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Soil physical properties under different cattle stocking rates on Mollisols in the Buenos Aires Province, Argentina

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ABSTRACT

This study evaluated the impact of different cattle stocking rates on different soil physical properties in different soils in an integrated livestock no-till agricultural system. We evaluated three stocking rates (0 animal unit ha^{-1}, moderate: 160 animal unit ha^{-1}, and heavy: 320 animal unit ha^{-1}) on three soil textures (loamy sand, sandy loam and sandy clay). We also evaluated sorghum's performance after the cattle trampling in a crop sequence including winter rye + hairy vetch/sorghum. The representative soil in the area is a fine-loamy, mixed and thermic Entic Haplustoll with variable clay + silt (30 to 40 g kg^{-1} soil). Only bulk density showed interaction between texture and stocking rate factors. The control and moderate stocking rates showed lower bulk density (1.35 Mg m^{-3}) than the heavy grazed treatment (1.43 Mg m^{-3}) in the loamy sand soil. No differences between moderate and heavy treatments were found in other soil indicators. Layers of 0–5 and 5–10 cm proved to offer a higher mechanical resistance that the control (39% and 30%, respectively). Hydraulic conductivity and macroporosity (>100 μm) showed a reduction close to 20% in both indicators due to cattle trampling. Sorghum crop showed no differences in plant rate emergence, biomass and grain yield. Results of this investigation indicate that grazing and animal trampling produced no significant effect on the variation of physical properties over the different soil texture, neither any impact on the emergence and development of sorghum.

1. Introduction

The arid and semiarid regions account for 40% of the earth's surface and are inhabited by 38% of the world's population (GLP, 2005). In these regions, the application of agricultural techniques from humid areas has caused severe episodes of wind erosion like the Dust Bowl in the USA (Lee and Gill, 2015) and similar processes in the western Pampas region of Argentina (Covas, 1989; Viglizzo et al., 1991; Lal, 1994). Semiarid regions are characterized for having few and highly variable rainfalls (Schlesinger et al., 1990). The expansion of the agricultural frontier into the semiarid region of Argentina has led to an increased productivity at the expense of environmental stability and sustainability (Viglizzo, 1986; Viglizzo et al., 1991).

The incorporation of no-tillage (NT) systems in the semiarid region allowed yields to rise as water is used more efficiently (Hansen et al., 2012; Cutforth & McConkey, 1997; Cutforth et al., 2006; Buschiazzo et al., 2007; Schuller et al., 2007), wind erosion is reduced (Buschiazzo et al., 2007; Hevia et al., 2007; Hansen et al., 2012) and organic matter (OM) is preserved (Bossuyt et al., 2002; Balesdent et al., 2000). In turn, the inclusion of livestock in agricultural systems led to increased economic revenues and diversified production (Franzluebbers and Stuedemann, 2008), leading to a more stable productive activity over time (Pawlowski, 2000; Schierre et al., 2002).

A potential risk of integrated production systems under NT is surface compaction (Morán et al., 2000; Álvarez et al., 2009), manifested in establishment and productivity issues with crops following grazing (Tracy and Zhang, 2008; Bell et al., 2011). High compaction rates are associated with increases in bulk density (BD) and mechanical resistance (MR) (Agostini et al., 2012) and low values of hydraulic conductivity (K) and macroporosity ($M\rho$) (Holt et al., 1996; Scapini et al., 1997; Esposito et al., 2002). The impact of grazing on the physical properties of the soil can be influenced by various factors: texture, stocking rate, soil structure, cover, moisture content of the soil profile, type of vegetation and slope (Gifford and Dadkhah, 1980; Roundy et al., 1990; Greene et al., 1994; Mwendera and Saleem, 1997; Ferrero and Lipiec, 2000; Donkor et al., 2002; Taboada, 2007). Texture, water content, structure and organic matter have been shown to be the main determining factors of susceptibility to soil compaction (Nawaz et al., 2013).

Direct grazing in clayey textures produced, in many cases, negative effects on the soil physical properties (Warren et al., 1986; Mapfumo, 1997; Morán et al., 2000; Zamora et al., 2006; Lanzanova et al., 2007; Taboada, 2007; Kiessling, 2012). In sandy textures, negative effects on the physical properties were also observed (Scapini et al., 1997; Silva

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et al., 2010; Venanzi et al., 2004; Franzluebbers and Stuedemann, 2008). On other hand, a null effect on the physical properties and crops yield in an integrated crop-livestock system in different soil textures at a field scale was also reported (Fernández et al., 2015; Quiroga et al., 2009). So it is difficult to establish the soil conditions that will have a negative impact for the cattle trampling on the yield of the following crops.

Soil texture offers spatial variability, with zones of different sensitivity to trampling being able to exist within the same plot. The spatial variability can be characterized using electromagnetic interference (EMI) sensors with high spatial resolution (Saey et al., 2009; Bosch Mayol et al., 2012; Paggi et al., 2013; Peralta et al., 2013; Simon et al., 2013; Islam et al., 2014). Several authors reported a high correlation between apparent electrical conductivity (EC_a) and clay content in the soil (Sheets and Hendrickx, 1995; Domsch and Giebel, 2004; Carrol and Oliver, 2005, Peralta et al., 2013). The soil physical spatial variability has been documented for machinery traffic (Aksakal and Öztaş, 2010; Barik et al., 2014) and livestock trampling (Aksakal et al., 2011; Imhoff et al., 2010). To our knowledge, there are no reports studying the change in different soil physical indicators as a function of spatial variability of topsoil texture at the field scale.

