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Topsoil structure in no-tilled soils in the Rolling Pampa, Argentina

C. R. Alvarez[A,E], *M. A. Taboada*[A,B,C], *S. Perelman*[D], *and H. J. M. Morrás*[B]

[A]Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, CP (1417), Ciudad Autónoma de Buenos Aires, Argentina.
[B]Instituto de Suelos, Instituto Nacional de Tecnología Agropecuaria, Nicolas Repetto y de los Reseros s/n, CP (1686), Hurlingham, Buenos Aires, Argentina.
[C]Consejo Nacional de Investigaciones Científicas y Técnicas. Av. Rivadavia 1917 (C1033AAJ) Ciudad Autónoma de Buenos Aires - República Argentina.
[D]IFEVA (Facultad de Agronomía, Universidad de Buenos Aires - Consejo Nacional de Investigaciones Científicas y Técnicas), Av. San Martín 4453, CP (1417), Ciudad Autónoma de Buenos Aires, Argentina.
[E]Corresponding author. Email: alvarezc@agro.uba.ar

Abstract. Some topsoil physical properties evolve unfavourably under continuous, no-till farming. On the Pampa, loam soils under no-till sometimes have lower infiltration rates than those conventionally tilled; this is due to the occurrence of platy and massive structures. In this study, we aimed to identify the soil management practices that promote platy structure formation, and explain the soil physical behaviour linked to the thickness of platy structures in relation to infiltration rate, bulk density and shear strength. Six fields with different numbers of years under agriculture and diverse previous crops (maize or wheat–soybean double crop) were sampled, distinguishing within each field headlands (areas with higher traffic) and centre (lower traffic). Twenty samples were taken at random along a 200-m transect to characterise soil structure (platy, granular or massive) and the thickness of the platy structure. Principal component analysis revealed linkages between previous crop and location in each field and type of structure. ANOVA showed a significant ($P < 0.05$) interaction of previous crop × location. The frequency and thickness of the platy structures were lower, and those of granular structures higher, under wheat–soybean double cropping and in the centre of the field. Greater thickness of the platy structure determined lower water infiltration rate ($r = -0.337$; $P < 0.01$) and greater soil shear strength ($r = 0.297$, $P < 0.01$). Micromorphological analysis indicated the dominance of massive and platy structure in the headlands and bioturbation in the centre of the fields with wheat–soybean double cropping. These results suggest bioturbation, crop-root binding and low machinery traffic as the main factors minimising soil evolution towards unfavourable structural types under no-till farming in the area.

Additional keywords: infiltration rate, machinery traffic, no-till, shear strength, structural types.

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Introduction

Physical properties are an important part of the evaluation of soil quality and health (Hussain *et al.* 1999). Soil structure is generally characterised by form, stability and resilience. Structural form can be studied from two perspectives: according to the arrangement of primary particles in aggregates; and by size, shape and continuity of intra- and inter-aggregate pores, resulting from the spatial arrangement of the different aggregate hierarchies (Gardner *et al.* 1999). Generally, high infiltration rates (IR) are related to the presence of pores exposed at the soil surface that are >50 µm, stable, continuous and vertically oriented.

Soils with high silt content are considered problematic in terms of structure, particularly because of high susceptibility to physical degradation associated with low mechanical resistance (Stengel *et al.* 1984), and are considered of low resilience, related to the low shrink–swell capacity of the minerals they comprise (Taboada *et al.* 2004, 2008). This is a common problem in the north-east of the Argentine Pampa (i.e. Rolling Pampa), one of the most important grain-cropping regions of the world. Soils are Mollisols with high natural physical and chemical fertility, but are highly susceptible to physical degradation. This is associated not only with the loss of organic matter when cultivated (Álvarez *et al.* 2009), but also with the high content of fine silt (2–20 µm) of biotic origin (bioliths) (Cosentino and Pecorari 2002). The preponderance of illitic-type clay gives these soils a low capacity for structural regeneration (Taboada *et al.* 2008). Therefore, they are highly fragile under uncontrolled machinery traffic, more so when organic matter content is low. It can be assumed that in these situations, the stress generated by machinery traffic would not be offset by biotic factors. After continuous no-till (NT) over several years, many soils develop compaction and hardening, showing increased bulk density and penetration resistance, and decreased macroporosity (Voorhees and Lindstrom 1984; Taboada *et al.* 1998; Rhoton 2000; Díaz-Zorita *et al.* 2002; Sasal *et al.* 2006). Some authors have noted that surface compaction reverts naturally after several years under NT (e.g. >5 years), a result of soil organic carbon stratification (Thomas *et al.* 1996; Rhoton 2000) and, eventually, stable macroporosity conformation through the formation of biopores by soil fauna and roots (Voorhees and Lindstrom 1984; Rhoton 2000; Hubert *et al.* 2007). Under these conditions, with the presence of continuous and more stable biopores, we would expect a higher IR than under conventional cropping (Strudley *et al.* 2008). However, field evidence, corroborated by recent research results, do not always show favourable evolution of soil surface structure under NT (Sasal *et al.* 2006; Álvarez *et al.* 2009; Morris *et al.* 2010). Although there is greater structural stability, it does not necessarily result in greater macroporosity or IR (Taboada *et al.* 1998; Micucci and Taboada 2006; Sasal *et al.* 2006; Taboada *et al.* 2008). Studies in other countries (Morris *et al.* 2010) and in other regions of Argentina do not show a favourable evolution of IR under NT (Ferreras *et al.* 2000; Bonel *et al.* 2005; Sasal *et al.* 2006). Lipiec *et al.* (2006) found, in an 18-year experiment, that the soil under NT had 64% lower IR than soil under conventional tillage (CT), because there was a higher proportion of macropores under CT. Sasal *et al.* (2006) evaluated soil under CT and NT in three long-term experiments. In two, the IR was 25% higher in CT soils, and in the third, no differences were found. The existence of platy structure with planar porosity in soils under continuous NT has been reported (De Battista *et al.* 2005; Sasal *et al.* 2006; Álvarez *et al.* 2009), but it is still not known what causes these structural forms. Morrás *et al.* (2004) and Bonel *et al.* (2005) have related their presence to the effect of machinery passage, although in some cases, their degree of generalisation within a field suggests that other mechanisms may be involved. Shipitalo and Protz (1987) and VandenBygaart *et al.* (1999) reported the formation of this structural type in Canadian soils during the first few years under NT, attributing their formation to the rearrangement of aggregates and particles once soil tillage was stopped, and to the freezing process. During freezing, the formation of ice tongues in the planar pores helps to form the platy structure. However, after 4 years under NT, there was a reversal due to biological activity, especially worms. This agrees with the widespread idea of development of favourable IR after a few years under NT (Rhoton 2000). Unlike the findings in Canadian soils, in the Rolling Pampa, platy structures can be observed after several years under NT and even under crop rotations and without freeze–thaw processes, which do not exist under the climate of this region.

