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Topsoil compaction and recovery in integrated no-tilled crop–livestock systems of Argentina

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ABSTRACT

Cattle trampling during grazing of crop residue may cause physical soil damage that may be repaired when animals are excluded. Understanding the interplay between soil deterioration and natural recovery of the soil physical condition allows for a better understanding of grazing management systems. Various soil physical properties (i.e., bulk density (BD), penetration resistance (PR), infiltration rate, structural instability) were determined up to 20 cm depth in a silty loam Typic Argiudoll and a sandy loam Typic Hapludoll of the Argentine Pampas from 2005 to 2008. Sampling was carried out before and after grazing, and at different moments of the crop cycle including harvest event. Grazing winter residues and weeds did not lead to the expected compaction processes (e.g., in average BD difference between after grazing and before grazing was from −0.072 to +0.137 Mg m^{-3} for both soils under grazing). In general, physical soil conditions improved during winter, independently of grazing. This might be related to the intrinsic soil characteristics (organic matter content, moisture, clay content) or grazing system (stocking rate, duration of grazing period), which prevented soil physical damage, suggesting that recovery forces were greater than grazing stress. Cropping to maize and soybean showed similar value or improved soil physical properties respect to the after grazing (e.g., in average PR difference between before harvest and after grazing was from +409 to −2561 kPa for both soils), acting as biotic a recovery factor. However, massive damage was harvest operation led to the highest soil deterioration (e.g., in average PR difference between before harvest and after harvest was 985 kPa).

1. Introduction

In recent years there has been a strong demand for farming systems to integrate crop and livestock production to avoid environmental problems caused by high cropping intensity and to improve soil quality and ecosystem services provided by soils, testing pastures and crop rotations (Franzluebbers and Stuedemann, 2008; García-Prechác et al., 2004; Fernández et al., 2011). A main risk of integrated crop–livestock systems is the generation of shallow soil compaction, especially in those under no-till management due to absence of mechanical disturbance (Díaz-Zorita et al., 2002; Strudley et al., 2008; Álvarez et al., 2009). A question that still remains regarding this management is the capacity of soils under no tillage to naturally reverse the soil compaction produced by this farming system. This includes how long the process takes for regeneration of topsoil compaction (if it does), and how the process operates in soils with different texture (Greenwood and McKenzie, 2001; Drewry, 2006).

Most studies on soil compaction occurrence and recovery have evaluated both processes in different soil types but in different years and in different climatic conditions, and could not compare between both situations. Drewry (2006) points out the importance of making evaluations in different soil types, but with simultaneous, short-term resilience studies. The exclusion of grazing during certain periods is an effective way to evaluate trampling effects and soil condition recovery (Warren et al., 1986b; Taboada and Lavado, 1993; Greenwood et al., 1998, 1997; Drewry, 2006). Greenwood et al. (1998) found an improvement in physical soil properties due to biological activity and wetting–drying cycles in the absence of animal trampling compaction. Soil physical condition improved when animals were completely excluded (Drewry, 2006) through exclosures (Zegwaard et al., 1998; Singleton et al., 2000; Greenwood and McKenzie, 2001).

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Some authors observed cyclical patterns in topsoil physical properties, characterized by periods of soil compaction by trampling and follow by natural recovery (Drewry et al., 2004; Monaghan et al., 2005). The initial physical condition and intrinsic soil characteristics are determinants of the recovery time of a soil (Nguyen et al., 1998; Nie et al., 1997; McDowell et al., 2004). Greenwood et al. (1998) found soil physical properties improved in 12 months in soils with 20–30% clay content. However, these changes would take longer in coarse-textured soils associated with a drier climate (Braunack and Walker, 1985).

The topsoil structural condition is the result of a dynamic equilibrium between disaggregation (e.g., slaking of aggregates, etc.) and aggregation or regeneration processes (Kay 1990; Drewry et al., 2004). In this balance, natural forces (e.g., texture and clay type, wetting–drying cycles, expansion–contraction processes, etc.), and anthropic forces (e.g., machinery movements, tillage, cattle trampling, etc.) are both involved (Kay, 1990).

In loamy soils, regeneration depends on the combined action of abiotic (i.e., wetting–drying cycles) and biotic mechanisms (Oades, 1993; Taboada et al., 2004). In silty loam soils, fragmentation of a compacted soil by wetting–drying cycles seems to be the necessary first step for regeneration (Taboada et al., 2004). Loamy soils are not completely rigid but are capable of noticeable volume changes and cracking by drying (Barbosa et al., 1999; Taboada et al., 2004). Coarse-textured soils, on the other hand, have a rigid skeleton, in which the biological stabilization is the main aggregate formation process (Oades, 1993).

In integrated crop–livestock production farming systems (ICL), soils alternate periods under pasture with cropping periods. Compaction by trampling can be mitigated by the protection of crop residues, which increase the soil bearing capacity and contribute to reducing damage, caused by cattle transit (Franzluebbers and Stuedemann, 2008).

This study reports the results of a 4 years field study in which the variation of soil physical properties was comparatively analyzed in ungrazed and grazed situations of a silty loam Typic Argiudoll and a sandy loam Typic Hapludoll under no till farming. This approach allowed us to identify and explain anthropogenic and natural effects on soil compaction and regeneration processes. The impact of winter grazing on soil properties are expected to be determined due to soil type, water status during grazing, and amount of residues present.