This work aimed to evaluate the effect of stocking rate on the implantation and production of the following crop in different soil textures present in a livestock-agricultural production plot under NT in the semi-arid region of Argentina. We hypothesized that clayey soils are more susceptible to animal trampling and in these soils animal trampling has a greater impact than sandy soils on the following crop. In this way, variability in the effects of animal trampling will be related to the variability of soil texture.

2. Materials and methods

2.1. Study area

The study was carried out at INTA's (National Institute of Agricultural Technology) Bordenave Experimental Station (37 46′ 5.7″ S; 63 5′27.5″ W) located in the south-west of the Buenos Aires province, Argentina (Fig. 1). This region is mainly grown to winter crops (wheat, oat and barley), alternating agriculture with livestock farming. The climate is mild, continental and shows a transition in NE-SW direction from dry subhumid to semiarid. Average annual temperature is 15.2 °C, with an average annual rainfall of 650 mm. Evapotranspiration averages 885 mm, with an important negative hydric balance in summer months (Kohli, 1991). The rainiest seasons are fall and spring but, like other semiarid areas, variability in the occurrence and distribution of rainfalls is one of the outstanding features. The soil of the area used in the study represents the driest part of the region and is characterized as fine loamy, mixed thermic Entic Haplustoll (Soil Survey Staff, 1999), with an A-AC-C_1-C_2 horizon sequence, average total organic carbon content in the surface horizon of 9 g kg^{-1}, pH values of 7.0, increasing to 7.8 in C_2 horizon, and a calcareous layer (petrocalcic horizon) at a depth ranging between 0.8 and 1 m. The effective root depth is between 0.6 and 0.8 m. Other soils present in the study site are associations of series sandy, sandy loam, and loamy sand topsoil classified as sandy, mixed, thermic Typic Ustipsamment, and coarse loamy, mixed, thermic Entic Haplustoll. The predominant clay type in the whole area is illite, coexisting with mixed layers of illite-smectite and/or chlorite-smectite (Scoppa, 1974; Blanco and Sanchez, 1995).

2.2. Soil management and experimental design

The experimental site was a field of 10 ha under ten years of integrated crop-livestock NT system. Since 2007 and previous to present experiment the crop rotation has been an annual sequence of forage crops (oat, barley and rye), consociated with hairy vetch. Ocassionally, a grain crop (wheat or barley) was seeded.

The main factor evaluated was cattle stocking rate, using three levels. Stocking rates levels were expressed in animal unit (AU) (Allen et al., 2011). Cows with an average weight of 450 kg were used in different stocking rates: control (CON), 0 AU ha^{-1}, moderate (MOD), 160 AU ha^{-1}, representing usual rates in many farms of the area, and heavy (HVY), 320 AU ha^{-1}. The stocking rates were applied on different soil textures: Loamy sand (LS), sandy loam (SL) and sandy clay loam (SCL) in plots of 392 m^2. The experimental design was a complete randomized block design, with stocking rate as main factor, with blocks considered

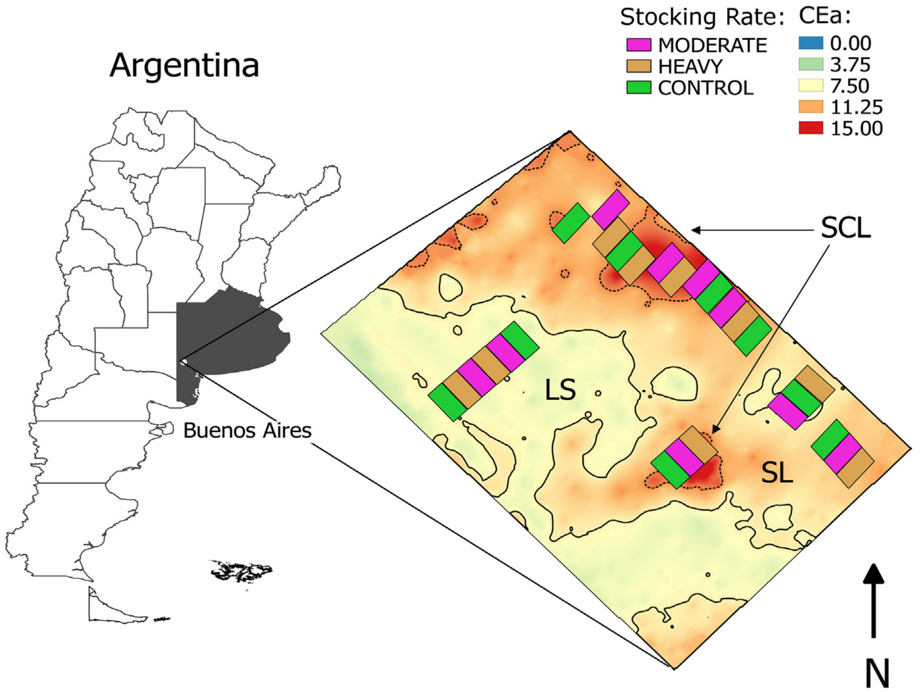

Fig. 1. Localization of the experimental site in the south west of the Buenos Aires province, Argentina, and apparent electro-conductivity map (ECa) performed with an EM38MK2 conductivity meter. Solid lines indicate loamy sand textures (LS), dotted lines indicate sandy clay loam (SCL) textures. Outside the solid and dotted lines, sandy loam texture (SL).

as random effect embedded in different textures. Three replications were used.

