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Improvement of Saline-Sodic Grassland Soils Properties by Rotational Grazing in Argentina☆

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ABSTRACT

We investigated the effectiveness of rotational and permanent grazing exclosure periods for improving topsoil quality in three commercial farms devoted to cattle breeding in sodic grassland (halophytic steppe) soils of the Flooding Pampa of Argentina. We compared two plots under continuous grazing (C1-C2) with two plots under more than 8 yr of rotational grazing management (R1-R2) and two adjacent plots under permanent grazing exclosure for more than 8 (E1) and 4 (E2) yr. Periodic and permanent grazing exclosure periods caused significant ($P < 0.05$) and progressive increases in topsoil organic carbon content and organic carbon stock (0 − 20 cm; from 24 to 61 Mg ha^{-1}) as follows: (C1 = C2) < (R1 = R2 = E2) < E1 plots. Topsoil physical properties (bulk density, structural instability, and bearing capacity) and salinity were higher ($P < 0.05$) in C1 and C2 than in the other plots, while infiltration rate was higher in the oldest exclosure (E1) than in the other plots. Topsoil pH decreased from C1-C2 plots (9.5 − 9.9) to R1-R2 plots (7.3 − 8.2) to E1-E2 plots (6.5 − 7.5), while SAR was highest in C1-C2 and lowest in E1 plots. We propose a conceptual model leading to soil recovery in this halophytic steppe community, triggered by organic carbon accumulation induced by grazing management. Short-time grazing exclusion periods (i.e., rotational grazing) are a plausible and low-cost management option to be recommended to the farmers in this highly restrictive environment.

Introduction

Native grasslands on saline-sodic soils are extensive in the world. The high soil salinity and poor drainage conditions of these soils determine low forage production; therefore they are usually devoted to extensive grazing by livestock (Taboada et al., 2011). The low economic returns of this livestock production activity impede the use of classical rehabilitation techniques in saline-sodic soils, such as chemical amendments and agricultural drainage, so improvement must be of low cost. Several authors showed improvements in the vegetation structure and topsoil quality of saline-sodic soils in the native grasslands of Argentina by the grazing exclosure for several years (Sala et al., 1986; Lavado and Taboada, 1987; Di Bella et al., 2015). These studies suggest that appropriate grazing management systems (e.g., adjusting stocking rate to vegetation requirements and grassland receptivity or excluding grazing for short periods) could be a viable option to improve soil quality, as well as plant community structure in saline-sodic soils. However, the effects of controlled grazing have not been well documented on sodic soils, which are often highly susceptible to grazing and trampling disturbances by livestock and can require long recovery periods. For example, periodic grazing exclusion for a few months caused no clear effects in highly sodic soils of a halophytic grassland community (Rubio and Lavado, 1990; Taboada and Micucci, 2009).

Continuous grazing may cause severe damage on topsoil quality, such as compaction and kneading. Soil compaction results from reduction in soil macroporosity rather than total porosity (Greenwood et al., 1997; Taboada et al., 2011). As a result of compaction, higher bulk density and surface resistance and lower structural stability are usually observed in grazed versus ungrazed topsoil (Schuman et al., 2002; Henderson et al., 2004). This damage may be reversed by short grazing-exclusion periods under rotational grazing systems (Gifford and Hawkins, 1978; Willat and Pullar, 1983; Warren et al., 1986; Greenwood and McKenzie, 2001; Drewry, 2006).

In fertile soils the ground is usually completely covered by litter and living vegetation, which contribute to maintaining good soil physical and chemical properties (Taboada and Lavado, 1993; Taboada et al., 1999; Greenwood and McKenzie, 2001; Cingolani et al., 2008). In

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contrast, less fertile soils are more restrictive for plant growth and have low ground cover by vegetation (Greenwood and McKenzie, 2001; Drewry, 2006; Milchunas, 2011). This situation is even more severe in salt-affected soils, exposed to not only low fertility and salinity but also alkalinity. The appearance of bare soil patches resulting from continuous grazing promotes movement of salt from depth in lowlands soils (Lavado and Taboada, 1987) and coastal marshes (Di Bella et al., 2015). In contrast, the grazing exclosure for several years limited movement of salt from depth and favored the leaching of salts in both ecosystems. These soil recovery processes were mainly driven by the deposition of plant litter on the soil surface and emergence of new colonizing species, which change both the floristic composition and canopy structure of grasslands and pastures (Sala et al., 1986; Taboada et al., 2011).

