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Assessment of topsoil properties in integrated crop–livestock and continuous cropping systems under zero tillage

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Abstract. A regional study was conducted in the northern Pampas of Argentina in order to compare soil quality at proximal cropland sites that are managed under either continuous cropping (CC) ($n = 11$) or integrated crop–livestock (ICL) ($n = 11$) systems under zero tillage. In the ICL system, samples were taken in the middle of the agricultural period. Although soil total and resistant organic carbon (TOC, ROC) were significantly higher in silt loam soils than in loam/sandy loam soils, variations in carbon concentration were not associated with differences in soil management. Soil relative compaction was the only property that was significantly ($P < 0.05$) affected by the soil type × management interaction. Soil relative compaction values were significantly lower with ICL in loam/sandy loam soils, but there were no significant differences in silt loam soils. Structural instability index showed little change from CC to ICL sites, indicating that there was no soil structural damage. Soil penetration resistance was significantly higher in ICL soils within the first 0.075 m of soil depth, slightly exceeding the critical threshold (2000 kPa). However, firmer topsoil under ICL was not due to shallow compaction, as evidenced by no increase in soil bulk density.

Additional keywords: cattle trampling, soil compaction, soil organic carbon fractions, soil physical properties.

Introduction

The majority of cropland in Argentina is managed for the large scale under continuous cropping, which is based on the extensive use of zero-till (ZT) farming, extensive application of herbicides (e.g. glyphosate and atrazine), and prevalence of soybean (*Glycine max* L. Merrill) within the crop rotations (Lavado and Taboada 2009). Although this production system is economically sound, at least on a short-term basis, it produces few agricultural products. The integration of crop and livestock production is an interesting alternative to increase the buffering capacity of the agroecosystem against variations in the climate and economy (Viglizzo 1986), but also adds diversity to the entire production system. Expected benefits of a crop–pasture rotation system are more efficient use of inputs (Siri Prieto and Ernst 2009), and increased input of organic carbon (Studdert *et al*. 1997; Gentile *et al*. 2005) and nitrogen (Armstrong *et al*. 2003) to the soil.

Although integrated crop–livestock production systems can yield several benefits, there may also be adverse effects, including shallow soil compaction (Willatt and Pullar 1984; Chanasyk and Naeth 1995; Greenwood *et al*. 1997) and other negative impacts on soil physical properties (Martínez and Zinck 2004). The magnitude and duration of compaction depend on multiple factors including livestock treading intensity, stocking rate, grazing management, and the animal species (Chanasyk and Naeth 1995; Mapfumo *et al*. 1999), as well as on intrinsic site characteristics such as soil texture, vegetation status, soil moisture, and organic matter content (Chanasyk and Naeth 1995; Smith *et al*. 1997). Several factors are likely to be simultaneously active, resulting in soil type × soil management interactions, as observed by van Haveren (1983). Soil damage due to grazing compaction may extend to a depth of 0.20 m (Greenwood *et al*. 1997, 1998; Drewry and Paton 2000; Drewry *et al*. 2004).

Higher bulk density (BD) and penetration resistance (PR), as well as lower infiltration rate (IR) and water availability, are usually characteristic of soil underlying a grazed area relative to an ungrazed field (Greenwood *et al*. 1997, 1998; Singleton and Addison 1999; da Silva *et al*. 2003; Franzluebbers and Stuedemann 2008). Increases in PR are related to the age of the pasture (Martínez and Zinck 2004), cattle management (Proffitt *et al*. 1995), and cattle stocking rate (da Silva *et al*. 2003). Although it may seem counter-intuitive, loosening of the soil by ploughing (e.g. mould-board plough) may also promote shallow compaction by grazing animals. The harder surface of ZT fields may protect deeper soil from further compaction (Alvarez *et al*. 2009).

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The physical effects of livestock treading on soil condition have generally been studied in grazed pastures under different management regimes or in annual forage crops (generally winter cover crops). Fewer data are available from grazed crop residues, particularly in ZT farming systems. Questions remain as to the benefits and/or liabilities of a crop–livestock management system. The main objective of this work was to provide quantifiable data regarding the possible tradeoff between the positive influence of integrated crop–livestock use of an area through higher soil organic carbon incorporation during pasture periods, and potentially negative effects of livestock trampling on soil physical properties. A regional study was conducted that included different soil textural groups in the northern Pampas of Argentina. The working hypothesis was that the condition of ZT soils, managed with integrated crop–livestock systems during the agricultural period, will show no deterioration of soil physical condition.

Materials and methods

Study area and experimental design

The study was conducted in Rolling Pampa of Argentina. This region has a climate that is temperate (mean annual temperature of 17.3°C) and humid (mean annual precipitation of 1044 mm). Precipitation varies with season; rainfall is concentrated during spring and summer. Soils have developed over aeolian sediments (loess) and with natural grassland vegetation (Soriano 1991).

Field measurements and soil sampling were conducted during winter (July–August) in 2006 and 2007. Twenty-two sites were evaluated, presenting soil textures ranging from silt loam ($n = 11$) to loam/sandy loam ($n = 11$) under two different managements: (*i*) continuous cropping (CC) under ZT; (*ii*) integrated crop–livestock (ICL) under ZT. The former is the most common management in this area. The crop sequence was maize (*Zea mays* L.) followed by soybean (*Glycine max* L. Merrill), with application of herbicide in the fallow. In the ICL system, farm fields were alternately cropped (alternating maize and soybeans, one per year) over 8 years, followed by a grass–alfalfa (lucerne, *Medicago sativa* L.) pasture for 4 years. During the winter, cattle (1.1 cow/ha) were allowed to graze maize and soybean residue and winter weeds (*Stellaria media* L. and *Bowlesia incana*). Grass–alfalfa pastures are managed with a rotational grazing system, with a stocking rate of 30–40 cows/ha. Plots selected for the ICL system were sampled over mid-way through the agricultural cycle, i.e. 4 years after pasture. The selected production farms were similar in terms of their technological level and general management systems (e.g. fertiliser rates, herbicides, and pesticides, and no irrigation). Each soil type and management combination corresponded to an experimental unit.