The correlation between soil parameters and apparent electrical conductivity (ECa) was used to determine zones of different granulometry in the field. The ECa was measured with an EM-38MK2 device (Geonics Limited, Ontario, Canada). The ECa data were simultaneously georeferenced with a DGPS (Trimble 132, Trimble Navigation Limited, USA), configured to take one ground positioning reading every second. Omnidirectional and directional semivariograms of ECa were generated, with later interpolations using an ordinary Kriging. After creating the maps, samples in layers of 20 cm up to a meter deep were taken in 10 locations with significantly different ECa. The percentage of clay (c), sand (S) and silt (s) in the surface layer (0–20cm) was determined using the Robinson pipette method (Robinson, 1922).

The experiment started at the end of January 2014, when a consociation of Rye (*Secale cereale (L.) M. Bieb.*) and hairy Vetch (*Vicia villosa Roth.*) was planted under NT. The seeding rates were 45 kg ha^{-1} and 10 kg ha^{-1} of seed for each species, respectively. In April and August, the forage crop was grazed. Both times and for each stocking rate level, cows spent the same amount of time in the experimental unit (6 h). In each block all plots were grazed at the same time. After each grazing cows were moved to other field. In September, the herbicide Glyphosate [N-(phosphonomethyl) glycine], was applied at a rate of 1.24 kg of active equivalent per ha to control weeds and forage plants in the experimental area Glyphosate [*N-(phosphonomethyl) glycine*], an herbicide, was applied at a rate of 1.24 kg of active equivalent per ha to control weeds and forage plants in the experimental area. In November, a hybrid grain sorghum (*Sorghum bicolor* L. *Moench*) called GEN210, was planted under NT using a seeding rate of 6.2 kg of seeds per ha. Both forage crops were planted with a no till grain seeder "Agrometal GX3", with a 18″ turbo disc coulter, a double disc V openers and V rubber closing wheels.

2.3. Soil and plant analysis

Different soil parameters (MR, BD, *K* and *Mp)* were analyzed at two different times, before the first and after the second grazing. MR was measured using a cone penetrometer (CN-970, SOILTEST Inc., Lake Bluff, Illinois) (Bradford, 1986), taking three readings in each experimental unit at depths of 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. Each time, samples were taken from the 0–20 cm layer of soil of the control plots and their soil water content was compared using Welch's *t*-test. BD was estimated using the cylinder method (Blake and Hartge, 1986), taking three samples per plot from the same layers as for MR. *K* was measured using tension disc infiltrometers (Perroux and White, 1988), at three tensions: 0 ($K_{(0)}$), 15 mm 0 ($K_{(-15)}$), 30 mm ($K_{(-30)}$), using three replications per plot. Saturated hydraulic conductivity ($K_{(0)}$) was calculated according to Wooding (1968), who proposed an algebraic approximation for the rate of infiltration at a constant set flow within the soil from a circular source (Eq. (1)).

$$Q = \pi.r^2.K(0).\left(1+\frac{4}{\pi.r.\alpha}\right) \qquad (1)$$

where, Q is the volume of water entering the soil (cm^3 h^{-1}), $K_{(0)}$ is the saturated hydraulic conductivity (cm h^{-1}), r is the radius (cm). On the other hand, Gardner (1958) proposed an exponential equation to describe hydraulic conductivity at different tensions (Eq. (2)).

$$K(h) = K(0).\ \exp(\alpha.h) \qquad (2)$$

where, $K_{(h)}$ is the hydraulic conductivity at a given tension, $K_{(0)}$ is the saturated hydraulic conductivity, α is the sorptivity number and h is the tension to estimate K. By replacing K in Eq. (1) by Eq. (2) we get an equation to estimate the flow of water within the soil (Eq. (3)) based on the tension applied (Wooding, 1968).

$$Q(h) = \pi.r^2.K(0).\ \exp(\alpha.h)\left[1+\frac{4}{\pi.r.\alpha}\right] \qquad (3)$$

where: Q is the average infiltration in cm^3 h^{-1}, $K_{(0)}$ is the saturated hydraulic conductivity, α is the sorptivity number, h is the measuring tension and r is the radius of the infiltrometer disc.

A non-linear adjustment was made to the infiltration values at the three tensions in Eq. (3), estimating $K_{(0)}$ and α. Having obtained $K_{(0)}$, $K_{(-30)}$ and $K_{(-15)}$ were calculated according to Eq. (2).

