological variables, especially number of faces and corners, and with soil variables related to clay content and type (CA). On the other hand, Vp and Ecc did not correlate with any of the variables considered.

Aggregate stability (AS), a key variable to assess soil quality and one linked to maintaining good structure, was strongly and

Table 5
Pearson correlations between morphostructural and physical and chemical variables and organic carbon fractions. ns: no significant.

Soil variables		Morphostructural variables						
		VESS (Sq)	Visible porosity (Vp)	Eccentricity (Ecc)	Roundness (Rd)	Faces	Corners	Edges
						number		
Clay (<2 μm)		ns	ns	ns	0.49**	ns	ns	ns
Silt (2–50 μm)		0.49**	ns	ns	ns	ns	ns	−0.35*
Sand (>50 μm)		−0.46**	ns	ns	−0.43**	ns	ns	ns
Cation Exchange Capacity	CEC	ns	ns	ns	0.37*	0.33*	ns	ns
Liquid limit	Ll	ns	ns	ns	0.50**	0.43**	ns	ns
Plastic limit	Lp	ns	ns	ns	0.40*	ns	ns	ns
Plasticity index	Ip	ns	ns	ns	0.48**	0.52**	ns	0.34*
Clay Activity	CA	ns	ns	ns	0.36	0.69***	0.44**	0.57***
Smectite + interestratified illite/smectite	S + I/S	ns	ns	ns	0.27	0.53***	ns	0.47**
Particle density	PD	−0.61***	ns	−0.43**	ns	ns	ns	ns
Electrical conductivity	EC	ns	ns	ns	−0.48**	0.45**	ns	ns
pH		ns	ns	ns	ns	ns	ns	ns
Ca^{2+}		ns	ns	ns	ns	ns	ns	ns
Aggregate stability (AS)								
$MWD_{fast10s}$		−0.66***	0.52**	−0.35*	ns	0.46**	0.42*	ns
MWD_{fast}		−0.74***	0.48**	ns	ns	0.49**	0.50**	ns
MWD_{stir}		ns	ns	ns	ns	ns	ns	−0.54**
MWD_{slow}		−0.57***	0.54***	−0.36*	ns	0.39*	ns	ns
MWD_{mean}		−0.56***	0.50**	ns	ns	ns	0.35*	ns
OC fractions								
SOC		ns	ns	ns	−0.36*	0.36*	0.28	ns
POC_c		−0.49**	ns	ns	ns	0.38*	0.31	ns
POC_f		−0.50**	0.50**	ns	ns	0.48**	0.43**	ns
MOC		ns	ns	ns	−0.35*	ns	0.22	ns
CH_t		ns	ns	ns	ns	ns	−0.08	−0.49**
CH_s		−0.47**	0.30*	−0.47**	ns	ns	0.36*	ns

VESS (Sq): visual evaluation of soil structure, soil quality. $MWD_{fast10s}$: mean weight diameter for fast 10 s wetting; MWD_{fast}: fast wetting; MWD_{stir}: stirred in water after ethanol submersion; MWD_{slow}: slow wetting and MDW_{mean}: mean of previous three variables; SOC: soil organic carbon; POC_c: coarse particulate organic carbon; POC_f: Fine particulate organic carbon; MOC: mineralizable organic carbon; CH_t: total carbohydrates and CH_s: soluble carbohydrates.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

positively correlated with Sq, the highest correlation coefficient with the latter variable was found with MWD_{fast} (Table 5). Vp was also positively correlated with several AS variables (Table 5). The number of faces and corners were correlated to AS variables particularly to MWD_{fast} and $MWD_{fast10sec}$, indicative of a slaking process (Table 5). The number of edges was only correlated with MWD_{stir}.

Sq, and the number of faces and corners presented positive correlations with the more labile organic carbon fractions (POC_c and POC_f), with slightly higher values for POC_f (Table 5). High and significant correlation coefficients were also found between CH_s and Sq, Vp, Ecc and number of corners. This last variable presented a positive and significant correlation with all organic carbon fractions (Table 5).

4. Discussion

4.1. Soil structure and VESS

The structural description of monoliths showed a strong structural differentiation between NE and the agricultural management treatments (GAP and PAP). The NE, in most management-soil type combinations, presented structural isotropy in the surface layer, with a more favorable structure for plant growth (crumbly, granular), higher porosity and more extensive root development. By contrast, the agricultural treatments presented an obvious anisotropy at 0–15 cm depth, with distinctive features between treatments (GAP and PAP) that were dependent on management and soil type.