In this study, we aimed to: (*i*) identify soil management practices that promote the formation of platy structures in soils with high silt content of the Pampa region; and (*ii*) explain physical soil behaviour through the influence of the thickness of platy structures on IR, bulk density and shear strength. We hypothesised that machinery traffic is the main factor controlling the appearance of platy structural types, such that the higher the traffic intensity, the higher the frequency of its structures.

Materials and methods

Soil

The study was conducted on a farm in the Rolling Pampa, Buenos Aires, Argentina, under a pasture–cropping rotation production system. The cropping sequence was wheat–short-season soybean–corn–full-season soybean, always under NT. Rotations that include a pasture allow us to sample fields with different numbers of years under agriculture starting from the same initial condition. Six fields that differed in the number of years under agriculture and/or in their most recent crop were selected for sampling (Table 1). A field with a 3-year-old pasture was also sampled, to determine the effect of the pasture on soil structure. The soil is a Typic Argiudoll, O'Higgins Series (Table 2; INTA 2013).

In each field, two different areas were identified according to intensity of machinery traffic, and considered as nested factors within each field: headland and centre of the field. The headlands, where machines are turned around, loaded and unloaded, have a higher traffic intensity than the centre of the field.

Measurements

Transects 200 m long were laid out in the headlands (high machinery traffic) and centre (low traffic) of each field. Twenty randomly selected points were sampled in each transect. At each point, we determined soil structural type

Table 1. Location of the sampled fields and management characterisation

Site number	Location	Last crop before sampling	Years after last pasture	No. of annual crops after last pasture
1	34°57′24.65″S 60°12′39.85″W	Maize	3	4
2	34°55′23.39″S 60°11′55.98″W	Maize	4	5
3	34°55′37.62″S 60°12′50.51″W	Wheat–soybean	6	7
4	34°56′7.44″S 60°12′41.23″W	Wheat–soybean	4	5
5	34°57′24.36″S 60°13′3.98″W	Maize	8	11
6	34°55′30.82″S 60°12′40.1″W	Wheat–soybean	5	7

Table 2. Soil analytical data of the O'Higgins Series (INTA 2013)

Soil horizon:	Ap	A2	Bt	BC	C
Soil sample depth (cm):	3–8	18–25	35–45	55–65	135–175
Clay <2 μm ($g\,kg^{-1}$)	185	215	245	168	67
Silt ($g\,kg^{-1}$)	440	400	357	380	348
Sand ($g\,kg^{-1}$)	375	385	398	452	585
CEC ($cmol_c\,kg^{-1}$)	19	20	18	16	14
Base saturation (%)	81	82	85	84	87