Macroporosity (*Mρ*) was calculated for up to 560 mm of tension in three unaltered samples from the 0–5 cm layer in each experimental unit by using the sand-suction table method (Stakman et al., 1969). The relationship between tension and pore diameter was determined using Eq. (4) (Imhoff et al., 2010).

$$r = -\frac{2.\delta.\ \cos\alpha}{p.g.h} \qquad (4)$$

where, δ is the water surface tension, α is the angle of contact between the water and the pore wall, p is the water density, g is the acceleration of gravity and h corresponds to the applied tension.

Tensions used were: 15 mm ($M\rho_{-15}$); 30 mm ($M\rho_{-30}$); 70 mm ($M\rho_{-70}$); 140 mm ($M\rho_{-140}$); 280 mm ($M\rho_{-280}$) and 560 mm ($M\rho_{-560}$), corresponding to pore diameters of 1866 μm; 933 μm; 400 μm; 200 μm; 100 μm and 50 μm, respectively. Macroporosity was estimated using the difference between the humid weight of the sample at each tension and the total porosity of the sample.

The impact of trampling on crop establishment was estimated by measuring the number of plants that emerged in four-meter lines per plot at 14, 20, 28, 32 and 62 days after sowing. At growing stage 3 of sorghum (Vanderlip, 1993), ten plants per experimental unit were cropped to determine: biomass weight, height, number of tillers, number of leaves and protein. At harvest, dry weight of the whole plant, spike and grains was measured in 3-meter lines per plot.

2.4. Statistical analysis

When the analysis of variance indicated significant differences ($p < 0.05$), all the possible measurement pairs were compared using the Tukey test ($\alpha_e = 0.05$). In the case of MR and BD, samples taken from different layers were considered as repeated measures. Differences between sampling dates were analyzed using the difference between the average values (Δ: Post-grazing – Pre-grazing). Hydraulic conductivity showed lack of normality, requiring to be normalized by the Box-Cox method, generating the transformed hydraulic conductivity variable (*Kt*). Statistical analyses were done using the R statistical software (R Core Team, 2014). Different R packages were used for the geostatistical procedures: Gstat (Pebesma, 2004), sp. (Pebesma and Bivand, 2005) and geoR (Diggle and Ribeiro, 2007).

3. Results

The interpolations done using directional and omnidirectional semivariograms did not produce different EC$_a$ zones, for which reason the omnidirectional map was used because of its greater ease for calculation purposes. The adjusted semivariogram function used was the Mattern with Stein parameterization (Mattern Ste), with a low Nugget value, indicating a good density of observations (Fig. 2). A positive correlation was observed between the contents of clay and silt ($c + s$) and the EC$_a$ ($R^2 = 0.83$), allowing us to identify three soil textures in a linear range. The textures found (Fig. 1) were LS ($c + s < 30$ g kg^{-1} soil, EC$_a < 8$ mS m^{-1}), SL (30 g kg^{-1} soil $< c + s < 40$ g kg^{-1} soil, 8 mS m^{-1} < EC$_a$ < 12 mS m^{-1}) and SCL ($c + s > 40$ g kg^{-1} soil, EC$_a > 12$ mS m^{-1}).

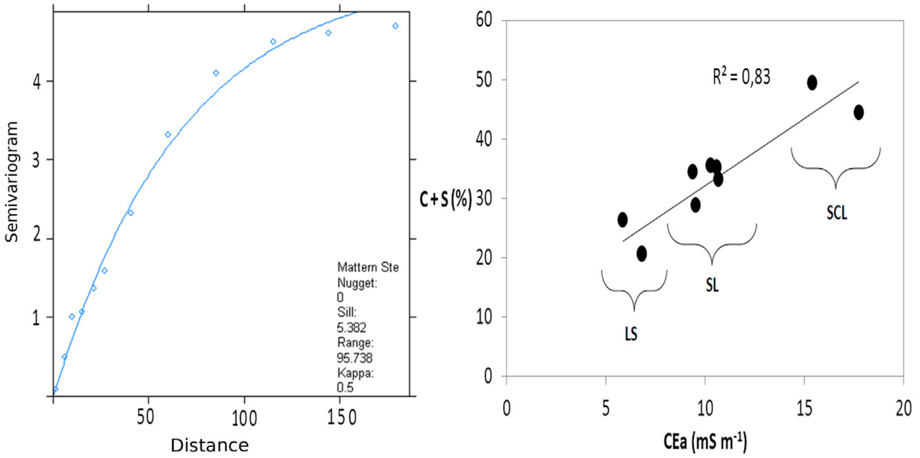

Fig. 2. Left: omnidirectional semivariogram of apparent electrical conductivity (ECa), right: Relationship between ECa and percentage of clay plus silt (0–20 cm). Letters on the graph indicate different soil textures: loamy sand (LS), sandy loam (SL) and sandy clay loam (SCL).

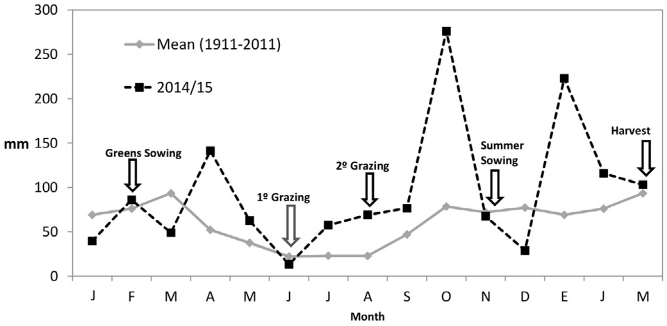

Fig. 3. Pattern of rainfall (mm) during the period studied. Arrows indicate the moment when the event occurred. Dotted lines indicate the pattern of rainfall in 2014 and 2015. Solid lines indicate the mean values for rainfall in the National Institute of Agricultural Technology (INTA) Bordenave Experimental Station.