These features were reflected in the VESS (Sq) and, although discrimination between GAP and PAP was not always possible (Fig. 5), this variable could capture structural differences arising from the different management variables and account for a high proportion of total variance (Tables 2 and 3).

Among management variables, ISI and ISI_{agr} were strongly related to VESS (Sq), suggesting that crop sequence intensification enhances structural modification toward more favorable features. This can be explained by the greater presence of roots and possibly higher microbial activity and fauna, due mainly to the larger presence of winter crops (Vaquero, 2011). A high frequency of biogenic aggregates was found by this author in the Argiudoll –Monte Buey under GAP that had the highest proportion of cultivated winter crops in this study (Table 1). Comparable results can be found in Askari et al. (2013), where under management that included crop rotations (high ISI), a better VESS (Sq) (1.66) than under monoculture (2.06) was found. The positive effect of crop intensification on VESS (Sq) is also supported by the AS related to a better VESS (Sq) (Table 5) and particularly by the responses to slaking pretreatments (MWD_{fast} and $MWD_{fast10s}$) and an important degradation process in silty soils (Cosentino et al., 2006; Le Bissonnais, 1996). Higher ISI values with more continuous root and soil microorganism activity could enhance formation and stabilization of soil aggregates (Álvaro-Fuentes et al., 2008; Shaver et al., 2003) compared to systems under frequent fallow (Álvaro-Fuentes et al., 2008; Franzluebbers et al., 1994).

No significant relationship between SOC and VESS (Sq) was found, in agreement with findings by Murphy et al. (2013). These results could be due to the interaction of SOC and type and clay content. However, when the behavior of labile organic carbon (POC_c and POC_f) was assessed –considering that these fractions are less associated with the soil intrinsic characteristics and more influenced by management-, strong correlations with VESS (Sq) were found (Table 5). Thus, when only Mollisols were considered in the analyses (lower contents of clay and expansible clay minerals) (Suppl. 1) those correlations increased significantly. These results demonstrate that VESS is more associated with labile organic matter fractions, the most dynamic and sensitive to management treatment, than the total organic matter.

On the other hand, the effect of soil type and particle size on VESS assessment is still being debated. In this study, sand content showed a significant correlation with VESS (Sq), presenting lower values in the sandy soil (Haplustoll) which reduces the sensitivity of this index, while clay content did not influence VESS (Sq). The same was found by Giarola et al. (2013) in Oxisols under NT and Guimarães et al. (2013) in two soils of contrasting texture (sandy loam and clay). It has been noted that in soils with high clay content (>30%) the use of visual indices is the best option for evaluating soil quality (Mueller et al., 2013). While in our study, clay content did not statistically affect this index, differences between GAP and PAP in the Hapludert may respond to clay content and type. The presence of expandable clays (higher in NE and GAP, suppl 1) produces a constant regeneration of the structure, mitigating the adverse impact of treatments (i.e. compaction). Thus, in this type of soil, measurements of extent of vertic features and wetting and drying cycles together with VESS should be included. These features were important in determining the lack of significant differences between management treatments in the Hapludert.

This vertic characteristics was also reflected in the relationship between bulk density (BD) and VESS (Sq) where no significant correlation coefficient was found between VESS (Sq) and $BD_{0–20\,cm}$ ($r = 0.31$, $P = 0.07$). However, when the analysis was restricted to the Mollisols, $BD_{0–20\,cm}$ showed a significant correlation coefficient with VESS (Sq) ($r = 0.45$, $P = 0.02$), reaching a r value = 0.53 for $BD_{0–}$