Unlike these impacts of grazing on soil salinization, the effects of grazing on soil organic carbon and soil physical properties are variable because of the influence of other factors such as the amount of carbon returns or the different recovery capacity of trampled soils (Fernández et al., 2011; Taboada et al., 2011; Peyroud et al., 2014). A crucial issue is the interaction between the changes induced by grazing on soil physical and chemical traits and soil organic carbon content. Does decrease in grazing pressure cause an improvement in soil physical and chemical traits, and in turn promote an increase in plant biomass leading to an increase in soil carbon content? Does decrease of grazing pressure promote an increase in plant biomass, leading to an increase in soil carbon content to improve soil physical and chemical properties?

The agriculture expansion in Argentina caused a progressive movement of cattle to areas covered with low-fertility soils (Paruelo et al., 2005; Peyroud et al., 2014). Therefore livestock stocking rates increased on these soils, including those affected by saline-sodic conditions covered by halophytic steppe communities, which in Argentina occupy > 12 million ha (INTA, 2013). In these fragile or highly vulnerable environments, conservation of ecosystem, flood regulation, and carbon sequestration is crucial to manage for the conservation of ecosystem services (FAO and ITPS, 2015). Therefore, it is important to explore management strategies to increase plant productivity and minimize damages by livestock grazing. The aim of this study was to evaluate the effectiveness of periodic grazing break periods for improving the quality of saline-sodic soils covered by halophytic steppe communities. We expected that such improvement comes from the increase of soil organic matter, which promotes a decrease in salt and exchangeable sodium concentrations in the topsoil.

Materials and Methods

Study Area

Our study was carried out in livestock farms in Magdalena County, province of Buenos Aires (35°13′54.372 S; 57°37′58.152 W), in the north Flooding Pampa of Argentina (Fig. 1). Most of the region is a lowland area covered by native grasslands devoted to extensive grazing by livestock. The climate is humid temperate with no dry season and a mean annual rainfall of 980 mm. The flat relief, with a slope of < 1%, does not allow water runoff, and drainage is slow. Native grasslands include a mosaic of plant communities with a wide variety of native and exotic species. In the study area, the plant community is dominated by C_4 grasses, mainly *Distichlis* spp., and minor proportions of other herbaceous species such as *Sporobolus pyramidatus* Lam, *Hordeum stenostachys* Godr, *Puccinellia glaucescens* Phil, *Chloris berroi Arechav, Pappophorum mucronulatum* Nees, *Spergularia laevis* Cambess, *Lepidium spicatum* Desv., and *Acicarpha procumbens* Less (Perelman et al., 2001; Chaneton et al., 2002).

This plant community grows on salt-affected soils characterized by high pH and sodicity and low levels of organic matter contents, structural stability, available soil water, and plant nutrient contents (Alconada et al., 1993; Otondo et al., 2015). Most of the study area is covered by sodic soils of the Poblet Series (thermic, fine, illitic, Vertic Natraqualf) (Table 1).

Field Sampling and Laboratory Analysis

Six plots of about 10 ha covered by halophytic steppe community were selected in three nearby commercial farms devoted to cattle breeding (cow-calf operations) (Fig. 1). The six plots were subjected to different grazing regimes, as follows:

a) Continuous grazing (C1 and C2): two plots in the same farm continuously grazed year-round by $0.8-1$ animal units (AU; cows and calves).ha^{-1} in the past 4 decades;
b) Rotational grazing (R1 and R2) in the past 8 yr: two plots in the same farm grazed from 1999 and during the study at instantaneous stocking rates of $10-12$ AU.ha^{-1}, and $0.8-1$ AU.ha^{-1} year-round stocking rate. Grazing times did not exceed 5 d, and grazing exclusion periods were between 60 and 100 d, depending on the season.
c) Grazing exclosure (E1 and E2): two plots in different and nearby farms excluded from grazing from 1999 (E1) and from 2004 (E2) were previously continuously grazed.