2. Materials and methods

2.1. Study sites, experimental design and sampling procedure

The study was conducted at two sites located in the northern Pampean Region, in a Typic Argiudoll (33°18′23.3″S; 61°58′2.3″W) and in a Typic Hapludoll (34°03′45.6″S; 62°25′19.4″W). This region has a temperate (mean annual temperature: 17.5 °C) and humid (mean annual precipitation: 1044 mm) climate. Most rainfall occurs in the spring and summer (September–March) and is often low during the winter.

The study was carried out in production farms under integrated crop–livestock systems, based on eight-year corn (*Zea mays* L.)-soybean (*Glycine max* L. Merrill) crop rotation and four years under grass-alfalfa pastures grazed at 5 cow ha^{-1} (average 420 kg cow^{-1}, mean pressure ca. 200 kPa) mean stocking rate. During the cropping period, maize or soybean residues and winter weeds, such as “chickweed” (*Stellaria media* L.) and “hoary bowlesia” (*Bowlesia incana* Ruiz & Pav.) were continuously grazed at of 1.1 cow ha^{-1} mean stocking rate. Livestock was temporarily removed from the fields during heavy rainy periods and definitely removed when ground cover by residues was lower than 60%.

The experiment started four years after a pasture period, i.e., in the middle of a cropping period. The experimental design was completely randomized, with three replicate plots per treatment. Treatments included: (1) grazed (G): grazing of crop residues and winter weeds; and (2) ungrazed (UN): cattle were excluded by electric fences during winter, while normal crop cycles continued. Sampling was carried out over a period of four years (2005, 2006, 2007, 2008) at the following times: (a) before grazing (April–May); (b) after grazing (September–October); (c) during the vegetative stage of maize or soybean; (d) during flowering; (e) before harvest (March). The first sampling year (2005) corresponded to a maize crop, followed by soybean in 2006 and maize in 2007, with the last sample after grazing in 2008.

2.2. Soils characteristics and rainfall during the experiment

The experiment was conducted on two soil types: (a) silty loam Typic Argiudoll; and (b) sandy loam Typic Hapludoll. Table 1 shows total organic matter content (TOM) (determined by the Walkley and Black method at 0–5 cm and 5–20 cm); soil pH (1:2.5, soil: water), and particle size distribution (determined by the pipette method at 0–20 cm layers; Soil Conservation Service, 1972).

Rainfall during the experiment is presented in Fig. 1. In general, lower precipitation was observed during grazing period and the highest precipitation occurred at the end of crop production at the time of harvest operation.

2.3. Determinations

2.3.1. Soil bulk density

Bulk density (BD) was determined with 100 cm^3 cylinders (Burke et al., 1986) before grazing, after grazing and before crop harvest. Four replicates at two depths (0–5 and 5–10 cm) were taken in each experimental unit.

2.3.2. Penetration resistance and soil water content

Soil penetration resistance (PR) was measured before and after grazing, and during the vegetative stage, flowering and before harvest of the crop. Five measurements per experimental unit were taken from 0 to 20 cm depth at 2.5 cm-intervals using a static digital penetrometer (Field Scout SC-900®) with a 30° tip angle. Soil water content (WC) was determined in composite samples at 0–5; 5–10; 10–20 cm depth. The PR and WC data helped establish relationships for the correction of PR, expressing PR at an average WC value for the whole experiment.

2.3.3. Infiltration rate

Field infiltration rate (IR) was determined by the method developed by the Soil Quality Institute (1999). A 15 cm-diameter cylinder was introduced to an 8 cm depth. A 2.54 cm sheet of distilled water was applied to homogenize soil moisture, another

Table 1
Soil characteristics of two soil types: Typic Argiudoll and Typic Hapludoll. Total organic matter at 0–5 cm and 5–20 cm depth; pH, clay, silt and sand content at 0–20 cm depth.

	Typic Argiudoll	Typic Hapludoll
Organic matter content (g kg^{-1})		
0–5 cm	52	34
5–20 cm	31.8	20.2
0–20 cm		
pH (1:2.5)	6.36	6.10
Clay (g kg^{-1})	21.8	11.7
Silt (g kg^{-1})	68.1	39.5
Sand (g kg^{-1})	10.1	48.8