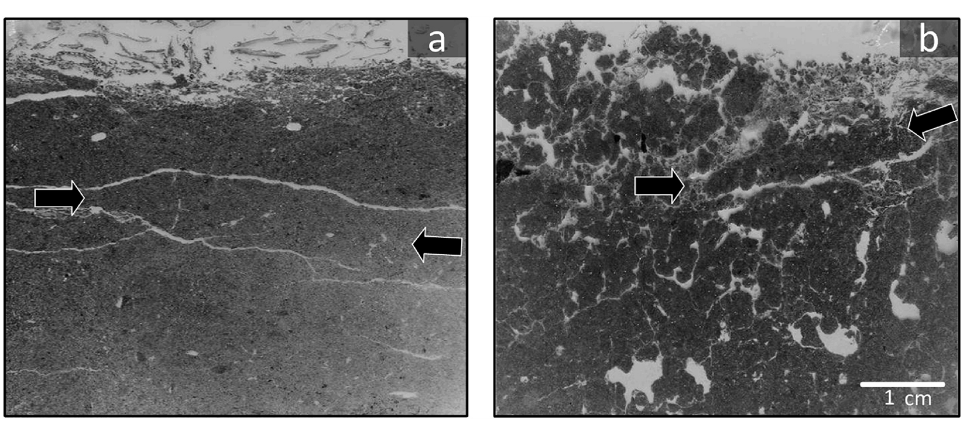

Fig. 7. Thin sections of topsoil (0–6 cm depth) exemplifying different types of platy structures. Area between arrows indicates: a) platy structures from a coarse textured soil matrix (GAP, Haplustoll); b) platy structures from densified and oriented biological aggregates with high internal porosity (GAP, Argiudoll – Monte Buey).

$_{5\,cm}$ (P = 0.004) (Kraemer, 2015). Similar results were found by Mueller et al. (2009) and Shepherd and Park (2003) in non-expandable soils, indicating the usefulness of this method to assess soil densification.

The use of VESS in the Pampean region raises another set of important issues to be considered. The application of this methodology in loamy soils of temperate climates (i.e. the Argentine Pampean region) must take into account the extent of no-till systems and their associated features. As pointed out by several authors (Morrás and Bonel, 2005; Sasal et al., 2006), the occurrence of laminar structures in these soils under NT has often been reported. This method records the presence of this structure with a score of 4 out of 5. Therefore, most soils in this region will have a score of 4. This value also corresponds to soils with anaerobic features and/or very poorly structured soils that is not appropriate for most of the cropping soils in the Pampean region. This same issue was noted by Cavalieri et al. (2009), who stated that laminar structures do not always lead to a critical state, these soils being more productive than predicted by the structural evaluation performed by VESS. Hence the location and morphology of this structure becomes important to establish the true effect on plant growth and soil quality. The extent, thickness and shape of the laminar structure may vary considerably in different soils (see thin sections of Haplustoll, Bengolea and Argiudol, Monte Buey in Fig. 7). As suggested by other ongoing studies by the authors, a more detailed analysis of layered structures, their formation, thickness and extent is probably necessary to establish quality subtypes that will reflect differences in behavior in water and thus improve the diagnosis provided by VESS.

Although the VESS method analyses and quantifies structure type by the thickness of each layer, the final value is the average of all the layers scores. According to Guimarães et al. (2009), this index would be enriched if calculated separately for each layer. Related to this, a recent study proposes a new guideline named SubVESS to assess soil structure in deeper layers (Ball et al., 2015). In this study, an increase of the index value was found with depth. This was expected due to the stratification of organic matter under NT and to the decline in biological activity with depth, also found by others who analyzed the biological activity in soils of these same locations and under the same types of management (Domínguez, 2012; Duval et al., 2013). Moreover similar results were found by Askari et al. (2013) in soils under NT management and by Guimarães et al. (2013) in sandy loam and clay loam soils with rigid clay mineralogy. In the Hapludert, the variation of Sq in depth was negligible because of the amount and type of clay present.

Finally, although this methodology is quick and simple and the operator only needs basic knowledge of soil science, timing of evaluation must be considered for the Pampas clay soils. Particular care should be taken of Vertisols as the period of optimum moisture content for field assessment is very short, due to high soil plasticity with intermediate and high soil moisture values and a hard structure under dry soil conditions.

4.2. Visible porosity and roundness

Vp and VESS (Sq) accounted for the highest proportion of variance due to management type (Table 2), although Vp did not present high correlation coefficients with inherent soil variables (Table 5). However, Vp was the only morphological parameter that showed significant correlations with all management variables (Table 4), detecting differences between agricultural management in three of the four soils studied (Fig. 6a). The lack of statistical differences between GAP and PAP in the Haplustoll can be explained by the high textural porosity of this soil (Kraemer et al., 2014). The sandy texture and the one year inclusion of peanut (*Arachis hypogaea L.)* in the recent past in the PAP crop sequence could have contributed to the absence of differences.