Accumulated rainfall during 2014 (967 mm) was 44% above the historic average for the site (670.9 mm). During the summer of 2015 there was a rise in precipitations which were 53% above the historical average, mainly due to January rainfall (223 mm) (Fig. 3).

Stocking rate and texture interacted in their effects on soil BD after grazing and on ΔBD (Table 1). The layers only had an interaction with texture ($p < 0.01$), without having combined effects with the different treatments. After grazing, lower BD values were observed throughout the profile for the SCL texture, while, in the 0–10 cm layer, BD values were similar for the LS and SL textures. Animal grazing did not produce significant effects at different layers, with the textural contents determining the differences in BD in the different layers evaluated. The interaction Treatment-Texture shows that, for the LS texture, the HVY treatment increased its BD (1.43 Mg m^{-3}) compared to MOD (1.36 Mg m^{-3}) and CON (1.35 Mg m^{-3}), with no differences in the remaining textures and the different layers. The ΔBD showed significant differences between stocking rates, with an increase in BD in the HVY treatment in the LS and SL textures after grazing.

Since MR values need similar water content to be comparable (Collazo, 2004), differences in water content in the 0–20 cm layer prior to grazing ($p = 0.013$) determined that only the post-grazing data could be analyzed. Between sampling dates we don't detected significant changes in the water content in the topsoil layer ($p = 0.013$). The MR showed interaction between Texture and Depth, and between stocking rate and depth (Table 2). MOD and HVY treatments increased MR when compared to CON in the 0–5 cm and 5–10 cm layers. In the same layers, LS texture had lower MR values than SCL and SL, with no differences in 10–15 cm and 15–20 cm. The Texture-Depth interaction showed a gradual decline in MR with depth in SL and SCL textures, and a more irregular variation in LS. SL and SCL showed significant differences in the 0–5 cm and 5–10 cm layers and no differences in 10–15 cm and 15–20 cm layers. For LS, only the 10–15 cm layer showed differences compared to the other layers. High rainfall determined high soil water content (close to field capacity) and a reduction in the mechanical resistance of the soil (Kondo and Dias Junior, 1999). This fact lowered the negative effects of grazing on physical properties of the soil.

K showed a significant effect of grazing with no interaction between stocking rates and texture. MOD and HVY treatments reduced K when compared to CON, with no differences between them. Related to their initial state, grazed treatments showed a reduction of 19 and 21% respectively, compared to an 8% increase in CON. Fig. 4 shows the values of *Kt* for the different tensions measured. $Kt_{(-15)}$ behaved the same way as $Kt_{(0)}$. Different stocking rates showed no significant reduction in $Kt_{(-30)}$. The greatest changes as a result of grazing occurred at lower tensions ($Kt_{(0)}$, $Kt_{(-15)}$), correlated to pores of greater diameter (>1866 μm). The K values varied with texture, LS showed higher $Kt_{(0)}$

Table 1
Average values of bulk density (BD) (Mg m^{-3}) for the 0–20 cm layers after grazing, and the difference between values Post-grazing – Pre-grazing (ΔBD). Lower-case letters show differences between stocking rate ($\alpha = 0.05$).

	BD Post-grazing			Δ BD		
	LS	SL	SCL	LS	SL	SCL
CON	1.35 a	1.34 a	1.26 a	−0.0057 a	0.0184 a	0.0314 a
MOD	1.36 a	1.34 a	1.24 a	−0.0148 a	0.0284 a	0.0220 a
HVY	1.43 b	1.37 a	1.23 a	0.0713 b	0.0500 b	0.0218 a

Table 2
Average values of mechanical resistance (MR) (MPa) for the following stocking rates: control (CON), moderate (MOD) and heavy (HVY), and soil textures: loamy sand (LS), sandy loam (SL) and sandy clay loam (SCL) in different layers. Different upper-case letters indicate significant differences between layers (cm); different lower-case letters indicate significant differences between stocking rates or textures.

Treatment	0–5		5–10		10–15		15–20	
CON	2.18	A b	1.86	BC b	1.70	C a	2.03	BA a
MOD	2.88	A a	2.53	B a	1.67	C a	1.92	C a
HVY	3.20	A a	2.75	B a	1.80	C a	1.91	C a
LS	2.11	A b	1.93	A b	1.57	B a	2.14	A a
SL	3.37	A a	2.91	B a	1.98	C a	1.91	C a
SCL	2.77	A a	2.31	B ab	1.63	C a	1.81	C a