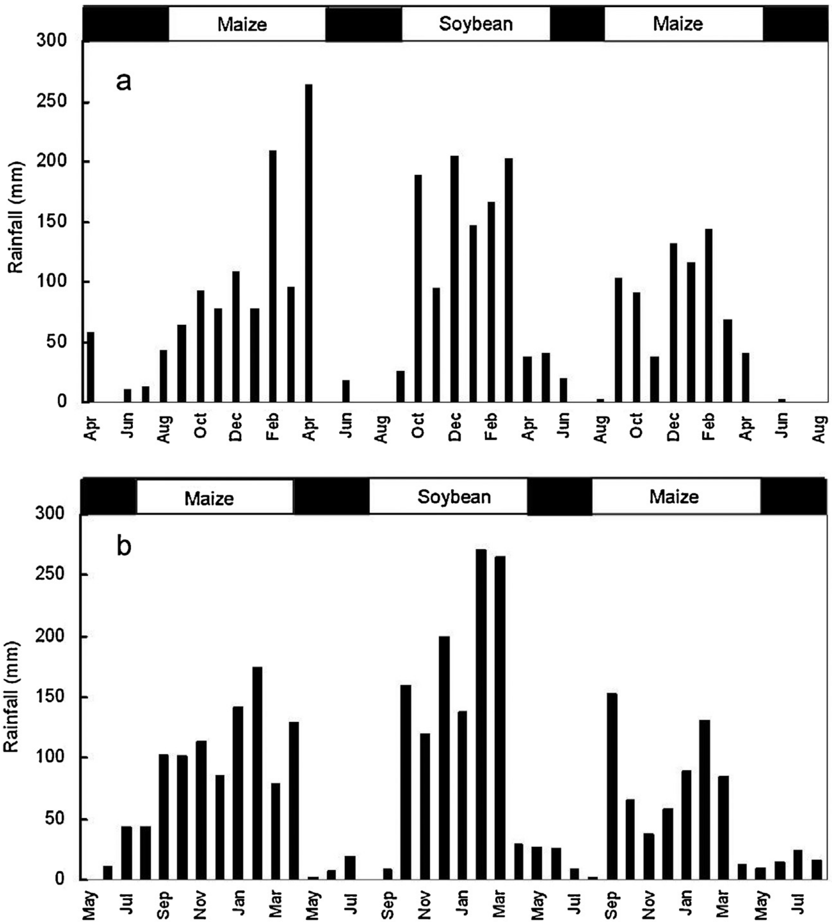

Fig. 1. Monthly rainfall during the study, (a) Typic Argiudoll, and (b) Typic Hapludoll. Black bar indicates period under winter grazing, maize and soybean growing period are indicated.

was then applied to measure the time required for water to penetrate into the soil. The IR obtained reflects the basic soil infiltration. Two replicates were taken in each experimental unit. The first determination was after grazing in 2005 and determination in the following years, was conducted before and after grazing.

2.3.4. Structural instability

Two non-disturbed samples (20 cm × 20 cm × 20 cm) were taken in each experimental unit before and after grazing and before harvest. The structural instability index (SI) was determined in the laboratory following De Leenheer and De Boodt (quoted by Burke et al., 1986). The SI was calculated as the difference between the dry-sieved aggregate mean diameter (4.8, 3.4, 2 mm mesh sieve openings) and wet-sieved mean diameter (4.8, 3.4, 2, 1, 0.5 and 0.25 mm mesh sieve openings). After dry-sieving, aggregates were pre-wetted to minimize slaking and then wet-sieved for 5 min in a Yoder-type equipment. The greater the difference between dry and wet aggregate weighted mean diameter, the lower the structural stability.

2.4. Statistical analysis

The variation of soil variables was analyzed for the grazed (G) and ungrazed (UN) treatments as repeated measures over time, to avoid the lack of data independence in repeated sampling. Three structures in the analysis of covariance (VC, CSH and ARH (1)) (Littell et al., 1998) were tested and the covariance structure VC resulted in the best agreement with the Akaike information criterion (AIC, Akaike, 1974).

Correcting these PR values allows to separation of moisture effect from treatment effect. The relationship between PR and WC for both soils was analyzed separately for the G and UG and the regression coefficients were compared ($P < 0.05$) between treatments. When no differences between treatments were found, the coefficients at each depth ($P < 0.05$) were obtained by pooling data from both treatments. When no difference was found between depths, all data was pooled and the sole regression slope obtained was used to correct PR values ($P < 0.05$).

3. Results

3.1. Bulk density

BD was significantly ($P < 0.05$) affected by the “treatment × date” interaction in the 0–5 cm layer of the Typic Argiudoll, which was due to BD changes during the first sampling year (2005, Fig. 2). Instead of the expected increase in BD under high soil WC by trampling, a BD decrease was observed as a result of grazing. Thus, in the second sampling date, the G treatment had significantly lower BD values than the UN treatment. No interaction was observed in the 5–10 cm layer (Fig. 2), in which significant differences between sampling dates were only observed. The pattern of BD variations in this layer was similar to that observed in the 0–5 cm layer. No difference was observed between treatments in any of the two layers in 2006, 2007 and 2008.

In the Typic Hapludoll, no interaction between factors was observed and, BD was only significantly affected by sampling date (Fig. 2). In this soil, BD fluctuated slightly around ca. 1.45 Mg m^{-3} in