In January 2007 five composited soil samples (10 subsamples each) were extracted from the 0- to 10-cm, 10- to 15-cm, and 15- to 20-cm layers on each of the six plots to determine soil pH (1:2.5 distilled water), soil salinity by electrical conductivity (EC) of saturation extracts, soil sodium adsorption ratio (SAR), and soil organic matter content (Walkley and Black, 1934). Soil SAR was calculated from the concentration of Na^+, Ca^{2+}, and Mg^{2+} in soil saturation extracts, determined by flame spectrometer (Rhoades, 1982).

In February 2008 (summer) and September 2008 (winter), five undisturbed soil samples (8-cm diameter cores) were taken from the first 15 cm at each of the six plots to determine soil bulk density (Grossman and Reinsch, 2002).Two undisturbed samples were taken from the first 15 cm of each plot to determine their structural instability (SI) index, resulting from the difference between the mean weight diameter of dry-sieved (4.8-, 3.4-, and 2-mm screen opening sieves) and wet-sieved (4.8-, 3.4-, 2-, 1-, 0.5-, and 0.3-mm sieves) aggregates (De Leenheer and De Boodt, quoted by Burke et al., 1986). Aggregates were separated by hand and then dry-sieved by vibration. These aggregates were moistened by capillarity up to field capacity to avoid slaking of dry aggregates and then were wet-sieved during 30 min in a Yoder apparatus. After cutting vegetation at ground level, the soil infiltration rate was determined ($n = 4$) using a fast method developed by the US Department of Agriculture (1999) in each plot.

Soil-bearing capacity was determined only in summer using a Proctor static penetrometer (Davidson, 1965), when the water content of the soil allowed us to perform the measurements. The late winter measurement could not be carried out because it coincided with the most severe drought of the century (2008). Bearing capacity measurements ($n = 100$) were randomly taken in each plot along a zig-zag transect.

Statistical Analyses

The plots subjected to a same grazing regime were located in different nearby commercial farms and, in the case of E1 and E2 grazing exclosures, were installed at different times. This spatial arrangement of plots did not allow for grazing regimes to be replicated in space, so the six plots were considered as separated treatments and the samples taken within them were considered as repetitions