An increase in Rd was related to PAP treatment (Figs. 3 and 6b). Similar results were reported in a Typic Kandihumult under *Ilex paraguariensis* monoculture by Morrás et al. (1999). They observed the presence of more rounded aggregates (>8 mm) than in the quasi-pristine soil and under management with *Ilex paraguariensis* and *Pennisetum purpureum* residues. Alvarez et al. (2008), in an Argiudoll from southeast Buenos Aires province (Argentina) found differences in roundness in soils under different agricultural management, with higher roughness (lower roundness) in non-cropped soils. Number of years under NT also affected Rd due to greater soil disruption in managements with shorter NT history as shown by Olszevski et al. (2004) who found less rounded aggregates under no–till management compared to conventional tilling (moldboard plough and disc harrow). However, Rd was heavily influenced by mineralogical and textural characteristics of the studied soils (Tables 2 and 5), resulting in higher average Rd values in the Haplustoll than in the Hapludert. This behavior could be explained by higher swelling and shrinkage intensity in the latter soil that prevented roundness of soil aggregates, favoring more angular and wedge-shaped features. In consequence, its usefulness in expansive soils is relative. On the other hand, it was of great interest in Mollisols as the effect of different crop sequences under a same management (NT) was reflected in changes in the degree of aggregate roundness.

4.3. Tridimensional aggregate analyses

Tridimensional aggregate analysis proved to be a good method to discriminate between managements, with the number of faces the more reliable variable to explain the differences (Tables 2, 3). This agrees with the significant correlation found between number of faces and penetration resistance (r = −0.39, P = 0.022) and bulk density (r = −0.57, P = 0.0004, 0–20 cm) (Kraemer, 2015), suggesting a relationship with soil compaction. Moreover, as with VESS, the number of faces was also related to labile carbon fractions (POC_c and POC_f), showing a high sensitivity to changes in agricultural management. The higher correlation with POC_f indicates also that the n° of faces depends on an accumulated management effect as this fraction, although sensitive, is more stable than POC_c. POC_f is also considered a key variable to assess changes in crop sequence in the study area (Pampa Region, Argentina) (Duval et al., 2016; Galantini et al., 2014). When considering only Mollisols in the correlation analyses, all correlation coefficients between OC fractions and number of faces gave higher values, a direct consequence of the effect of high clay and smectite content of the Hapludert on face formation and stability.

Face formation is a process related to soil shrinkage and swelling (Hartge et al., 1999) and to other soil aggregation factors. Management practices could modify this process, as can also intrinsic soil characteristics as clay type and content and rheological properties. This agrees with the high correlation coefficient found between number of faces and clay activity, liquid and plastic limit and smectite + interestratified illite-smectite clay percentage.

Although the number of corners showed the same pattern of response to management (NE > GAP > PAP) as face numbers, there was an interaction with soil type that lowered the usefulness of this variable (Table 2, Fig. 6c). Sensitivity differences among these variables were also reported by Hartge et al. (1999), were the lack of sensitivity (power of the statistical test) was attributed to a high variability in the determination of this geometric feature, as the standard deviation of the n° of corners was four times larger than the one of the n° of faces.

5. Conclusion

Our study shows that in the Argentine Pampean region the intensification of crop sequences due to a higher inclusion of winter crops showed better score values for VESS, high visible porosity and less rounded aggregates with more faces and corners. In the case of VESS and Vp, this was corroborated by a high correlation coefficient with ISI (sequence intensification index) suggesting that crop sequence intensification enhances modifications toward more favorable structural features. All management variables related to soybean preponderance in the rotation had an opposite and detrimental effect compared with those associated with corn cultivation. These results highlight the influence of crop type on soil structural development. VESS, Vp, number of faces and corners were strongly and positively correlated with aggregate stability (AS) and with the more labile organic carbon fractions (POC_c and POC_f). This supports the idea that the morphological variables examined were highly sensitive to changes in crop sequence and could be used as a good soil quality in the Pampean region under no-till management and subjected to physical degradation and water erosion processes.

According to the results obtained the effect of agricultural intensification on these morphostructural variables is dependent on the variable and the soil type. VESS and number of faces were affected by soil inherent characteristics but were still sensitive enough to untangle management effects. Roundness was useful to evaluate different managements in Mollisols but no relevant information was obtained in the Hapludert. On the other hand, visible porosity and number of corners were less affected by soil composition and have a better discrimination value for management practices.

Finally, it is necessary to consider the limitations associated with each methodology, such as high Sq values associated with coarse textures. On the other hand, the common occurrence of platy structure under NT that heavily impacts VESS scores, shows the need to adjust the original methods to this agricultural system. Overall, morphostructural variables evaluated could be seen as suitable soil indicators to track crop sequence effects under no-till management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2017.01.013.

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