(i.e. granular, platy or massive) to 10 cm depth according to the Soil Survey Division Staff (1993). When platy structure was present, its thickness (mm) was determined. The data obtained was used to calculate the proportion of each structural type in each transect. Four of these points in each transect (total 48) were sampled with cylinders 5 cm in diameter by 5 cm high to determine bulk density of the soil (Burke *et al.* 1986); 10-cm-diameter cylinders were also used to extract undisturbed soil samples for analysis. In the laboratory, IR was determined on undisturbed samples ($n = 48$) using a similar approach to that proposed by the Soil Quality Institute (2011) for field determinations. First, 400 mL of water was added to each cylinder (10 cm height) to homogenise water content of the soil. Then a 1-inch (2.54-cm) sheet of water was applied. IR was calculated as the time taken for this sheet of water to disappear into the soil. On the surface of each of these samples, shear strength was determined using a Pocket Vane Tester (Eijkelkamp, Giesbeek, The Netherlands). On a composite sample consisting of 30 subsamples, total organic carbon content (TOC) was determined by the Walkley–Black method (Nelson and Sommers 1982). Micromorphological analyses were carried out on undisturbed samples of the topsoil (5 cm by 5 cm by 5 cm depth) taken in a vertical plane in two farm fields with different previous crops (corn and wheat–short-season soybean) and locations within the field (headlands and central areas). The undisturbed samples were impregnated with a polyester resin, and the thin sections obtained were analysed by polarising optical microscopy with Leica-Wild MZ8 equipment (Leica, Wetzlar, Germany). Micromorphological descriptions were made according to Stoops (2003).

Statistical analyses

Patterns of variation between fields were identified via principal component analysis, a multivariate technique that allows the main variation gradients between fields to be identified and ordered in relation to the gradients of maximum variation between possible linear combinations of observed variables. The axes that represent these gradients are termed main components. The variables considered were: number of years since the most recent pasture; number of crops since the last pasture; previous crop (maize value = 0; wheat–short-season soybean value = 1); location (low machinery traffic value = 0, high traffic value = 1); proportion of platy, massive and granular structures; thickness of the platy structure; and TOC content. The variation in frequency of platy and granular structure was analysed with analysis of variance for the split-plot model, where previous crop (wheat–short-season soybean or maize) was assigned to the main field, and field location (high and low traffic) to the subplot. We also calculated the linear correlation between the different variables (Neter and Wasserman 1974).

Results

Factors related to soil structure type

The first principal component explained 42% of the variability among sites (Fig. 1, Table 3). This axis mainly reflects proportion of unfavourable structure (platy + massive), the granular structure and thickness of the platy structure associated with the effects of traffic intensity (location) and the previous crop. The frequency of the granular structure was higher and frequency of the unfavourable structure was lower when the preceding crops were wheat–short-season soybean, and in the centre of the fields (low traffic). The other factors: number of years, number of crops since the last pasture and TOC (mean 30 $g\,kg^{-1}$, range 25.5–37.3 $g\,kg^{-1}$) had low weight in this first axis. These factors became important in the second axis (which explained 25% of the variability), showing no relationship or change with the dominant structure type.

The structures prevailing in the field were platy and granular, with massive being only a minor proportion (0–0.35). Frequency of platy (Fig. 2*a*) and granular (Fig. 2*b*) was significantly affected by the interaction of previous crop × location within the field. The lowest frequency of platy structures occurred when the preceding crops were wheat–short-season soybean, in the centre of the field (frequency 0.47). In any other situation, frequency of platy structures was always >0.78. The opposite occurred with granular structure. This clearly shows that the best structural condition was achieved in the centre of the field after a wheat–short-season soybean crop. The same trend was observed with thickness of the platy structure (Fig. 2*c*), which reached 2 cm in the centre of the field after a wheat–short-season soybean crop, whereas all other situations averaged a thickness of 5.5 cm. This indicates that sectors with the higher frequency of platy structure had also greater thickness or development of this structure.

Effect of structural type on some soil physical properties

From the analysis of the 48 undisturbed samples, platy structure thickness varied from 0 cm (total absence) to 9 cm (Table 4). This morphological property and infiltration rate showed higher variability than bulk density and shear strength. Thickness of the platy structure was negatively correlated with infiltration rate ($r = -0.3373$, $P < 0.01$) and positively correlated with shear strength ($r = 0.2969$, $P < 0.05$). No correlation was found between the other variables.

Micromorphology

The coarse fraction of the samples was composed of euhedral and subhedral angular grains, mainly quartz, feldspars and plagioclases, with a small proportion of shards of acid volcanic glass, phytoliths, and mica and pyroxene grains. Grain size was predominantly 50–100 μm with a random basic distribution pattern (Figs 3 and 4). The colour of the fine-fraction groundmass was dark brown, due to a high proportion of humified organic matter. The coarse : fine ratio