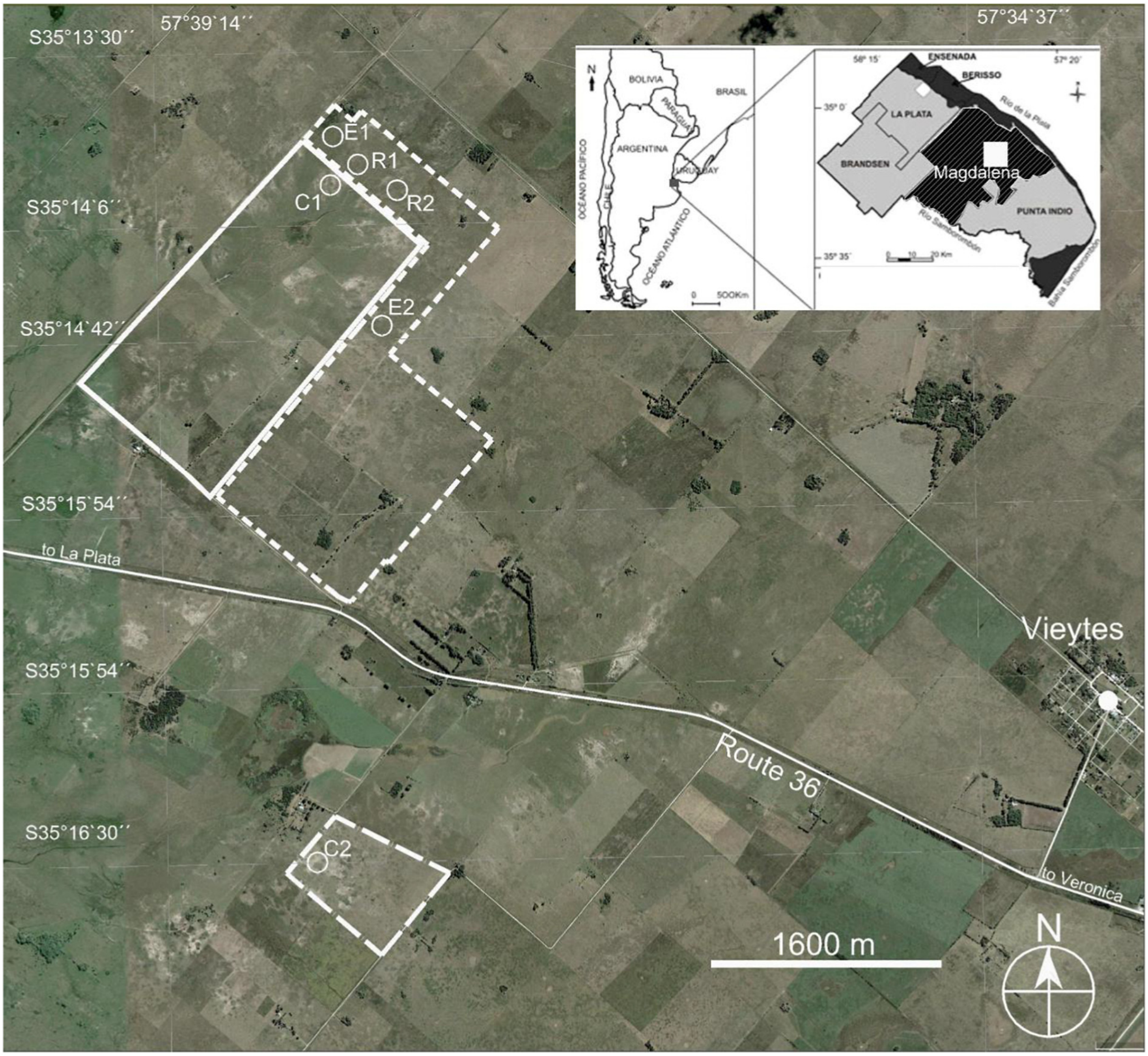

Figure 1. Location of study site in the Province of Buenos Aires, Argentina and field plots with different treatments. C1 and C2: plots under continuous grazing; R1 and R2: plots under rotational grazing since 1999; E1 and E2: plots under permanent grazing exclusion since 1999 and 2004, respectively. The three polygons correspond to different ranches.

(Hurlbert, 1984). Soil properties among the six plots were compared by analysis of variance, arranged in split-plot to compare the two sampling dates. A split-plot arrangement was also used to analyze the differences among the three soil layers. Comparisons between means were carried out by Tukey test at a significance level of $\alpha = 0.05$.

Table 1
Soil profile description of the Poblet Series (thermic, fine, illitic, Vertic Natraqualf). Adapted from INTA (2013).

		Horizons			
		An	Btnz	Btssn	BCckn
Depth (m)		0-0.10	0.1-0.56	0.56-1.15	1.15-+
Color (Munsell Chart)	**moist**	Very dark brown (10YR 2/2)	Black (10YR 2/1)	Brown to dark brown (7.5 YR 4/4)	Brown (7.5 YR 5/4)
	dry	Gray (10 YR 5/1)	Grayish brown (10YR 4/2)	Pink gray (7.5 YR 7/2)	Light brown (7.5 YR 6/4)
Texture		Silty clay loam	Silty clay	Silty clay	Silty clay
Structure		Medium moderate, subangular, blocks, breaking to granular	Fine, strong subangular blocks, breaking to granular prism, breaking to fine blocks and	Composed medium, strong irregular prisms	
Consistence	**dry**	Very hard	Extremely hard	Extremely hard	Slighly hard
	moist		Very firm		Firm
	wet		Very plastic very adhesive		Plastic adhesive
Root abundance		+++	+	+	-
Concretions	**Fe-Mn**	-	++	-	-
	$CaCo_3$	-	+	+++	+++