Soil physical characterisation and soil organic carbon pools

Soil chemical analyses were realised from composites samples. Each one consisting of at least 20 subsamples, collected from the 0–0.05 and 0.05–0.20 m soil depth at each experimental unit. These composite samples were analysed in the laboratory for total organic carbon (TOC) by the Walkley and Black method, pH (1 : 2.5 soil : water), and particle size by the pipette method and the resulting textural classification.

Soil samples obtained from 0–0.05 and 0.05–0.20 m were separated by wet sieving to determine carbon fractions (Cambardella and Elliott 1992). Air-dried soil (10 g) was mixed with 30 mL of sodium hexametaphosphate (5 g/L). The mixture was shaken over 15 h, and the dispersed samples were wet-sieved through a 53-µm mesh; the <53-µm fraction was recovered. This fraction was oven-dried at 60°C, weighed, and ground for organic carbon determination. Carbon content in the smaller size fraction (<53 µm, resistant organic carbon (ROC)) was determined by wet combustion (Walkley and Black). The particulate organic content (POC) was calculated as the difference between TOC and ROC.

Soil IR was determined (four subsamples in each experimental unit) using a method developed by the Soil Quality Institute (1999). A 0.15-m-diameter ring infiltrometer was driven 0.08 m into the soil; the soil surface exposed within the ring was lined with plastic film (i.e. common kitchen plastic wrap). Distilled water (444 mL) was poured into each ring and the plastic was removed. The time required for all of the water to soak in (infiltrate) was recorded (infiltration 1). After determination of infiltration 1, an additional 444 mL of distilled water was applied in the same way, and IR was again recorded (infiltration 2). This second IR reflected steady-state infiltration.

Soil for each experimental unit was tested for compaction (Proctor test) in the laboratory, following the ASTM standard method (ASTM International 1982). Dry soil subsamples (~3 kg) were moistened with different amounts of water to achieve various water contents. These moistened soil subsamples were compacted into three layers in a compaction chamber (944 cm^3). Each layer received 25 blows from a hammer (2.5 kg) falling from a height of 30.5 cm. Soil water content (SWC, determined by oven-drying at 105°C) and BD were both determined in each moistened and compacted soil sample. By plotting the SWC–BD relationship, the maximum BD (maxBD) and critical water content (CWC) indices were obtained. Soil BD was determined by the core method (Burke *et al.* 1986) using cores of 100 cm^3 volume (10 subsamples in each experimental unit). The coring device was inserted from 0 to 0.05 m and again in the middle interval of the 0.05–0.20 m layer. Soil was kept shaded, transported on ice to the laboratory, and processed within 24 h of returning to the laboratory. The field core soil BD values and maxBD values (from the compaction test) were used to obtain the relative compaction (RC):

$$\mathrm{RC}\,(\%) = [(\mathrm{BD}\,(\mathrm{Mg/m^3})/\mathrm{maxBD}\,(\mathrm{Mg/m^3})] \times 100 \qquad (1)$$

The critical BD (BDc) was calculated as suggested by Pilatti and de Orellana (2000) in an equation for soil of the Pampean region:

$$\mathrm{BDc} = 1.52 - 0.0065 \times \mathrm{clay}\,(\%) \qquad (2)$$

Soil PR from 0 to 0.20 m depth was determined (10 subsamples in each experimental unit) at 0.025-m intervals using a static digital penetrometer (Fieldscout SC-900®, Spectrum Technologies, Plainfield, IL, USA) with a tip angle of 30°. The SWC was determined in composite samples collected from the 0–0.05 and 0.05–0.20 m layers. The PR was corrected according to the mean of the SWC values, 227 and 206.2 g/kg, for 0–0.05 and 0.05–0.20 m, respectively.

Two undisturbed samples were taken from the first 0.20 m to determine their structural instability index (SI), as described by De Leenheer and De Boodt (cited by Burke *et al*. 1986). This index is calculated as the difference between the mean weight diameter of dry-sieved (4.8-, 3.4-, and 2-mm mesh) and wet-sieved (4.8-, 3.4-, 2-, 1-, 0.5-, and 0.25-mm mesh) aggregates. An increase in this difference indicates a decrease in structural stability. After dry-sieving (vibration), soil aggregates were wet-sieved for 5 min in a Yoder apparatus. These aggregates had been previously moistened by capillary action up to field capacity, to avoid slaking of dry aggregates.

Statistical analysis

The experimental design allowed for the evaluation of both independent and interactive effects of soil type and soil management on soil properties. Soil type had two levels: (*i*) silt loam and (*ii*) loam/sandy loam; soil management also had two levels: (*i*) CC and (*ii*) ICL. Soil properties were analysed at two depths: (*i*) 0–0.05 m and (*ii*) 0.05–0.20 m. This division attempts to consider the minimum and maximum depths reported in the literature as affected by cattle trampling (Herrick and Lal 1995; Greenwood *et al*. 1997, 1998; Drewry and Paton 2000; Villamil *et al*. 2001; Drewry *et al*. 2004). Data were evaluated by factorial analysis of variance (ANOVA) for the 0–0.05 and 0.05–0.20 m layers within each sampling depth. Significant differences were determined at $\alpha = 0.05$. Associations between soil properties were evaluated using simple and multiple regressions (Neter and Wasserman 1974). Soil PR was analysed for each layer (0.025 m depth) by ANOVA. Multivariate analysis (principal component analysis) was used to determine the principal gradients responsible for variability among sites.