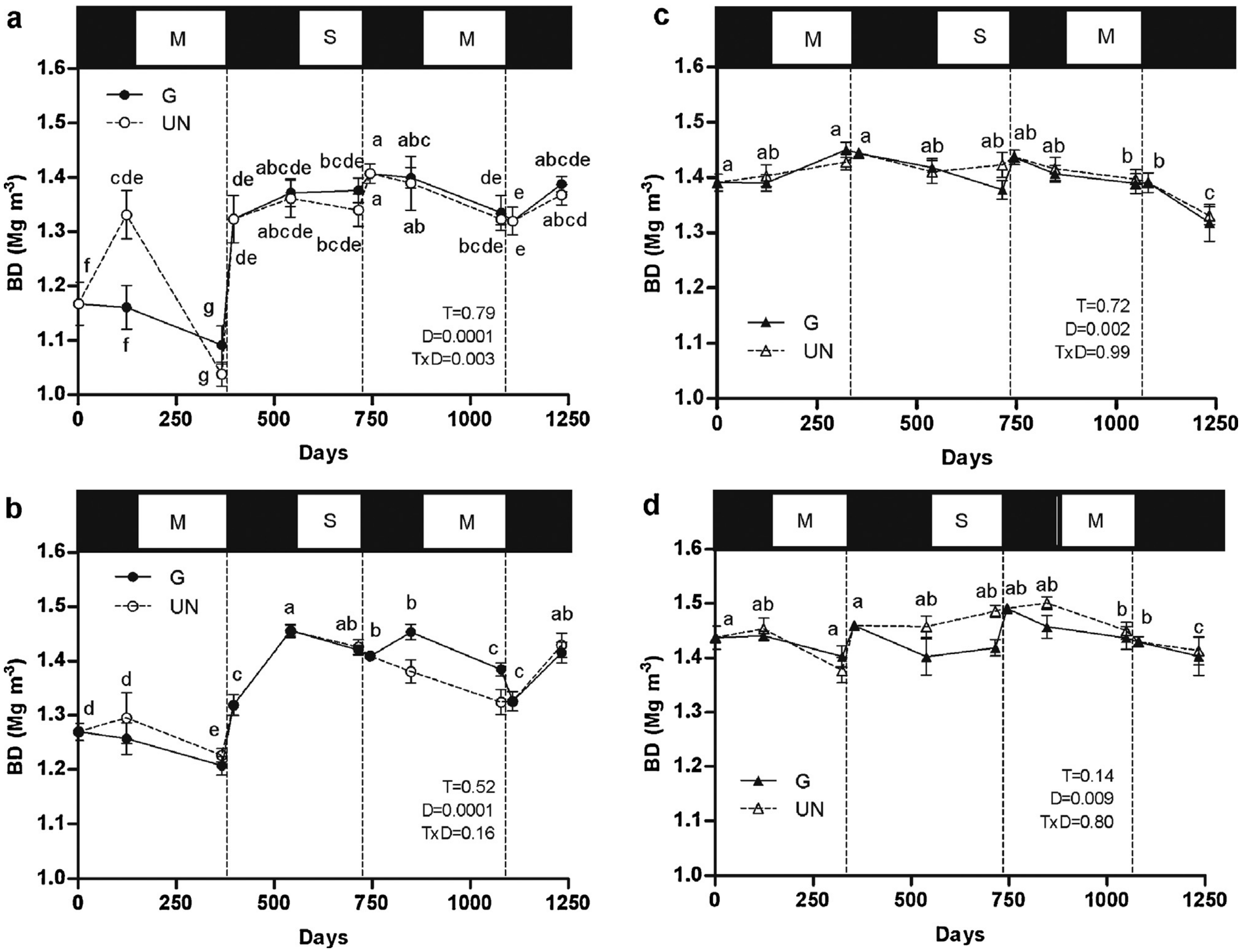

Fig. 2. Variation of mean bulk density (BD) with time (days since the start of the experiment) in the grazed (G) and ungrazed (UN) treatments. Typic Argiudoll: 0–5 cm (a) and 5–10 cm (b); Typic Hapludoll: 0–5 cm (c); 5–10 cm (d). Bars at the top of each graph corresponds to: (black) residue-grazing winter period and (white) summer crop (M: maize, S: soybean). The dotted vertical line indicates the moment of the summer crop mechanical harvest. T: treatment p-value, D: date p-value, T × D: "treatment × date" interaction p-value. Different letters indicate significant differences ($P < 0.05$) due to the interaction or factors. Vertical bars indicated standard errors.

both layers, which can be attributed to soil rigidity due to its fine sandy matrix (~48% of the sand fraction).

3.2. Penetration resistance

Soil water content affects penetration resistance (PR) measurements (De León González et al., 1998; da Silva et al., 2003; Hamza and Anderson, 2005). Correcting these values allows for the separation of moisture effect from treatment effect. No differences were found between the slopes of the G and the UN treatments, so all data were pooled, and straight lines were fitted for each soil depth. Regression coefficients (intercept and slope) for the 0–5 cm layer differed significantly from the others (5–10 cm and 10–20 cm), which were then pooled. In the Typic Argiudoll, about half of the variation in PR was explained by WC (Fig. 3a). Fitted linear slopes were used to standardize PR values at constant moisture. In the Typic Hapludoll, determination coefficients were lower than in the Argiudoll but straight lines were also fitted for 0–5 cm and 5–20 cm layers (Fig. 3b).

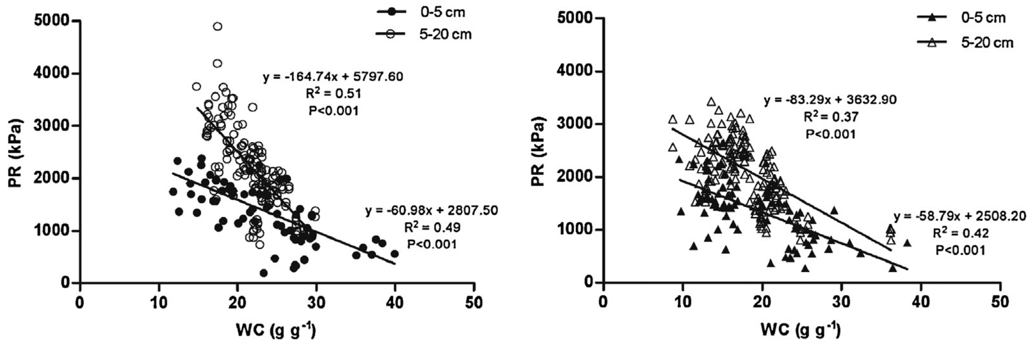

Fig. 3. Penetration resistance (PR) as a function of soil water content (WC) for a Typic Argiudoll (a) and a Typic Hapludoll (b).