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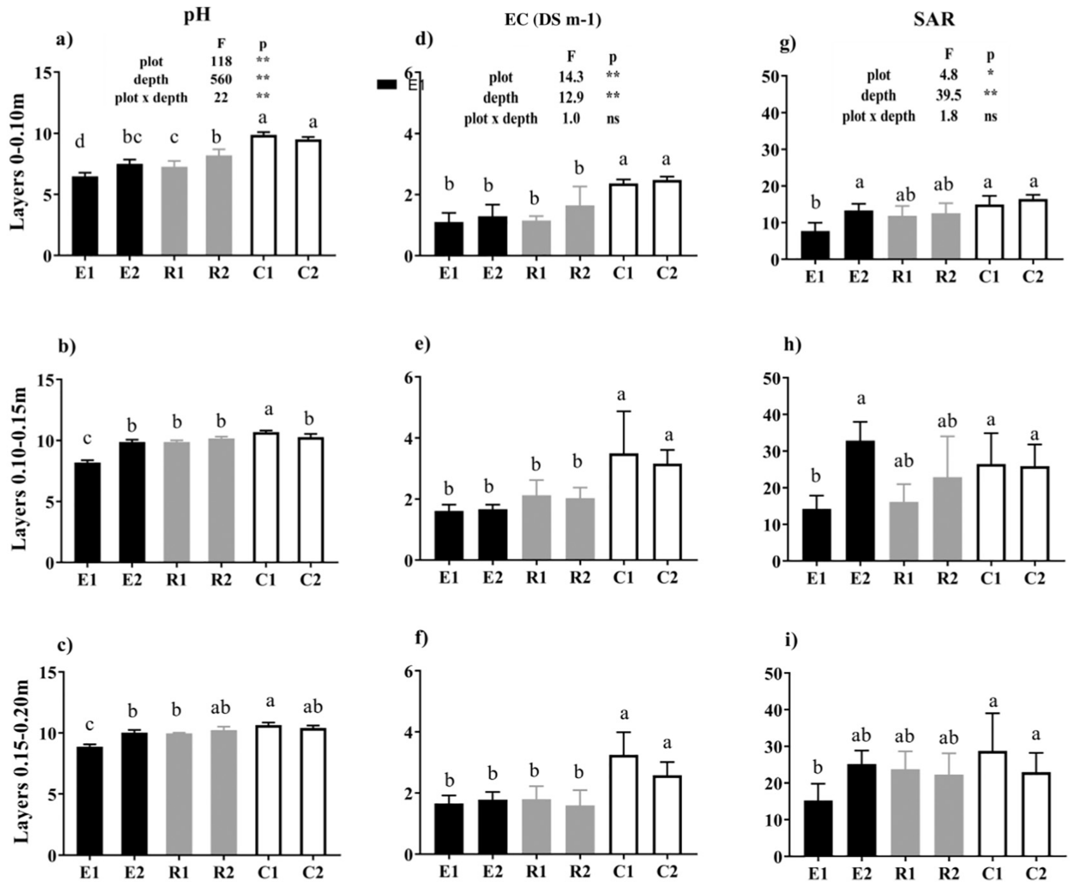

Figure 2. Soil pH (a, b, c), the electrical conductivity (EC) (d, e, f), and sodium adsorption ratio (SAR) (g, h, i) of three soil layers. In the first panel of each variable are consigned the F-values obtained by ANOVA test, indicating their statistical significance: **= p<0.01, 0.01>p>0.05, ns= p>0.05. Different lower letters indicate significant differences among the 18 combinations of six plots and three soil layers. The standard deviations of the means are indicated by vertical bars.