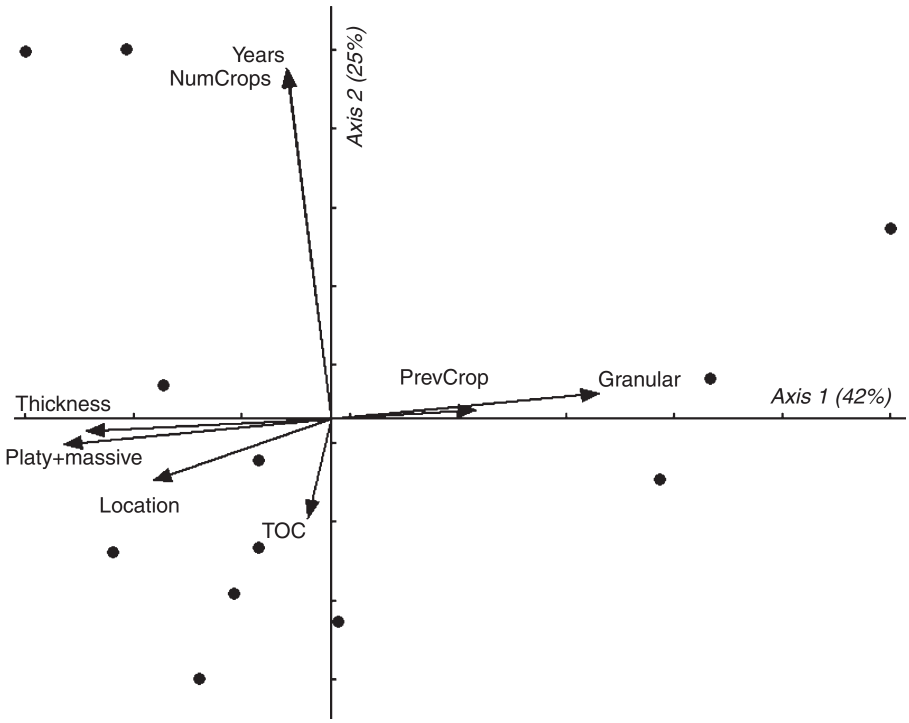

Fig. 1. Principal component analysis. Length of vectors indicates the relative weight of a variable on the axis. Platy+massive or Granular, Frequency of platy plus massive or granular structures in the field; PrevCrop, previous crop (maize or wheat–short-season soybean); Location, centre or headland of the field; Years, years since last pasture; Num crop, number of annual crops since last pasture; Thickness, thickness of the platy structure; TOC, total organic carbon.

Table 3. Eigenvectors of the different variables for each of the two axes of the principal component analysis

Location: 0 for centre and 1 for headlands. Previous crop: 0 for maize and 1 for wheat–soybean doubled crop

Variables	e1	e2
Location	–0.35	–0.12
Previous crop	0.28	0.02
Granular	0.52	0.05
Platy+massive	–0.52	–0.05
Thickness	–0.48	–0.02
Years	0.09	0.69
Number crops	–0.09	0.69
TOC	–0.05	–0.19

was ~85 : 15, with a simple spaced porphyric distribution and an undifferentiated b-fabric.

In the headlands of a field that had maize as previous crop and intense machinery traffic, the top part of samples had a moderately separated, platy microstructure (Fig. 3*a*, top) with fissure microstructure in its lower part (Fig. 3*a*, bottom). The top of the thin section in Fig. 3 showed horizontal and sub-horizontal, smooth, undulating thick planes (~600 µm wide) with sub-horizontal thin planes. The bigger planes define platy aggregates ~5–10 mm thick. In the middle and lower part of the sample (Fig. 3, bottom), the groundmass was relatively dense, with sub-horizontal and sub-vertical thin planes, and some irregular to rounded small voids. A few dense, infilled channels were found, particularly in the lower part of the sample. Fresh and slightly humified plant residues were observed in the surface; at the bottom, the organic residues were scarce and small. This microstructure is typical of the platy under no-till (L) model described by Morrás *et al*. (2012).

Unlike the dense, platy morphology observed in the headlands, the samples in the sector with lower traffic intensity revealed, in upper and lower parts, a combination of platy and crumb microstructure (Fig. 3*b*). In this case, the individual platy aggregates were rather small, separated by thin and short planar voids. The biggest plates also showed an internal fragmentation with fissures and small, subangular peds. Moreover, platy aggregates appeared partly disturbed by biological activity, as shown by a significant proportion of tubular voids and infilled channels. Compound packing voids between non-accommodating granules and crumbs were the main type of pores in these biodisturbed areas. Some of the channels filled with partly welded, sub-spherical faecal pellets were as big as 10 mm in diameter. Small plant fragments in different stages of humification were occasionally observed. Thus, in the inner part of plots with maize, microscopic analysis revealed a transitional situation between a platy microstructure model (L) and a biodisturbed model (B) (Morrás *et al*. 2012).

Figure 4 exemplifies the platy (L) microstructure model found in the A horizon of fields cultivated with wheat–soybean as previous crops. In the upper part of the horizon of