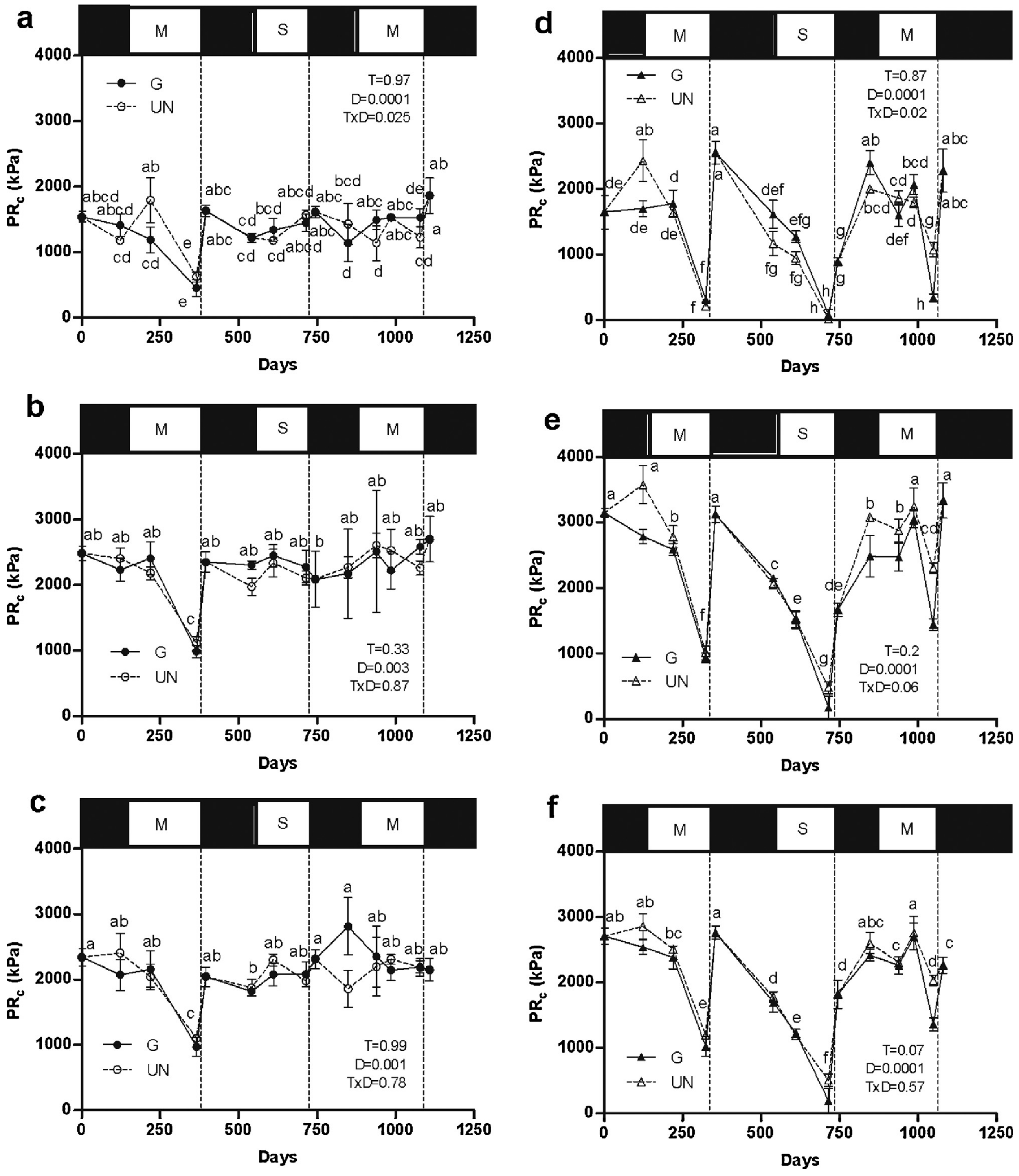

Fig. 4. Variation of mean penetration resistance (corrected for average soil water content: PR_C) with time (days since the start of the experiment) in the grazed (G) and ungrazed (UN) treatments. Typic Argiudoll: 0–5 cm (a), 5–10 cm (b), 10–20 cm (c); Typic Hapludoll: 0–5m (d), 5–10 cm (e), 10–20 cm (f). Bars at the top of each graph corresponds to: (black) residue-grazing winter period and (white) summer crop (M: maize, S: soybean). The dotted vertical line indicates the moment of the summer crop harvest. T: treatment *p*-value, D: date *p*-value, T × D: "treatment × date" interaction *p*-value. Different letters indicate significant differences ($P < 0.05$) due to the interaction or factors. Vertical bars indicated standard errors.

Penetration resistance of the Argiudoll was corrected by the mean WC, using the linear slopes obtained for the 0–5 cm and 5–20 cm layers. As expected and shown in Fig. 4, the range of PR_c variations was narrower than that of uncorrected PR (data not shown). Only in the 0–5 cm layer, PR_c was significantly affected ($P < 0.05$) by the "treatment × date" interaction (Fig. 4a). At greater depths, only sampling date showed significant variations in PR_c (Fig. 4b and c).