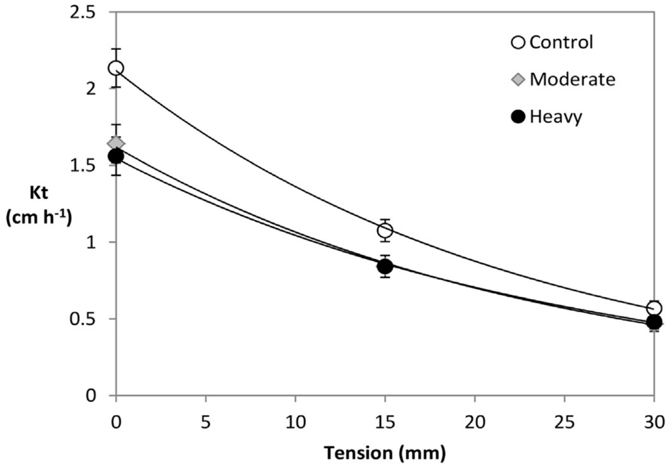

Fig. 4. Transformed hydraulic conductivity (*Kt*) for different measuring tensions under the stocking rate evaluated. Bars indicate standard error. The line corresponds to the exponential adjustment of data.

and $Kt_{(-15)}$ with respect to SL and SCL. No differences were observed in $Kt_{(-30)}$ between textures for any sampling date.

Mρ only showed effects on stocking rate at the greatest tension (560 mm) measured following grazing, without any interaction with soil texture. At this tension, HVY (4.43 cm^3 100 cm^{-3}) and MOD (5.04 cm^3 100 cm^{-3}) reduced *Mρ* when compared to CON (5.8 cm^3 100 cm^{-3}) (Fig. 5). For similar soil textures, other studies in the region showed a greater value of macroporosity on agricultural fields (López et al., 2016), suggesting a probable negative effect of the actual crop rotation on the physical health of the soil. Between sampling dates, the effects of stocking rate were slightly non-significant ($p = 0.07$) with a percentage reduction of about 40% under MOD and HVY treatments and 15% under CON. At both times, soil texture LS had a greater macroporosity, but there were no differences between SLC and SL (data not shown).

The emergence of sorghum was not affected by stocking rate or texture (Fig. 6). Also, no effects of stocking rate on crop production parameters were observed (Table 3). Sorghum productivity varied with soil texture: SL and SCL showed higher accumulation of aerial biomass, taller plants and higher protein content in forage (data not shown).

4. Discussion

Depending on soil texture, there is a critical BD which limits the growth of plants (Daddow and Warrington, 1983). This BD is 1.76, 1.70, and 1.63 Mg m^{-3} for LS, SL, SCL, respectively. In our study, BD after grazing did not come close to the critical values (Table 1). Although changes in BD are indicators of changes in soil porosity, they do not provide information about the distribution of those spaces, their connectivity or the changes in their connectivity (Alaoui et al., 2011). The lack of sensitivity of this indicator to detect changes in the transport of water and solutes in the soil has been reported (Horn et al., 2003; Lipiec and Hatano, 2003; Gebhardt et al., 2009). Other authors reported strong associations between BD and crop productivity (Singa Rao et al., 1989; Pulido et al., 2016), although in these cases the range of BD was larger than the one studied in this research. BD was only affected by the heaviest animal load in LS textures. The few changes observed in SCL can be attributed to its higher content of OM, which produces a dampening effect on the change in BD (Díaz-Zorita and Grosso, 2000). Decreases in OM content are associated with increasingly adverse soil physical conditions (Dexter, 2004). Significant increases in BD in the surface layers of the soil have been observed in other studies as a consequence of grazing (Chanasyk and Naeth, 1995; Greenwood et al., 1997; Greenwood and McKenzie, 2001; Pulido et al., 2016).

No relationship was observed between BD and other physical parameters or crop production. The structural porosity calculated from actual and maximum bulk density could be a more promissory indicator (Aparicio et al., 2007).

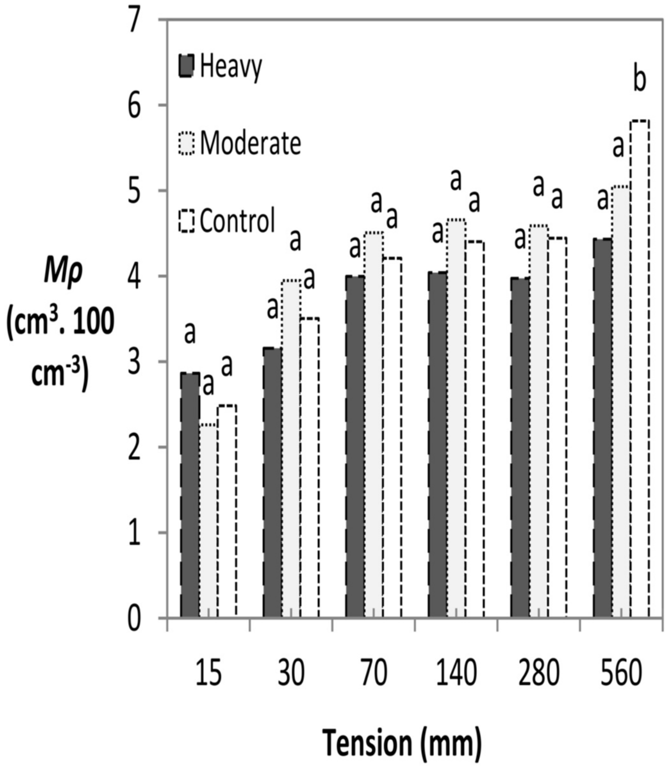

Fig. 5. Macroporosity for different tensions measured in the 0–5 cm layers; different letters indicate significant differences between treatments ($\alpha = 0.05$).