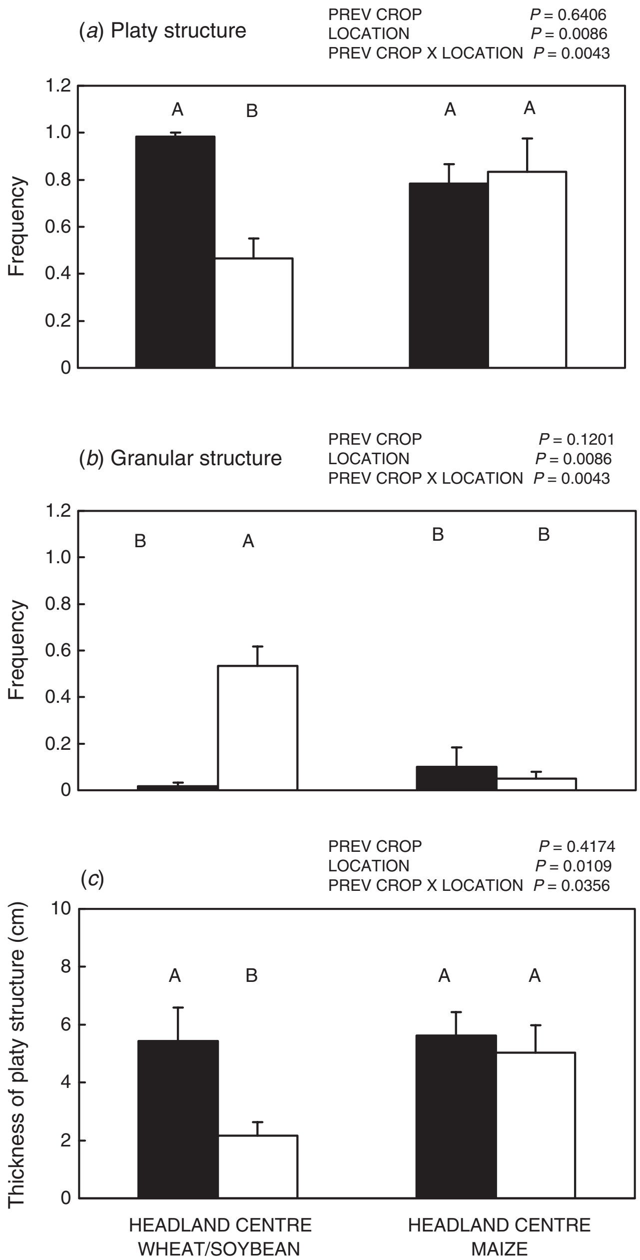

Fig. 2. Frequency of (*a*) platy and (*b*) granular structures, and (*c*) thickness of platy structure for the previous crop × location interaction. ANOVA *P*-values are shown for each comparison. Bars with the same letter are not significantly different between treatments. Capped lines indicate standard error.

Table 4. Mean, minimum, maximum values and standard errors for soil properties, measured in 48 samples taken in the different fields

	Mean	s.e.	Minimum	Maximum
Thickness of platy structure (cm)	4.16	0.44	0	9
Bulk density (Mg m^{-3})	1.21	0.02	0.95	1.45
Infiltration rate (mL min^{-1})	19.9	2.48	2.7	84
Shear strength (kg cm^{-2})	2.7	0.08	1.5	3.7

the headlands, the microstructure was platy; the lower part had a platy and fissure microstructure (Fig. 4*a*, top and bottom). Thick planes separating thick plates characterised the upper portion of this sample. Compound packing voids between biological microaggregates and plant residues were observed at the soil surface. In the lower part of the sample, the groundmass was dense, with horizontal thin planes. Few root channels, and some rounded to irregular voids, were also present in the soil groundmass. Excrements were relatively scarce, mainly concentrated in the upper and medium part of the sample. Few sub-spherical pellets and some plant residues in different degrees of humification were observed at the soil surface.

By contrast, samples under the same treatment (wheat–soybean previous crops) but under low traffic intensity showed crumbly microstructure formed by biological microaggregates in both the upper and lower portion (Fig. 4*b*). In this thin section, some sectors had a spongy microstructure, whereas a fissure microstructure appeared in restricted areas. There were abundant infilled, mostly disturbed channels, their edges hardly recognisable because of intense biological activity. Porosity consisted mainly of compound packing voids. Few smooth, short, thin planes with different orientation were observed, related to channel walls, coalescent biological aggregates and few small subangular blocks ~5 mm in diameter. The micromorphological features in this case are representative of the biodisturbed (B) model described in no-till systems (Morrás *et al.* 2012).

Discussion

The results highlight three issues: (*i*) the widespread distribution of platy structures in the studied soils; (*ii*) the positive effect on aggregation of the wheat–short-season soybean double crop; and (*iii*) the negative effect of machinery traffic, which overrode the positive effect of double cropping on the headland of the fields (high traffic).

The first issue, presence of platy structures in soils under NT, has been mentioned in the literature (Kay *et al.* 1985; Shipitalo and Protz 1987; VandenBygaart *et al.* 1999; Bonel *et al.* 2005; Sasal *et al.* 2006; Álvarez *et al.* 2009; Soracco *et al.* 2010). Platy structure formation has been attributed to the collapse of macropores in the absence of tillage, which produces soil settlement and consolidation, forming a planar structure with clear dominance of horizontal porosity (Kay *et al.* 1985; Shipitalo and Protz 1987; VandenBygaart *et al.*1999). In regions with cold climate, the freeze–thaw cycles reinforce this planar structure (VandenBygaart *et al.* 1999). Many of these soils have high levels of organic carbon, as is the case of the temperate-climate soil that we studied (TOC 30 g kg^{-1} average). These high concentrations of TOC are in accord with TOC stratification with soil depth under NT in the Pampa (Álvarez *et al.* 2009).