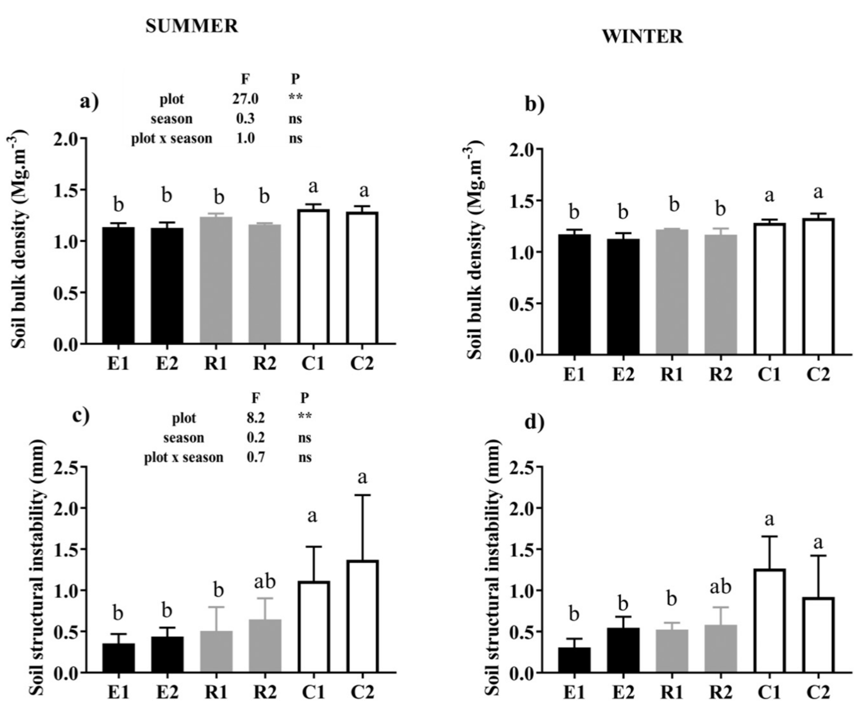

Figure 3. Soil bulk density (a, b) and soil structural instability measured by the change in mean weight diameter between dry-sieved and wet-sieved aggregates in summer (a, c) and in winter (b, d). In the first panel of each variable are consigned the F values obtained by ANOVA test, indicating their statistical significance: **= p<0.01, 0.01>p>0.05, ns= p>0.05. Different lower letters indicate significant differences among the six plots. The standard deviations of the means are indicated by vertical bars.

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Results

Soil Halomorphism

In all layers, soil pH was significantly higher ($P < 0.05$) in continuously grazing (C1 and C2) intermediate with rotationally grazing (R1 and R2) plots and lowest in grazing exclosure (E1 and E2) plots. Considering both grazing exclosure plots, notably the lowest pH values were found in the oldest exclosure (E1). Although differences in pH between treatments and plots were more evident in the 0- to 10-cm layer, this pattern did not substantially differ in 10- to 15-cm and 15- to 20-cm layers (Fig. 2a-c). The entire profile was highly alkaline (pH ≥ 9), except in the upper layer of R1-R2 and E1-E2 plots, where significant pH decreases to 6.5 − 8 were observed ($P < 0.05$).

Soil salinity also varied significantly ($P < 0.05$) among plots, but it never exceeded an electric conductivity of 4 $dS.m^{-1}$, the taxonomic EC_{sat} threshold defining saline soils (Fig. 2d-f). Differences were only significant in the 0- to 10-cm layer, where, like soil pH, soil EC also decreased significantly ($P < 0.05$) from C1 and C2 to R1 and R2, and E1 and E2 plots. Soil sodicity measured by SAR values also varied significantly ($P < 0.05$) in the 0- to 10-cm layer (Fig. 2g-i). Differences in soil SAR were similar but lower than those in pH and EC. Like in soil pH, significantly ($P < 0.05$) lower SAR values were found in E1 than other sites (Fig. 2g). Both soil salinity and SAR were highest in the upper soil layer (Fig. 2d vs. Fig. 2e and f and Fig. 2g vs. Fig. 2h and i).

Soil Physical Properties and Organic Matter

Soil bulk density and structural instability were significantly ($P <$ 0.05) affected by grazing management in summer but not in winter (Fig. 3a-d). In summer, both soil bulk density and structural instability decreased significantly ($P < 0.05$) from C1 and C2 to R1, R2, E1, and E2 plots (Fig. 3a and b). Soil structural instability was up to three times higher under continuous grazing (C1 and C2) than under grazing exclosure (E1 and E2).

Like bulk density and structural instability, soil infiltration rate only varied significantly ($P < 0.05$) in summer and in the older exclosure (E1), where the infiltration rate was twofold higher in E1 than in all the other plots (Fig. 4a and b). Summer soil-bearing capacity was about twofold significantly ($P < 0.05$) higher in C1 and C2 plots than in the rest of the plots (Fig. 4c).