In the Typic Hapludoll, PR_c was significantly affected ($P < 0.05$) by the "treatment × date" interaction (Fig. 4d and e) except in the 10–20 cm layer (Fig. 4f). The variation of PR_c was more pronounced in the Hapludoll than in the Argiudoll.

3.3. Infiltration rate

The variation of IR was evaluated before and after grazing periods. In the Argiudoll, neither the "treatment × date" interaction nor grazing caused significant effects on soil IR (Fig. 5a). It varied significantly between sampling dates, with the highest IR values during the first year. Soil IR showed a decreasing trend with time, with lower values at the end of the study. Sometimes, soil IR was lower in the grazing treatment, but differences were not significant.

In the Hapludoll, soil IR did not show any decreasing trend with time and, like in the Argiudoll, was neither affected by the "treatment × date" interaction nor grazing effects (Fig. 5b). In this soil, IR was only significantly ($P < 0.05$) affected by sampling date, although the variation range was narrower than in the Argiudoll.

3.4. Structural instability

In the Argiudoll the structural instability index (SI) was significantly affected ($P < 0.05$) by the "treatment × date" interaction (Fig. 6a). The highest values (i.e., lower structural stability) were observed at periods with either high or low WC values. Grazing increased significantly soil structural instability both in wet and dry years, such as happened at the beginning and end of the study.

In the Hapludoll, neither the "treatment × date" interaction nor grazing affected soil SI (Fig. 6b), which was only significantly affected by sampling dates. Like in the other studied physical properties, SI variations with time were less pronounced in the Hapludoll than in the Argiudoll.

4. Discussion

4.1. Grazing effect on soil physical properties

The effect of residues winter grazing was evaluated through the differences between the G and UN treatments, as well as through the persistence of differences over time (comparing between, before, and after G treatment).

Our expectation from previous works (Singleton and Addison, 1999; Greenwood and McKenzie, 2001; Drewry et al., 2004) was that cattle trampling would increase soil BD by compaction in the G treatment. On the contrary, it was expected that livestock exclusion improved soil physical properties in UN treatment (Warren et al., 1986b; Stephenson and Veigel, 1987; Taboada and Lavado, 1993; Greenwood et al., 1998, 1997; Taboada et al., 1999; Drewry, 2006). Instead, our results showed a non-single BD variation pattern in the Argiudoll in which BD was affected by the "treatment × date" interaction. This was due to a significant BD decrease in the G treatment during the first year (2005), which was caused by swelling of wet soil around the hoof marks at high WC (Fernández et al., 2010). As a result, the lowest BD values of the study were observed in the G treatment (Fig. 2a). This highly responsive BD variation pattern over time can be associated with the higher proportion of clay in its textural composition (Table 1; Figs. 1 and 2a and b). In the more rigid sandy loam, Hapludoll, soil BD varied only slightly with time ("date" effect) and was not affected by G treatment (Fig. 2c and d).

Results shown in Fig. 2a–d was in agreement with the findings of other authors (Greenwood et al., 1997; Drewry et al., 2004), where the patterns of BD variation in the topsoil of both soil types coincided roughly with the ones observed at sub-surface, although here BD variations were of lesser magnitude.

Soil BD changes could be assessed through the difference of results between two moments in the scheme of production, instead of its absolute value (Martínez and Zinck, 2004). This was applied in the topsoil of the G treatment, in which differences in BD between "after grazing" and "before grazing" moments were a little importance ranging -0.007 to $+0.068$ Mg m^{-3} in the Argiudoll and -0.072 to -0.001 Mg m^{-3} in the Hapludoll. These BD variations ranges were lower than ranges observed by Drewry et al. (2004) when comparing different moments of G treatment. It can be concluded that in our study, grazing had only minor effects on soil BD.

As expected, there was a negative relationship between PR and WC (Fig. 3a and b). However, the PR–WC relationship fitted different straight lines in the different soil types and soil depths. Linear slope was lower in the 0–5 cm than in the 5–20 cm soil layer, with greater differences in the Argiudoll. The response of soil PR to WC in topsoil was not as high as expected, which agrees with results found by other authors (Franzluebbers and Stuedemann, 2008; Álvarez et al., 2009). This weak response of PR was ascribed to the damping effect of the organic matter (OM) accumulated over several years on the surface in systems under no-till management (Wander and Bollero, 1999; Álvarez et al., 2009). In fact, OM contents were 68% and 63% higher in 0–5 cm than in 5–20 cm