In the absence of freeze–thaw cycles, the abiotic formation of aggregates is related to crack formation caused by alternating wetting–drying cycles, which allows for soil volumetric expansion (Dexter 1988; Oades 1993). The soils of the Rolling Pampa have illitic clay minerals of low expandability. However, some recent results showed that,

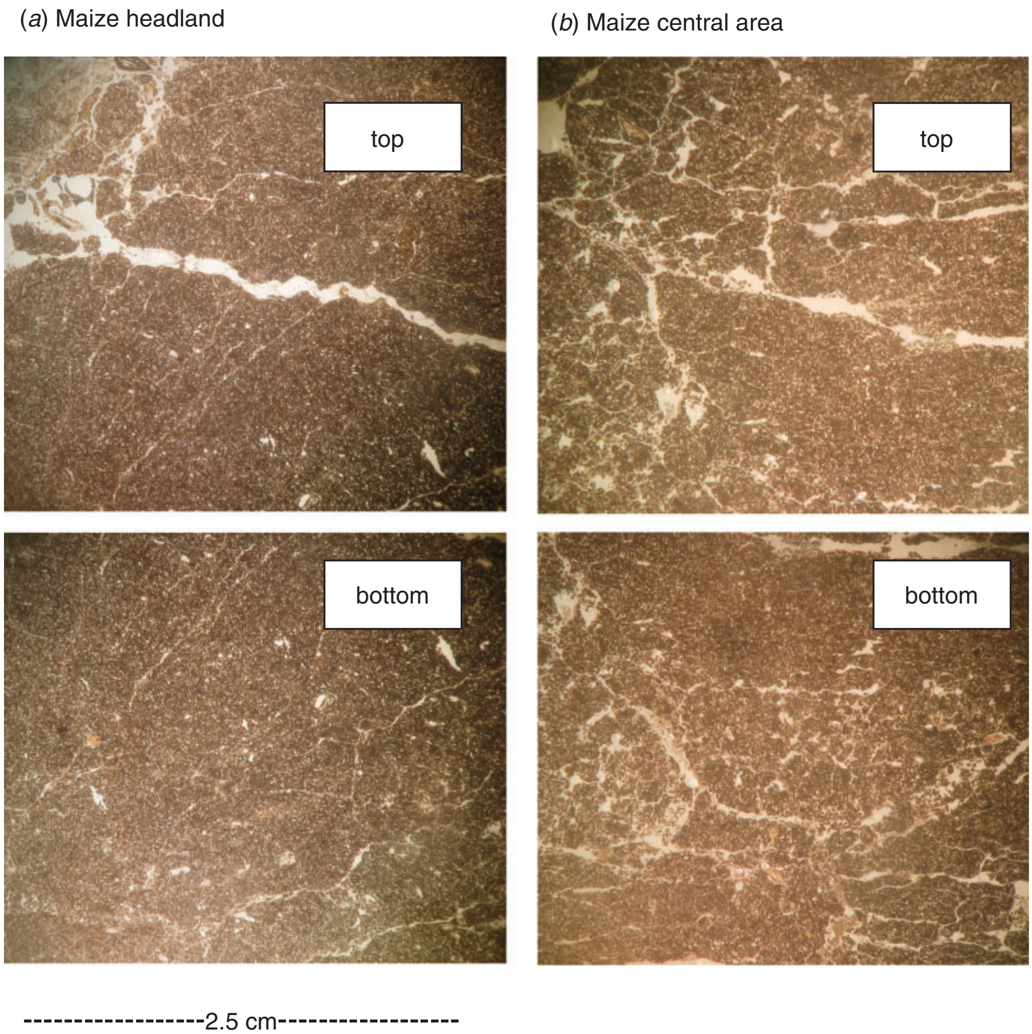

Fig. 3. Vertically oriented soil thin section with maize as previous crop, and different locations inside the field: (*a*) headlands and (*b*) central region (site 2).

despite their silty character, these soils have some expansion capacity during the wetting–drying cycles (Barbosa *et al.* 1999; Cosentino and Pecorari 2002; Taboada *et al.* 2004, 2008). One little-explored mechanism is the presence of 'differential swelling' with fast wetting, as described by Dexter (1988). This mechanism is based on the generation of tension stresses, a consequence of the contact between water (matric potential = 0) and layers of very dry soil (very negative matric potential). As a result, trapped air pressure is generated within the pores, giving rise to the formation of cracks parallel to the wetting front (Dexter 1988). These pressures have been identified as generating volumetric expansion under low water content in Pampean soils (Taboada *et al.* 2001; Fernández *et al.* 2010). This mechanism may also take place in the field at the end of prolonged drought periods, when a heavy rain wets the ground suddenly, although there is no direct impact of the drops as in a soil under NT. This may help to explain the wide distribution of planar structures in Pampean soils under NT.