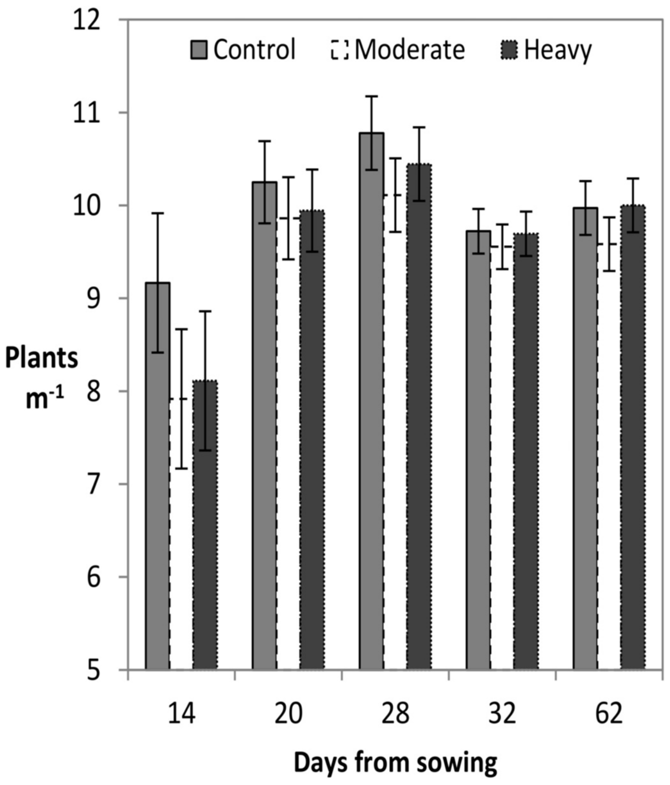

Fig. 6. Number of sorghum plants that emerged per linear meter, as a function of time in days after sowing. Bars indicate standard error.

Table 3
Means and standard deviations for the variables analyzed at growing stage 3 and at harvest in different cattle stocking rates: control (CON), moderate (MOD) and heavy (HVY).

	Treatment		
	CON	MOD	HVY
Height (cm)[a]	89.02 ± 12.5	91.5 ± 14.07	89.58 ± 16.97
No. Tillers[a]	1.34 ± 0.35	1.51 ± 0.47	1.31 ± 0.34
DM (g $pl.^{-1}$)[a]	19.93 ± 5.21	20.69 ± 6.82	20.57 ± 7.78
No. Leaves[a]	10.16 ± 0.54	10.14 ± 0.50	10.26 ± 0.80
Protein (%)[a]	11.34 ± 3.56	10.49 ± 1.34	10.40 ± 3.09
Accumulated biomass (kg ha^{-1})[b]	11,240 ± 2688	11,713 ± 2963	11,240 ± 2641
Yield (kg ha^{-1})[b]	4142 ± 1103	3956 ± 974	3607 ± 1120

[a] Measurements at growing stage 3.
[b] Measurements at harvest.

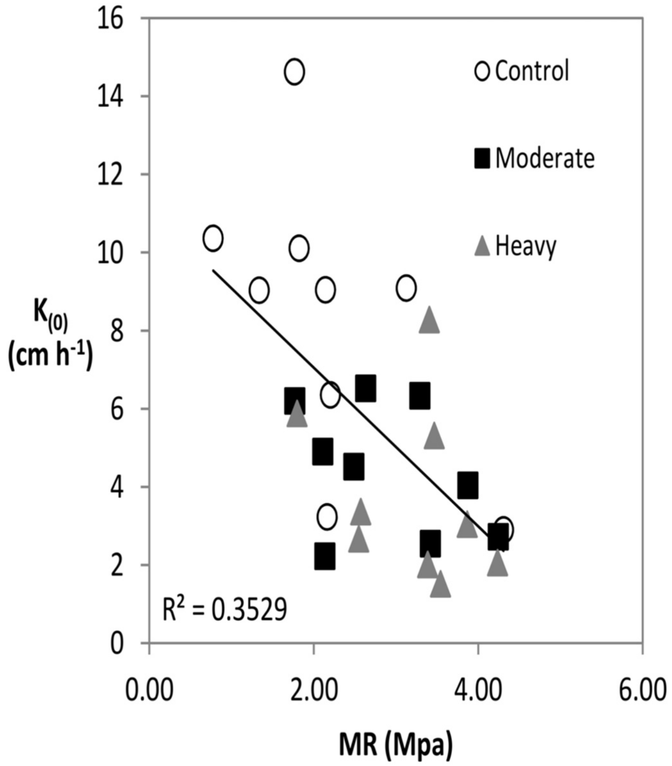

Fig. 7. Relationship between the average values of mechanical resistance (0–5 cm) and the average values of hydraulic conductivity (cm h^{-1}) without transformation.