Results and discussion

Characterisation of study sites

The loam/sandy loam textural group averaged 142 g clay and 382 g silt/kg, while the silt loam group had 238 g clay and 601 g silt/kg. The selected study sites were a balanced representation of these two textural groups in the region (Table 1). Soil pH was not affected by soil type × soil management interaction, or by additive effects of both factors. Soil pH averaged 6.47, showing that the soils were slightly acidic at all study sites.

Soil organic carbon pools

Soil organic pools were not affected by soil type × management interaction in any of the layers (Table 2). Similar concentrations of TOC, POC, and ROC were found in CC and ICL production systems in all layers. Soil TOC and ROC concentrations were significantly higher in silt loam soils than in loam/sandy loam soils. Soil carbon stocks were calculated from carbon concentrations and BD data for the first 0.20 m layer (Fig. 1).

Table 1. Silt and clay content (g/kg) and pH of sampled soils under different management and soil type (0–0.20 m)

CC, Continuous cropping systems; ICL, integrated crop–livestock systems; s.e., standard error

		Silt	Clay	pH
	Soil management			
CC ($n = 11$)	Mean	478	190	6.42
	s.e.	44	17	0.09
	Min.	244	128	5.90
	Max.	688	266	7.00
ICL ($n = 11$)	Mean	485	181	6.52
	s.e.	38	19	0.13
	Min.	343	78	5.80
	Max.	683	264	7.30
P-value		0.86	0.56	0.57
	Soil type			
Silt loam ($n = 10$)	Mean	601	238	6.56
	s.e.	23	9	0.13
	Min.	484	200	5.80
	Max.	688	266	7.30
Loam/sandy loam ($n = 12$)	Mean	382	142	6.39
	s.e.	20	11	0.10
	Min.	244	78	5.90
	Max.	495	215	7.00
P-value		<0.01	<0.01	0.33
	Soil management × soil type interaction			
P-value		0.88	0.67	0.91

Soil TOC and ROC stocks were also similar between CC and ICL sites and were significantly different between soil types. Loam/sandy loam soils had ~5 Mg and 7 Mg/ha less ROC and TOC, respectively, than found in the silt loam soils (Fig. 1). In a region with a relatively homogeneous climate, the amount of fine mineral particles is one of the main factors controlling TOC and ROC levels (Alvarez and Lavado 1998; Quiroga *et al*. 1999), which explains the lower carbon stocks found in the loam/sandy loam soils.

Soil TOC, especially the POC fraction, usually increases during the pasture period and decreases during the first 3 or 4 years when land is in the crop production phase (Galantini and Rosell 1997; Díaz-Zorita *et al*. 2002; García-Prechác *et al*. 2004; Gentile *et al*. 2005; Franzluebbers and Stuedemann 2009). In our study, however, TOC and POC concentrations did not vary between management strategies. This consistency may be the result of: (*i*) a probable decrease in TOC and POC after 4 years of continuous cropping after pasture, and (*ii*) the high stocking rates (30–40 cows/ha) for grazing in sown pastures, which prevents the accumulation of belowground biomass.

Soil physical properties

Bulk density and relative compaction

Soil BD was significantly higher in the loam/sandy loam than in the silt loam textural group (Table 2). Soil BD values (0–0.20 m) were correlated with texture, and TOC and POC concentrations. In order to test the occurrence of excessive compaction using BD values, an equation estimating the

Table 2. Main physical properties and organic compounds under different management systems and soil types for different depths (0–0.05 and 0.05–0.20 m)

CC, Continuous cropping systems; ICL, integrated crop–livestock systems; TOC, total organic carbon; POC, particulate organic carbon; ROC, resistant organic carbon; BD, bulk density; IR, infiltration rate. Within columns, values followed by the same letter are not significantly different ($P > 0.05$) between soil management or soil type for each depth. Standards errors are given in parentheses

	TOC	POC (g/kg)	ROC	BD (Mg/m^3)	IR (mm/h)
		0–0.05 m			
CC	20.41 (1.02)a	8.08 (1.00)a	12.74 (0.42)a	1.30 (0.02)a	88.91 (22.14)a
ICL	21.72 (1.48)a	8.27 (1.13)a	13.45 (0.69)a	1.34 (0.02)a	63.27 (8.16)a
P-value	0.43	0.91	0.18	0.18	0.90
Silt loam	23.31 (1.48)a	9.56 (1.35)a	14.22 (0.49)a	1.30 (0.02)a	70.74 (16.18)a
Loam/sandy loam	19.18 (0.75)b	7.02 (0.62)a	12.16 (0.48)b	1.35 (0.02)a	80.54 (17.57)a
P-value	0.02	0.11	0.01	0.10	0.53
Soil type × management interaction					
P-value	0.81	0.89	0.48	0.89	0.23
		0.05–0.20 m			
CC	15.58 (0.59)a	4.27 (0.36)a	11.50 (0.60)a	1.40 (0.02)a	
ICL	15.97 (1.07)a	4.44 (0.60)a	11.55 (0.79)a	1.37 (0.02)a	
P-value	0.71	0.67	0.93	0.18	
Silt loam	17.27 (0.88)a	4.55 (0.54)a	12.91 (0.62)a	1.35 (0.02)b	
Loam/sandy loam	14.54 (0.64)b	4.18 (0.46)a	10.38 (0.53)b	1.41 (0.01)a	
P-value	0.03	0.81	0.01	0.01	
Soil type × management interaction					
P-value	0.78	0.86	0.84	0.87	