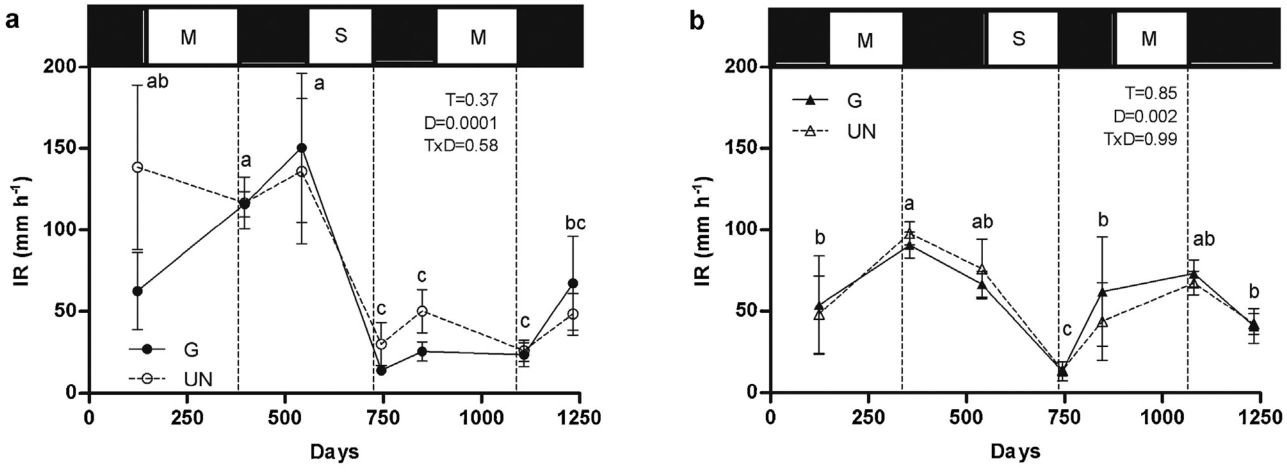

Fig. 5. Variation of mean infiltration rate (IR) with time (days since the start of the experiment) in the grazed (G) and ungrazed (UN) treatments. Typic Argiudoll (a); and Typic Hapludoll (b). Bars at the top of each graph corresponds to: (black) residue-grazing winter period and (white) summer crop (M: maize, S: soybean). The dotted vertical line indicates the moment of the summer crop harvest. T: treatment p-value, D: date p-value, T × D: "treatment × date" interaction p-value. Different letters indicate significant differences ($P < 0.05$) due to the interaction or factors. Vertical bars indicated standard errors.

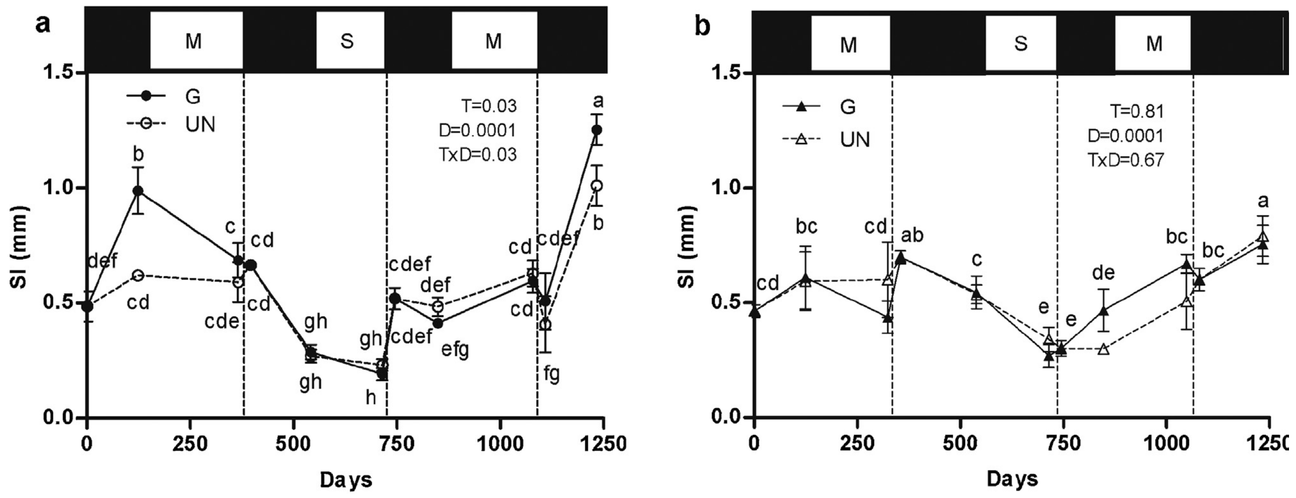

Fig. 6. Variation of mean structural instability (SI) with time (days since the start of the experiment) in the grazed (G) and ungrazed (UN). Typic Argiudoll (a); and Typic Hapludoll (b). Bars at the top of each graph corresponds to: (black) residue-grazing winter period and (white) summer crop (M: maize, S: soybean). The dotted vertical line indicates the moment of the summer crop harvest. T: treatment p-value, D: date p-value, T × D: interaction "treatment × date" p-value. Different letters indicate significant differences ($P < 0.05$) due to the interaction or factors.

layers in the Hapludoll and the Argiudoll, respectively. The influence of OM in PR results was similar to the finding of da Silva et al. (2003) for sites with different amounts of residues. Considering the effect of OM content on the PR, Breune et al. (1996) suggested the importance of taking into account not only WC but also OM values when measuring PR. Unlike many studies showing PR increases as a result of livestock trampling (Greenwood et al., 1997; da Silva et al., 2003), in our study corrected PR values were either equal or lower after winter grazing (Fig. 4a–f). This shows grazing would not to lead to the expected topsoil PR increases.

Soil infiltration rate (IR) was only significantly affected by sampling "date" in both soils (Fig. 5a). It is likely that grazing effects on soil IR were highly variable, due to the non-uniform spatial distribution of cattle hoofprints in the grazed area (Greenwood and McKenzie, 2001). In the Argiudoll, opposite to expected, every year IR increased after 5–6 months of grazing (Fig. 5b). In a soil with similar texture, Warren et al. (1986a) found a decrease in IR as a result of grazing, showing compaction due to cattle trampling.