As a result of grazing, at any level of stocking rate, in the surface layer (0–10 cm), MR increased to values above 2.5 Mpa, which is considered critical for root growth (Pabin et al., 1998; Hamza and Anderson, 2005). The impact of grazing reached a greater depth than the one observed in other studies: 5 cm (Agostini et al., 2012), or 8 cm (Lanzanova et al., 2007). This could be due to the higher stocking rate used in this study, or the higher soil water content at grazing time. Even then, the roots have mechanisms to avoid high mechanical impedances (Materechera et al., 1991) and impedance is influenced by the water content of the soil, due to its inverse relationship with the MR (Krüger et al., 2008). In this respect, at sampling the soil had high water content. It is to be expected that the values of MR will show greater differences in years with rainfall closer to the regional average.

Both hydraulic conductivity and macroporosity were reduced in grazed treatments (MOD and HVY) when compared to CON. Vahhabi et al. (2001), and Mwendera and Saleem (1997), also detected reductions in the hydraulic conductivity due to animal trampling. The changes observed in the flow of water indicate that the effects are limited to pores of a diameter > 1000 μm, which are largely responsible for the flow of water in soil (Luxmoore, 1981). Porosity below this tension (30 mm) participates in 25% to 27% of $K_{(0)}$, so that a reduction in these values does not have a direct influence on *K*.

A positive correlation was observed between $M\rho_{(-560)}$ and $K_{(0)}$ ($R^2 = 0.32$) and a negative linear correlation between MR and $K_{(0)}$ in the superficial layer ($R^2 = 0.35$) (Fig. 7) and 5–10 cm ($R^2 = 0.32$) (data not shown). If we disaggregate the correlation between$_{)}$ $M\rho_{(-560)}$ and $K_{(0}$ according to the textures studied, we get different results for SCL ($R^2 = 0.76$), SL ($R^2 = 0.6$) and LS ($R^2 = 0.033$), with the latter being influenced by two extreme values. Those relationships are important since direct measure of $K_{(0)}$ is difficult and time-demanding. A new set of data at different soil water contents is necessary to assess the possibility of using MR values as indicators of K.

There was no significant correlation between $M\rho_{(-30)}$, or $M\rho_{(-15)}$ and *K* as it would be expected according to what was observed with tension disc infiltrometers in the field. This could be attributed to the low percentage of this fraction in the total porosity of the soil (2.2–2.8%), or by the presence of roots blocking pore spaces (Pietola et al., 2005). The threshold value of $M\rho_{(-560)}$ (d > 50 μm) when integrating information about all the pore space above this, allows us to observe the trends. $M\rho_{(-560)}$ forms a break-point in the trampling effect on the porosity, being very close to the limit of macropores (d > 50 μm) stated by Oliveira (1968). In line with the data obtained in this study, Zhao et al. (2010) indicated that the reduction in macroporosity (d > 50 μm), due to animal trampling, was reflected in a decrease in the saturated hydraulic conductivity.

The negative effects observed in the physical properties of the soil did not have any repercussions in the establishment and development of the following summer crop, not taking into account a slight tendency to fewer plants emerged in the early determinations (Fig. 6). These results agree with other studies on cattle compaction in integrated crops-livestock systems, where the negative effect in the soil properties had low effect on crop productivity (Franzluebbers and Stuedemann, 2007; Bell et al., 2011; Fernández et al., 2015). The effects of animal grazing on the establishment and development of the following crop were unnoticeable due to the abundant rainfall before sowing and during the summer of 2015, which overcame other limitations of the crop.

This results are valid for short time grazing events, long term evaluations in crop-livestock no-till farming systems indicate a lower effect of the cattle trampling in the soil properties and crop productivity (Tracy and Zhang, 2008; Quiroga et al., 2009; Fernández et al., 2015). However, the short time between winter grazing and the sowing of summer crops in intensified crop rotations prevents the action of soil recovery forces (Fernández et al., 2015) with a probably negative effect in the next crop productivity, especially in dry years and in coarse textures (Braunack and Walker, 1985; Greenwood et al., 1998; Sidhu and Duiker, 2006). In this experiment, higher BD and MR were associated with lower *K* and *Mρ* in grazed treatments when compared to the control, evidencing the detrimental effect of animal grazing on soil under NT. This effect was attenuated in the SCL texture, probably because it contained a higher OM level. With rainfall close to the normal for the location studied, a lower soil water content would increase MR, delaying crop establishment and root growth. Likewise, the reduced hydraulic conductivity and macroporosity could have stronger effects under a more limited rainfall regime. Similar non-response situations to soil compaction due to favorable weather conditions were reported by Venanzi et al. (2004), and by Morán et al. (2000). It will be important in the next future to perform new studies, in order to encompass a wider range of climatic conditions (years with average rains) and soil textures, to obtain climatic thresholds that allow predicting the impact of livestock trampling on crop productivity.

5. Conclusions

Negative effects of animal trampling on the physical parameters of soil were proved under usual and doubled stocking rates on winter forage crops. Bulk density increased slightly, mechanical resistance surpassed critical values, and hydraulic conductivity and macroporosity were reduced. However, these effects did not have an impact on the establishment and development of the following summer crop due to the high level of rainfall. The cattle trampling in clayey soils (higher clay +silt) did not have a greater negative impact on the physical properties of the soil. The degree to which $M\rho$, MR and K were affected by the stocking rate was similar through the different textures studied.

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