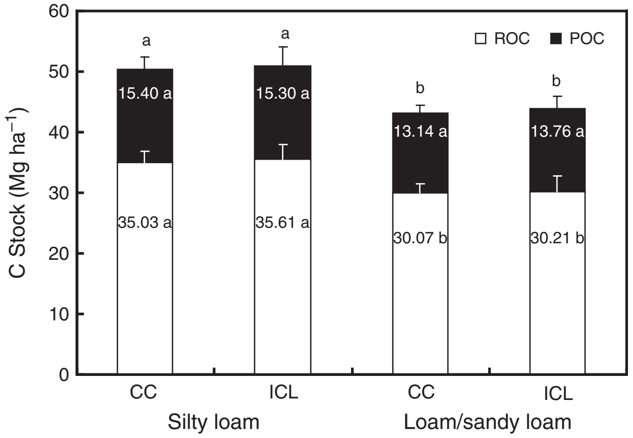


Fig. 1. Total organic carbon stock and resistant organic carbon (ROC) and particulate organic carbon (POC) stocks for different management treatments (CC, continuous cropping systems; ICL, integrated crop–livestock systems) and soil types within the 0–0.20 m soil layer. Vertical bars indicate standard error. Different letters indicate significant differences ($P < 0.05$) between management treatments.

threshold of BD for the Pampean soils on the basis of their clay content was used (Pilatti and de Orellana 2000). For the studied sites, the mean threshold was 1.36 Mg/m^3 for the silt loam soils and 1.43 Mg/m^3 for the loam/sandy loam. Few BD values exceeded these thresholds for the different soils and management practices (Table 2).

Several studies have reported an increase in BD as a consequence of direct grazing in pastures (Chanasyk and Naeth 1995; Proffitt *et al.* 1995; Drewry *et al.* 2004; Martínez and Zinck 2004; Pietola *et al.* 2005) or ZT cover crops (Franzluebbers and Stuedemann 2008), and Quiroga *et al.* (2009) observed a higher BD with grazing of crop residues in conventional tillage and ZT. In our study, however, no BD increase was observed from CC to ICL treatments, either in the surface or subsurface layers. The absence of elevated BD due to grazing may be associated with the low stocking rate at which crop residues are grazed during the winter, and/or the high bearing capacity of soil during dry winter periods. Díaz-Zorita *et al.* (2002) found similar BD values when comparing ungrazed and grazed fields with maize and soybean crop residues in the semi-arid Pampas of Argentina, in the western part of the study region.

Only soil RC was significantly affected by a soil type × management interaction ($P = 0.0266$). Soil RC was significantly higher in the CC sites than the ICL sites, but only in the loam/sandy textural group (Fig. 2). Differences in RC were the result of significantly higher maxBD in loam/sandy loam soils under ICL management (average maxBD: ICL, 1.63 Mg/m^3; CC, 1.49 Mg/m^3). This suggests soils in the coarser textural group are potentially more compactable than those in the fine textural group. Soil RC in the 0–0.20 m layer was positively related to silt content and negatively related to sand content (Table 3).

Soil penetration resistance

Soil PR has been reported to be strongly associated with SWC (da Silva *et al.* 2003; Franzluebbers and Stuedemann 2008); a similar relationship was found in the present study. Significantly different ($P < 0.001$) linear models were fitted to the data from the 0–0.05 and 0.05–0.20 m layers (Fig. 3). In the

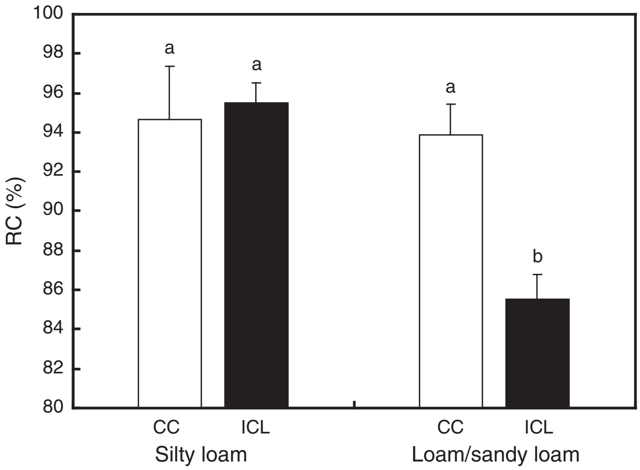


Fig. 2. Relative compaction (RC) under different management systems (CC, continuous cropping; ICL, integrated crop–livestock) and soil types. Vertical bars indicate standard error. Different letters indicate significant differences ($P < 0.05$) between management treatments.

top layer, the straight line models were also significantly different ($P < 0.001$) between the CC and ICL systems. In both cases, SWC accounted for approximately half of the variation in PR. The fitted lines had similar slopes but significantly different intercepts. Because of this, the production system was included as a dummy variable in a multiple regression model (Fig. 3). The value of this coefficient indicated that soil PR was 490 kPa higher in ICL than CC sites over the whole SWC range.

Soil PR was the only physical property that could distinguish between CC and ICL management systems. Increased soil PR in association with grazing activities has been observed at depths as shallow as 0.05 m (da Silva *et al*. 2003) or as deep as 0.20 m (Hamza and Anderson 2005; Franzluebbers and Stuedemann 2008). In the present study, differences in PR, corrected according to the mean of the SWC values for each depth, were observed within the first 0.075 m of soil (Fig. 4). The critical threshold value (2000 kPa) reported for the penetrometer with a 30° tip angle was only exceeded below a depth of 0.05 m. These results agree with other studies

Table 3. Correlation coefficients between pairs of soil properties of compaction for 0–0.20 m depth ($P < 0.01$)

TOC, total organic carbon; POC, particulate organic carbon; ROC, resistant organic carbon; BD, bulk density; PR, penetration resistance; WC, water content; maxBD, maximum bulk density; CWC, critic water content; RC, relative compaction; SI, structural instability

	Sand	Clay	Silt	TOC	POC	ROC	BD	PR	WC	maxBD	CWC	RC
Clay	–0.7980	1										
Silt	–0.9638	0.6085	1									
TOC	–0.6695			1								
POC				0.7376	1							
ROC	–0.7598		0.7670	0.7897		1						
BD	0.5509		–0.5743	–0.6552	–0.5949		1					
PR								1				
WC					0.5656		–0.5447	–0.7862	1			
maxBD	0.7928		–0.7765	–0.6502		–0.6302	0.5137			1		
CWC	–0.7582		0.7060	0.5065		0.6546				–0.6517	1	
RC	–0.5603		0.5314							–0.8101	0.5391	1
SI												