All layers showed significant ($P < 0.05$) effects from grazing management on soil organic carbon (SOC; Fig. 5a-c). In the 0- to 10-cm and 10- to 15-cm layer, SOC content was significantly higher with C1 and C2

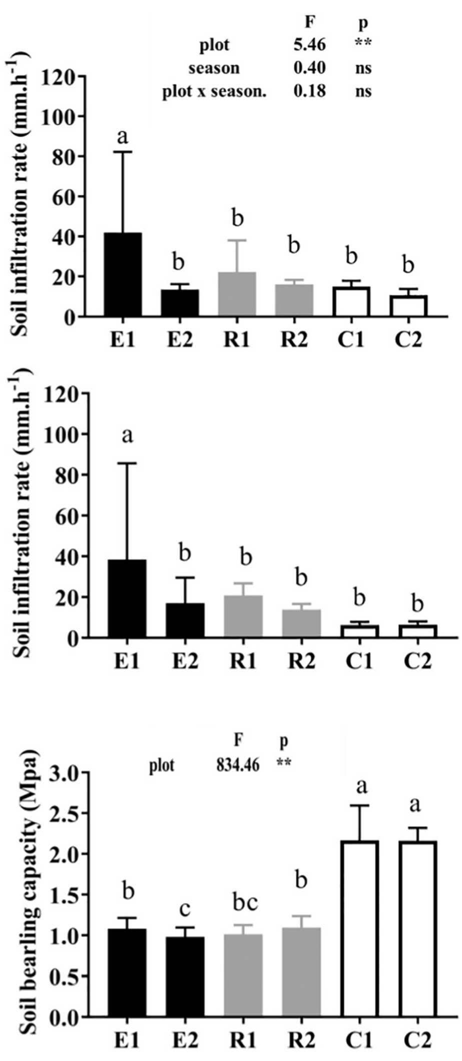

Figure 4. Soil infiltration rate in winter (a) and summer (b) and soil bearing capacity (c). In the first panel of each variable are consigned the F values obtained by ANOVA test, indicating their statistical significance: **= p<0.01, 0.01>p>0.05, ns= p>0.05. Different lower letters indicate significant differences among the six plots (only in the winter panel for soil infiltration rate because no plot x season interaction was found). The standard deviations of the means are indicated by vertical bars.

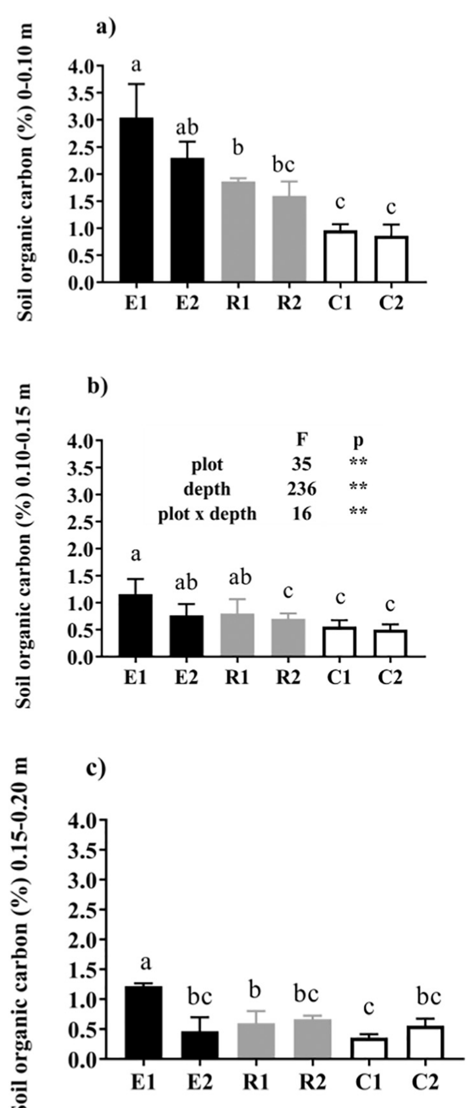

Figure 5. Soil organic carbon contents in the 0-10 cm (a), 10-15 cm (b) and 15-20 cm (c) layers. Different lower letters indicate significant differences among plots in three soil layers. The standard deviations of the means are indicated by vertical bars.

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compared with R1, R2, and E2 plots and reached its highest values in the E1 plot. In the 15- to 20-cm layer, soil organic carbon variations were similar but smaller. As expected, soil organic carbon contents decreased from the 0- to 10-cm to the 10- to 15-cm and 15- to 20-cm layers. As a consequence of the patterns described along the different layers, soil organic carbon stocks (0 − 20 cm) were significantly lower ($P < 0.05$) with C1 and C2 (24.3c and 24.7c $Mg.ha^{-1}$) relative to R1, R2 (40.2b and 36.5b $Mg.ha^{-1}$), and E2 (41.7b $Mg.ha^{-1}$) plots and reached their highest values in the older exclosure (E1) plot (61.2a $Mg.ha^{-1}$, different letters following numbers indicate significant differences).