The second issue, which is the other aggregation and stabilisation mechanism, is associated with biological factors. Our results show that the continued presence of roots throughout the year in wheat–short-season soybean crops was associated with a higher proportion of granular structure. This highlights the importance of rhizosphere biotic mechanisms such as root 'binding' and glueing by labile organic carbon compounds (Oades 1984; Dexter 1988; Degens 1997). These mechanisms have been found to cause short-term stable aggregation in loamy soils with non-expandable clays in the Pampa region (Taboada *et al.* 2004). To explore this idea, we carried out a structural survey in a 3-year-old pasture in the same farm. We found granular aggregation both in the headland and in the centre of the field, which can be considered the result of biological aggregation mechanisms (Degens 1997; Taboada *et al.* 2004). A pasture, being a multi-year crop with the coexistence of different root types (grasses and legumes), would maximise the root-binding effect. This type of aggregation mechanism is temporary, as some authors have

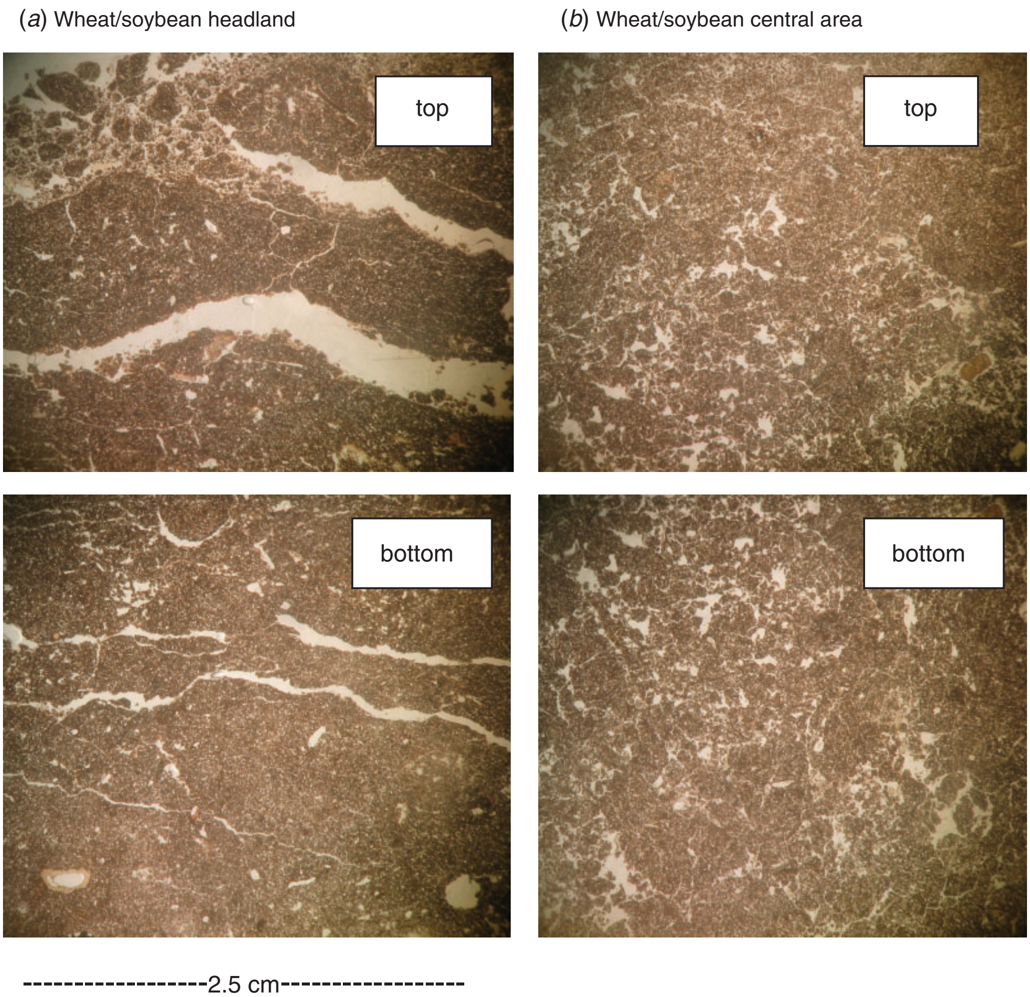

Fig. 4. Vertically oriented soil thin section of wheat–soybean as previous crop and different locations inside the field: (*a*) headlands and (*b*) central region (site 6).

established (Tisdall and Oades 1982; Dexter 1988). This may explain the lack of association between years since the last pasture and frequency of unfavourable structures. Frequencies >80% of unfavourable structures were observed in soils cropped for 3 years since the most recent pasture. In greenhouse experiments, Barbosa *et al*. (1997) and Taboada *et al*. (2004) found a higher number of large and stable aggregates when wetting–drying cycles were combined with the presence of roots (ryegrass). Those authors highlighted the importance of wetting–drying cycles to fragment, and that of biological stabilisation to strengthen, soil structure. This sequence of formation and stabilisation mechanisms was not dependent on the presence of swelling clays. Only four 1-month cycles, and the presence of ryegrass, were sufficient to rebuild the structure. Another factor that may have contributed in this double-cropping situation is the narrow spacing between wheat rows. Wheat sowing could generate a mechanical disruption of the surface of the platy structure, with subsequent stabilisation by roots.

Bioturbation by soil fauna has a significant impact on soil structural organisation. Thus, the role of invertebrates on pore and aggregate formation under conservation tillage is increasingly recognised (Bartlett and Ritz 2011). Comparative studies of systems under different soil management have provided evidence of a significant increase in the number and diversity of soil fauna under NT (Warburton and Klimstra 1984; Wilson-Rummenie *et al.* 1999; Ríos de Saluso *et al.* 2001). In a Pampean Mollisol with different degrees of degradation from mouldboard plough tillage, Morrás *et al*. (2001) found a higher density and a greater diversity of meso- and macrofauna in sites that were subsequently cultivated under NT than in sites under continued CT. Moreover, clear faunal differences were observed among sites under NT with initially different degree of degradation, which may be partly related to different organic matter contents arising from their management histories (Morrás *et al.* 2001).