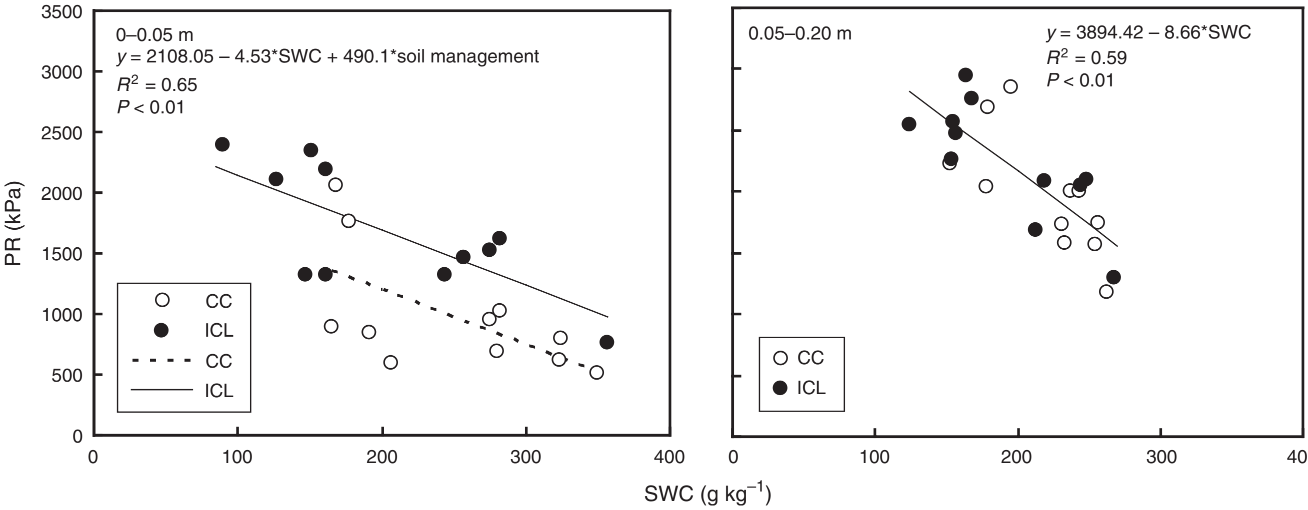


Fig. 3. Relationship between penetration resistance (PR) and soil water content (SWC) at different soil depths. CC, Continuous cropping; ICL, integrated crop–livestock. Dummy variable (soil management): CC = 0; ICL = 1.

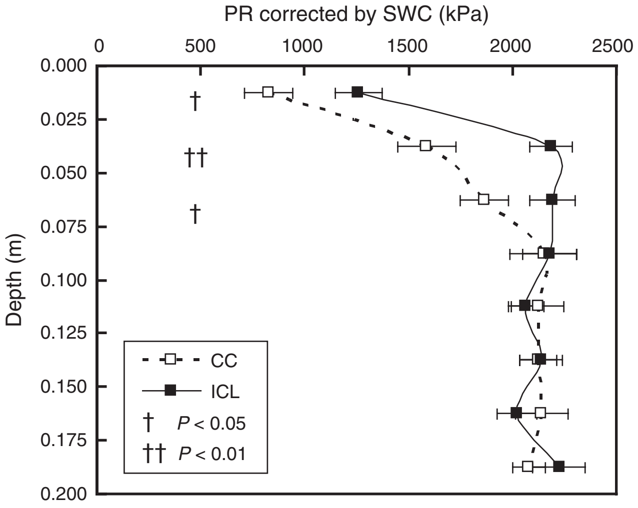


Fig. 4. Soil penetration resistance (PR) corrected by soil water content (SWC) at depth, under CC (continuous cropping) and ICL (integrated crop–livestock) systems. Horizontal bars represent standard error.

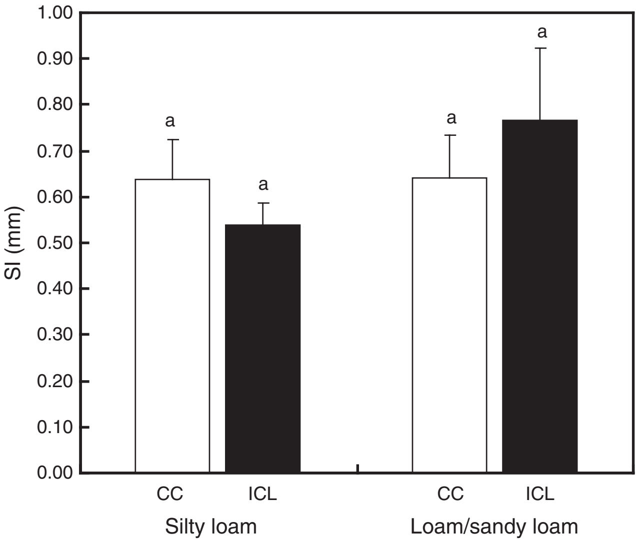


Fig. 5. Structural instability (SI) for different management systems (CC, continuous cropping; ICL, integrated crop–livestock) and type of soil. Vertical bars indicated standard error. Different letters indicate significant differences ($P < 0.05$) between management treatments.

which showed that soil PR is increased by grazing (da Silva *et al.* 2003; Hamza and Anderson 2005; Franzluebbers and Stuedemann 2008), and confirm the usefulness of soil PR as a parameter for describing changes in soil compaction status over short depth increments (Martínez and Zinck 2004).

Increases in PR were not a consequence of increases in BD, showing that total porosity was not affected by grazing. These rises in PR cannot be attributed to compaction processes, which typically occur in parallel to soil densification (Hamza and Anderson 2005). Rather than compaction, the elevation in soil PR found here is likely to be in response to a process of topsoil hardening, as previously found in ZT topsoil of the Pampas region (Taboada *et al.* 1998; Díaz-Zorita *et al.* 2002; Alvarez *et al.* 2009).