In both soils the SI varied with "date" in Hapludoll and a interactive effects in the Argiudoll was observed (Fig. 6a and b). It can be concluded that in our study, changes in SI were related to the natural soil dynamics and not associated with grazing. Bullock et al. (1988) also found that changes in stability were much larger between seasons than between soil types.

Despite some point or short-term changes attributable to grazing, the general picture was that none of the evaluated soil properties were affected by grazing treatments. This allowed us to conclude that in the study site grazing did not cause persistent long-term structural damages associated with compaction by trampling, and consequently, any soil physical improvement was found after the cessation of grazing, as observed by Greenwood et al. (1998). Under continuous no-till management, the studied soils evolved to a harder condition that prevents the occurrence of structural damage by trampling. Similar results of a lack of damage by trampling was found by other authors on grazed soils under no-till management (Franzluebbers and Stuedemann, 2008; Quiroga et al., 2009).

4.2. Crop effects on soil physical properties

In general terms soil, cropping decreased soil BD in the Argiudoll, although these differences varied across sampling "dates", and were not always significant. These BD decreases are attributable to the generation of biopores by crop root growth and development (Campbell et al., 1996; Alakukku, 1998; Miglierina et al., 2000). Soil cropping did not affect soil PR in the Argiudoll, but significantly decreased PR in all studied situations of the Hapludoll (Fig. 4d–f). This indicates a regeneration process, probably attributable to biotic factors in this loamy sand soil (Oades, 1993). Indeed, Alakukku (1998) observed that crop roots can be a potential tool for soil recovery after soil compaction.

There are numerous works showing deleterious effects of soybean crops on topsoil structure, particularly as compared to positive effects by maize (e.g., Ellsworth et al., 1991; Álvarez et al., 2014). This different crop behavior is due to the different amount of plant roots, playing an important role in stabilizing soil aggregates through a binding effect, as the root network stops the disruptive action of exogenous forces on soil aggregates (Reid and Goss, 1981, 1982; Tisdall and Oades, 1982). However, in our study, not only maize but also soybean caused significant SI decreased, or in other words, structural stability increases (Fig. 5a and b). Plant roots were found to be primarily responsible for the regeneration of plow pans in the Pampa region (Taboada et al., 1998; Micucci and Taboada, 2006; Taboada and Alvarez, 2008), and together with the wetting–drying cycles have been identified as primary recovery factors of loamy soils (Barbosa et al., 1999).

4.3. Effect of harvest machinery traffic on soil physical properties

In the general picture of significant variations with "date" of the studied soil physical properties, changes with time were particularly greater after periods of crop harvest, typically during autumn. Soil BD increased significantly or remained the same after crop harvesting in both in the Argiudoll (in average difference between after harvest and before harvest = +0.232 Mg m^{-3}, 0–5 cm; +0.112 Mg m^{-3}, 5–10 cm) and in the Hapludoll (+0.059 Mg m^{-3}, 0–5 cm; +0.072 Mg m^{-3}, 5–10 cm) (Fig. 2a and b). Botta et al. (2004, 2007),) also observed increases in BD and in cone index due to machinery traffic. This effect can persist one year or more by residual memory of the soil, as shown by Montavalli et al. (2003). The pressure exerted by a cow ranges from 120 to 240 kPa, depending on whether it is or is not moving (Willatt and Pullar, 1983; Greenwood et al., 1997; Di et al., 2001; Hamza and Anderson, 2005). In comparison, the pressure exerted by machinery during harvesting is as high as 602.45 kPa (Botta et al., 2007). This higher pressure can affect greater soil surface than a cow. Therefore, machinery traffic could have had a significantly great impact on soil physical properties.

During the experiment rainfall was usually higher in autumn (harvest period) than in winter (grazing period) (Fig. 1). As a result, soil bearing capacity was lower during harvest than during livestock grazing. Likewise, Greenwood and McKenzie (2001) also considered that the effect of cattle trampling is more superficial than that of machinery traffic. In our study, soil PR increased after harvesting up to a depth of 40 cm (data not shown), which agrees with the expected effect of heavy machinery traffic (Alakukku, 1998; McQueen and Shepherd, 2002; Montavalli et al., 2003). These effects can persist in the sub-surface soil layer even four years later (Alakukku, 1998).

The IS showed significant difference of machinery traffic after harvest in most of the years, although in a few years the IS presented lower values in both soils (Fig. 6a and b) which coincided with the lack of direct links between aggregate structural stability and compaction often observed in this study they had effects (e.g., greater cohesion) which confuse result (Schäffer et al., 2008; Álvarez et al., 2012). This lack of correlation was observed in both soil types (Fig. 6).

5. Conclusions

1. Winter grazing of crop residues (1 cow ha^{-1}) did not lead to an expected topsoil compaction, but hardsetting appear and increase structural instability when soil was wet. Trampling in dry soil also resulted in increase structural instability.
2. Crop harvest was the most important impact on soil physical properties, in particular when it was carried out in wet soil conditions, leaving effects on soil properties.
3. Soil physical properties were improved during crop growing period (maize and soybean), which recovered soil physical properties damaged by harvest operations (in most cases up to 20 cm).
4. Results show no negative impacts of cattle grazing (1 cow ha^{-1}) during winter should encourage farmers to integrate crop–livestock systems in the study area.

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