Micromorphology has provided direct information on the activity of soil fauna in NT soils. The analysis carried out by Shipitalo and Protz (1987) on a Brunisol in Ontario, Canada, showed that in fields under NT there is a tendency for pores to become elongated and parallel-oriented to the soil surface, as well as an increase in bioporosity, compared with tilled fields. In a soil in Kentucky, USA, Drees *et al*. (1994) identified a strong, horizontal platy structure in the top 5 cm of NT fields; earthworm channels filled with excrements were abundant but absent in conventionally tilled soils. As previously mentioned, VandenBygaart *et al*. (1999) observed a greater number of horizontally oriented, elongated macropores in the top horizon of an NT Luvisol in Ontario, Canada, and a significant increase with time in the number of rounded macropores, attributed to the effect of roots and soil fauna.

Micromorphological analysis carried out on the surface horizon of different Mollisols in the northern Pampa have also shown important micromorphological differences between NT sites and those tilled with disk ploughing or undisturbed control sites (Morrás *et al.* 2004, 2008; Morrás and Bonel 2005; Bonel *et al.* 2005). Recently, Morrás *et al*. (2012) proposed three microstructural models to characterise no-till systems. The platy model exhibits a well-developed platy microstructure. The biodisturbed model is dominated by tubular voids and infillings; in some cases, these biological features appear disturbing platy aggregates, which become broken and tilted; in others, faunal activity has been intense and no remains of platy structure are observed in the topsoil. In the densified model, the surface horizon is densely packed and has very low porosity.

Although the platy structure of the topsoil seems intrinsic to the NT cropping system, as referred in the literature and in our field description, our micromorphological analysis also showed the important role of soil fauna in the process of aggregate formation in this system, with higher fauna activity in the centre than in the headlands of the fields.

Our analysis is still limited in its ability to distinguish more precisely the effect of crop rotation on faunal activity and on the evolution of soil structure. This may be due to the high spatial heterogeneity of the topsoil structure under no-till (Morrás *et al.* 2012) and to the small soil volume sampled and evaluated by the micromorphological method used compared with the field description. Nevertheless, it can be assumed that the continuous root growth associated with wheat–soybean double cropping provides the soil fauna with a more constant food supply and a better environment throughout the year. The greater ‘rhizospheric action’ of double cropping on the development of granular structures could be associated not only with a greater ‘binding’ effect but also with an increased and continuous faunal activity in the soil surface layer.

The third issue is the effect of machinery traffic. Under heavy traffic conditions, unfavourable (platy and massive) structures were dominant, regardless of the type of previous crop. Sub-vertical thin planes observed in headlands of the field with maize as the previous crop (Fig. 3*a*) may be also related to mechanical stresses produced by tyres of vehicles (Morrás *et al.* 2012). Therefore, machinery traffic can be considered an additional factor that favours development and persistence of both structural types. The effect of machinery passage is known to lead to the formation of platy to massive structures. Using a sensor system, Horn *et al*. (2003) observed that the first passage of a tractor has a vertical force component up to 2 cm and then it produces horizontal soil displacement. It can be speculated that this horizontal displacement is probably the determinant of platy structure formation. As the number of machinery passages increases, the shift becomes mostly vertical, because of the sharp structural deterioration. Słowińska-Jurkiewicz and Domz al (1991) evaluated the structural changes produced by the passage of a tractor’s front and rear wheels on a sandy and a loamy soil. Microstructure analysis performed by those authors showed that repeated passages produced greater changes in the loamy soil, in which after three passes, a platy structure with regular horizontal fissures was formed. This was assumed to be caused by ‘soil shearing’ and displacement from the passage of tractor. The authors also warned that, although bulk density changes were not as important, the change in this type of horizontal porosity had a significant impact on air and water permeability. Soracco *et al*. (2010), too, found a negative effect of this pore design on conductivity and IR in Pampean soils. Both properties become more important when soil samples are taken perpendicular to the surface. Our results show that, the greater the thickness of the layer with platy structure, the lower the IR and the higher the shear strength. In this way, the negative effect of this structural type on soil water dynamics has been shown.

Conclusions

We hypothesised that machinery traffic is the main factor controlling the appearance of platy structural types. Results showed that this kind of structure was found in headlands and in centre locations; however, its proportion was maximised in headlands, and in centre locations under maize. This shows that the low traffic intensity of centre locations was enough to develop platy structures in NT soil under maize. These platy structures were denser in the trafficked headlands; hence, the proposed hypothesis is accepted. Therefore, we conclude that machinery traffic was a main factor for the appearance of platy structures in NT soil, but the proportion of these structural forms can be alleviated by crop-root binding and soil bioturbation. Taking this into account, better management practices such as controlled agricultural traffic and crop rotations maximising living roots all year round (e.g. cover crops, double cropping, crops with fibrous root system, etc.) are recommended to attain sustainable soil management under continuous no-till farming in this area.

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