Infiltration rate and structural instability

Soil IR showed no effects from both soil management and soil type (Table 2). However, soil IR tended to be lower in ICL than CC sites. This lack of significant differences is counter to general reports in the literature. Greenwood and McKenzie (2001) reviewed several studies and found that water infiltration rates were 75% lower in pasture than in closure areas. Our field IR measurements showed a substantial range of values, as demonstrated by high coefficients of variation. That no significant differences between management strategies were found was likely due to the observed variability. Proffitt *et al.* (1995) reported similar IR variation.

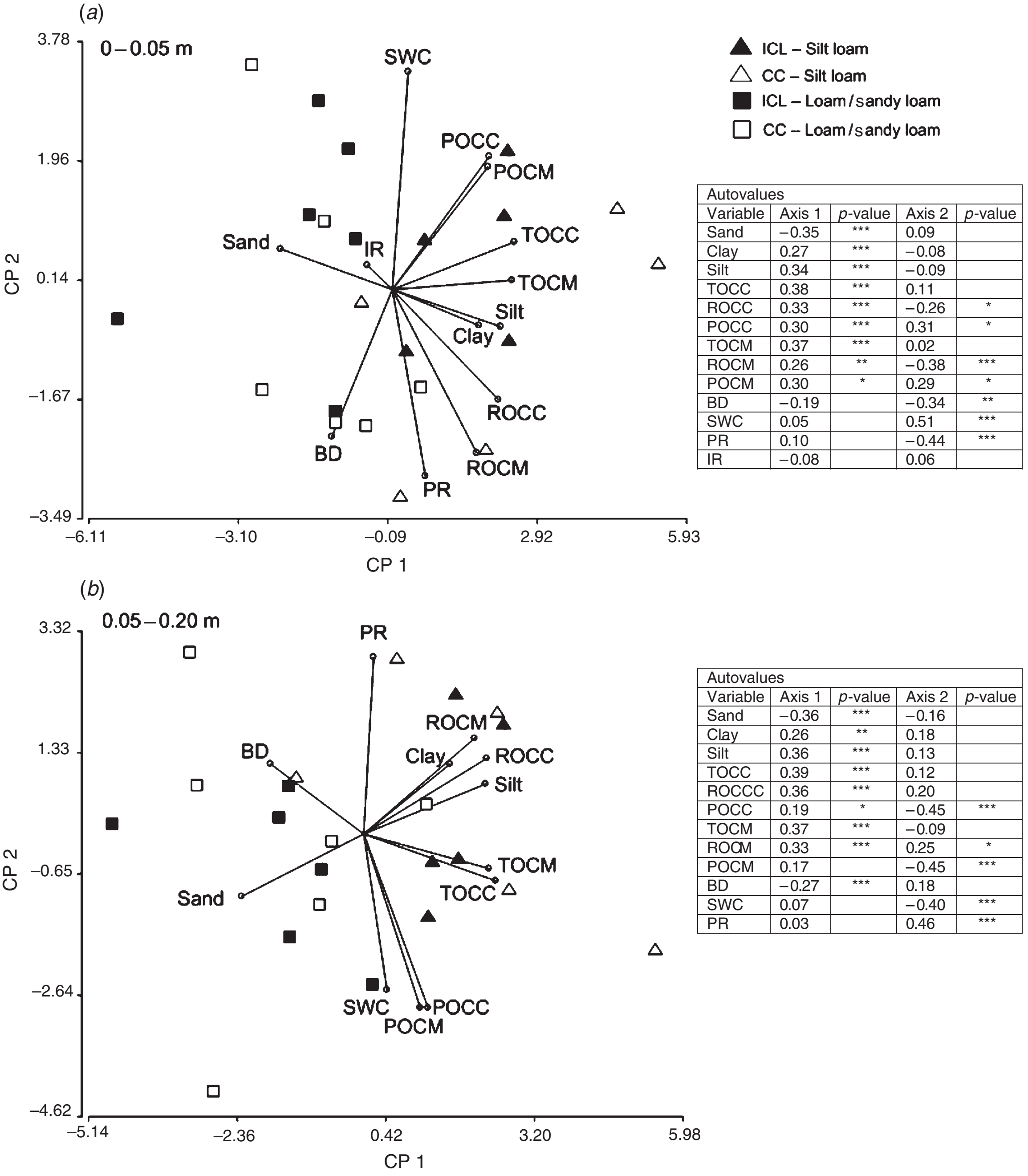
No significant effects were found for the SI index (Fig. 5). As with IR, research has shown that soil structural stability decreases in response to trampling by livestock (Warren *et al.* 1986; Greenwood and McKenzie 2001). It is likely that the mechanical impact delivered by cattle hooves at the studied stocking rate (1.1 cow/ha.year) was not enough to compress and destroy topsoil aggregates at the ICL sites. Franzluebbers and Stuedemann (2008) also observed that treading by livestock did not have a significant effect on soil structural stability. It is probable the combination of the higher load-bearing capacity of soil under ZT farming conditions and low stocking rates largely prevented structural deterioration from grazing.

Principal components analysis

This analysis provides a summary of the information and identifies the most relevant variables that can explain the majority of variability within the dataset. Results from principal component (PC) analysis for physical properties and organic carbon pools (TOC, POC, and ROC), expressed as concentration or mass for the 0–0.05 and 0.05–0.20 m layers, are depicted in Fig. 6*a, b*. Approximately 70% of the variance was explained by the first two PCs for both of the studied depths. For the 0–0.05 m layer, the first PC axis (PC1) explained 47% of the variance. Sand fraction was negatively weighted and was counter-balanced by silt and clay content and the organic carbon pools (TOC, ROC, POC), expressed as concentration or stock. This first PC axis clearly distinguished sites with silt loam soils from those with loam/sandy loam soils. The second PC axis explained 25% of the variance; the main components were SWC and the labile fraction of the organic carbon, counter-balanced by PR, BD, and ROC.

For the 0.05–0.20 m soil layer, 48% of variance was explained by the first axis (PC1) and 27% by the second axis (PC2). The variables and their relative weights in this layer were similar to those of the upper (0–0.05 m) soil layer, except POC in PC1 and BD and ROC in PC2.

Conclusions from this analysis corresponded to those determined by traditional hypothesis testing, which relies heavily on data variance (i.e. ANOVA). Both methods of analysis showed that soil type, represented in PC1 by texture and carbon pools, was the main variable that differentiated the sampling sites, and in PC2, soil PR and SWC were the main variables discriminating between production systems.



Autovalues				
Variable	Axis 1	*p*-value	Axis 2	*p*-value
Sand	−0.35	***	0.09	
Clay	0.27	***	−0.08	
Silt	0.34	***	−0.09	
TOCC	0.38	***	0.11	
ROCC	0.33	***	−0.26	*
POCC	0.30	***	0.31	*
TOCM	0.37	***	0.02	
ROCM	0.26	**	−0.38	***
POCM	0.30	*	0.29	*
BD	−0.19		−0.34	**
SWC	0.05		0.51	***
PR	0.10		−0.44	***
IR	−0.08		0.06	

Autovalues				
Variable	Axis 1	*p*-value	Axis 2	*p*-value
Sand	−0.36	***	−0.16	
Clay	0.26	**	0.18	
Silt	0.36	***	0.13	
TOCC	0.39	***	0.12	
ROCCC	0.36	***	0.20	
POCC	0.19	*	−0.45	***
TOCM	0.37	***	−0.09	
ROCM	0.33	***	0.25	*
POCM	0.17		−0.45	***
BD	−0.27	***	0.18	
SWC	0.07		−0.40	***
PR	0.03		0.46	***

Fig. 6. Biplot of principal components analysis: (*a*) 0–0.05 m, (*b*) 0.05–0.20 m. Vectors indicate the relative weight of each variable on the axes. $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$.

Conclusions

This regional study showed that the physical condition of the soil was minimally affected by a switch from continuous ZT crop management to an ICL production system. The soil organic carbon components, as well as the structural instability index, showed little change from CC to ICL sites, indicating there was no residual pasture effect at the time soils were sampled. In the same manner, soil revealed no evidence of compaction from livestock trampling. There was some slight topsoil hardening in ICL that only in some cases exceeded the critical threshold for soil penetration resistance.

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References

Alvarez R, Lavado RS (1998) Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. *Geoderma* **83**, 127–141. doi:10.1016/S0016-7061(97)00141-9

Alvarez CR, Taboada MA, Gutierrez Boem F, Bono A, Fernández PL, Prystupa P (2009) Topsoil properties as affected by tillage systems in the Rolling Pampa Region of Argentina. *Soil Science Society of America Journal* **73**, 1242–1250. doi:10.2136/sssaj2008.0246

Armstrong RD, Millar G, Halpin NV, Reid DJ, Standley J (2003) Using zero tillage, fertilizers and legume rotations to maintain productivity and soil fertility in opportunity cropping systems on a shallow Vertosol. *Australian Journal of Experimental Agriculture* **43**, 141–153. doi:10.1071/EA01175

ASTM International (1982) Standard test methods for moisture relations using a 5.5 lb (2.5 kg) hammer and 12 inch (304.8 mm) drop. In 'ASTM Standards in Building Codes'. pp. 836–842. (American Society for Testing and Materials: Philadelphia, PA)

Burke W, Gabriels D, Bouma J (1986) 'Soil structure assessment.' (A.A. Balkema: Rotterdam)

Cambardella CA, Elliott ET (1992) Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Science Society of America Journal* **57**, 1071–1076. doi:10.2136/sssaj1993.03615995005700040032x

Chanasyk D, Naeth A (1995) Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. *Canadian Journal of Soil Science* **75**, 551–557.

da Silva AP, Imhoff S, Corsi M (2003) Evaluation of soil compactions in an irrigated short-duration grazing system. *Soil & Tillage Research* **70**, 83–90. doi:10.1016/S0167-1987(02)00122-8

Díaz-Zorita M, Duarte G, Grove J (2002) A review of no-till systems and soil management for sustainable crop production in the sub-humid and semi-arid Pampas of Argentina. *Soil & Tillage Research* **65**, 1–18. doi:10.1016/S0167-1987(01)00274-4

Drewry JJ, Paton RJ (2000) Effects of cattle treading and natural amelioration on soil physical properties and pasture under diary farming in Southland, New Zealand. *New Zealand Journal of Agricultural Research* **43**, 377–386. doi:10.1080/00288233.2000.9513438

Drewry JJ, Paton RJ, Monaghan RM (2004) Soil compaction and recovery cycle on a Southland dairy farm: implications for soil monitoring. *Australian Journal of Soil Research* **42**, 851–856. doi:10.1071/SR03169

Franzluebbers AJ, Stuedemann JA (2008) Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. *Soil & Tillage Research* **100**, 141–153. doi:10.1016/j.still.2008.05.011

Franzluebbers AJ, Stuedemann JA (2009) Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. *Agriculture, Ecosystems & Environment* **129**, 28–36. doi:10.1016/j.agee.2008.06.013

Galantini JA, Rosell RA (1997) Organic fractions, N, P and S changes in an Argentine semiarid Haplustoll under different crop sequences. *Soil & Tillage Research* **42**, 221–228. doi:10.1016/S0167-1987(97)00002-0

García-Prechác F, Ernst Benech O, Siri-Prieto G, Terra JA (2004) Integrating no-till into crop-pasture rotations in Uruguay. *Soil & Tillage Research* **77**, 1–13. doi:10.1016/j.still.2003.12.002

Gentile RM, Martino DL, Entz MH (2005) Influence of perennial forages on subsoil organic carbon in a long term rotation study in Uruguay. *Agriculture, Ecosystems & Environment* **105**, 419–423. doi:10.1016/j.agee.2004.05.002

Greenwood KL, MacLeod DA, Scott JM, Hutchinson KJ (1997) Long-term stocking rate effects on soil physical properties. *Australian Journal of Experimental Agriculture* **37**, 413–419. doi:10.1071/EA96131

Greenwood KL, MacLeod DA, Scott JM, Hutchinson KJ (1998) Changes to soil physical properties grazing exclusion. *Soil Use and Management* **14**, 19–24. doi:10.1111/j.1475-2743.1998.tb00605.x

Greenwood KL, McKenzie BM (2001) Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* **41**, 1231–1250. doi:10.1071/EA00102

Hamza MA, Anderson WK (2005) Improving soil physical fertility and crop yield on a clay soil in Western Australia. *Australian Journal of Soil Research* **53**, 615–620.

Herrick JE, Lal R (1995) Soil physical property changes during dung decomposition in a tropical pasture. *Soil Science Society of America Journal* **59**, 908–912. doi:10.2136/sssaj1995.03615995005900030040x

Lavado RS, Taboada MA (2009) The Argentinean Pampas: A key region with a negative nutrient balance and soil degradation needs better nutrient management and conservation programs to sustain its future viability as a world agroresource. *Journal of Soil and Water Conservation* **64**, 150A–153A. doi:10.2489/jswc.64.5.150A

Mapfumo E, Chanasyk DS, Naeth MA, Baron VS (1999) Soil compaction under grazing of annual and perennial forages. *Canadian Journal of Soil Science* **79**, 191–199.

Martínez LJ, Zinck JA (2004) Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. *Soil & Tillage Research* **75**, 3–17. doi:10.1016/j.still.2002.12.001

Neter J, Wasserman W (1974) 'Applied linear statistical models: regression analysis of variance and experimental design.' (Ed. RD Irwin) p. 872. (Homewood Publishing Co.: Chicago)

Pietola L, Horn R, Yli-Halla M (2005) Effects of trampling by cattle on the hydraulic and mechanical properties of soil. *Soil & Tillage Research* **82**, 99–108. doi:10.1016/j.still.2004.08.004

Pilatti MA, de Orellana JA (2000) The ideal soil: II critical values of an 'ideal soil' for Mollisols in the north of the Pampean Region (in Argentina). *Journal of Sustainable Agriculture* **17**, 89–112. doi:10.1300/J064v17n01_08

Proffitt APB, Bendotti S, McGarry D (1995) A comparison between continuous and controlled grazing on a red duplex soil. I. Effects on soil physical characteristics. *Soil & Tillage Research* **35**, 199–210. doi:10.1016/0167-1987(95)00486-6

Quiroga A, Buschiazzo DE, Peinemann N (1999) Soil compaction is related to management practices in the semi-arid Argentine pampas. *Soil & Tillage Research* **52**, 21–28. doi:10.1016/S0167-1987(99)00049-5

Quiroga A, Fernández R, Noellemeyer E (2009) Grazing effect on soil properties in conventional and no-till systems. *Soil & Tillage Research* **105**, 164–170. doi:10.1016/j.still.2009.07.003

Singleton PL, Addison B (1999) Effect of cattle treading on physical properties of three soils used for dairy farming in the Waikato, North Island, New Zealand. *Australian Journal of Agricultural Research* **37**, 891–902.

Siri-Prieto G, Ernst O (2009) Manejo del suelo y rotación con pasturas: efecto sobre la calidad del suelo, el rendimiento de los cultivos y el uso de insumos. *Informaciones Agronómicas* **45**, 22–26.

Smith CW, Johnston MA, Lorentz S (1997) Assessing the compaction susceptibility of South African forestry soils. II. Soil properties affecting compactability and pressibility. *Soil & Tillage Research* **43**, 335–354. doi:10.1016/S0167-1987(97)00023-8

Soil Quality Institute (1999) 'Soil quality test kit guide.' (NRCS Soil Quality Inst.: Auburn, AL). Available at: www.solvita.com/pdf-files/USDA-SOIL-RESPIRATION.pdf.

Soriano A (1991) Río de la Plata grasslands. In 'Ecosystems of the world. 8A. Natural grasslands'. (Ed. RT Coupland) pp. 367–407. (Elsevier: Amsterdam)

Studdert AG, Echeverría HE, Casanovas EM (1997) Crop–pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. *Soil Science Society of America Journal* **61**, 1466–1472. doi:10.2136/sssaj1997.03615995006100050026x

Taboada MA, Micucci FG, Cosentino DJ, Lavado RS (1998) Comparison of compaction induced by conventional and zero tillage in two soils of the rolling Pampa of Argentina. *Soil & Tillage Research* **49**, 57–63. doi:10.1016/S0167-1987(98)00132-9

van Haveren BP (1983) Soil bulk density as influenced by grazing intensity and soil type on a shortgrass prairie site. *Journal of Range Management* **36**, 586–588. doi:10.2307/3898346

Viglizzo EF (1986) Agroecosystems stability in the argentine pampas. *Agriculture, Ecosystems & Environment* **16**, 1–12. doi:10.1016/0167-8809(86)90071-X

Villamil MB, Amiotti NM, Peinemann N (2001) Soil degradation related to overgrazing in the semi-arid southern caldenal area of Argentina. *Soil Science* **166**, 441–452. doi:10.1097/00010694-200107000-00002

Warren SD, Thurow TL, Blackburn WH, Garza NE (1986) The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. *Journal of Range Management* **39**, 491–495. doi:10.2307/3898755

Willatt ST, Pullar DM (1984) Changes in soil physical properties under grazed pastures. *Australian Journal of Soil Research* **22**, 343–348. doi:10.1071/SR9840343

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