Discussion

It has been demonstrated elsewhere that the grazing exclosure of livestock for some years leads to organic matter increases in the topsoil as a result of the higher carbon returns to soil (Pei et al., 2008; Golluscio et al., 2009; Taboada et al., 2011; Teague et al., 2011). However, this positive impact of grazing exclosure had not been previously observed in halophytic steppes such as those of the Flooding Pampa. Previous studies in the halophyte steppe had not been able to detect organic matter recovery as a result of rotational grazing or grazing exclosure (Lavado and Alconada, 1994; Taboada and Micucci, 2009). Recently, Di Bella et al. (2015) found that topsoil organic matter decreased when an originally grazing-excluded coastal salt marsh was subjected to continuous grazing. In contrast, soil organic matter did not recover after grazing exclosure in those grazed coastal marshes. Our results are a valuable contribution to this issue because they show a clear increase of soil organic carbon content (Fig. 5a-c) and C stocks (0 − 20 cm) in a conspicuous halophytic community of the Flooding Pampa as a result of both rotational grazing and grazing exclosure. Such recovery of soil organic carbon occurred in both grazing excluded plots, but it was higher in the oldest one (E1).

The carbon recovery here observed could be related to a better topsoil environment, as shown by decreases in soil pH and EC (Fig. 2a-f), as well as decreases in soil bulk density (Fig. 3a), structural instability (Fig. 3b), and bearing capacity (Fig. 4c) and increases in infiltration rate (Fig. 4a) observed in summer. Interesting to note, higher recovery was shown in not only soil organic carbon content and stock but also soil pH, SAR, and structural instability in the oldest exclosure (E1), which suggests a possible influence of time on the impacts of grazing management. Soil changes under rotational grazing or the 4-yr grazing exclosure were only evident in the 0- to 10-cm layer. The lowest amount of organic carbon in C1 and C2 plots would be an indirect effect of grazing reducing plant vigor and then limiting biomass allocation to the root system (Caldwell et al., 1981).

Soil organic carbon stocks in the 0- to 10-cm layer were almost three times higher in the plot with 8 yr of grazing exclosure (E1) than in C1 and C2 plots, with intermediate values in E2, R1, and R2 plots. Organic carbon storage in soils represents an effective way of carbon sequestration because of the recalcitrant forms of carbon in organic compounds in the soil (Jobbagy and Jackson, 2000; Piñeiro et al., 2009). The higher vegetation cover in the E1 grazing exclosure (Vecchio, 2014) possibly favored a greater accumulation of soil organic carbon. The C sequestration is of utmost importance in natural ecosystems because it represents one of the most important reservoirs of organic carbon on the planet. Practices that stimulate additional carbon accumulation in the soil improve fertility and positively affect productivity and the environment because they stimulate the dynamics and availability of the main plant nutrients (Robert and Chenu, 1991).

The lower storage of organic carbon from decomposing residues under continuous grazing (C1 and C2) restricts pore formation, which impairs soil microbial activity (Singh and Gupta, 1977) and consequently the stability of soil aggregates (Bullock et al., 1985; Tisdall and Adem, 1986; Unger, 1997). This indirect effect of grazing reduces infiltration and soil water storage capacity and promotes surface compaction by trampling (Franzluebbers et al., 2000). In this continuously grazed halophytic steppe community, livestock remain in the pasture even when it is waterlogged or very wet during winter, thus allowing soil structural damages by the action of kneading and poaching by animal hooves (Willat and Pullar, 1983; Warren et al., 1986; Taboada et al., 2011). As a result, damages to topsoil structure occurred, such as the increase of bulk density, structural instability and bearing capacity, and the decrease of infiltration rates.

We suggest that the improvement of soil physical environment is related to the increase of organic carbon concentration under grazing exclosure and rotational grazing. The greater creation of biopores generated by grass roots promotes rapid bypass water flows in depth (Edwards and Softy, 1978; Kladivko et al., 1986) and leaching of sodium salts. The increase in root respiration caused by the increase in root growth leads to increases in CO_2 partial pressure that contribute to the

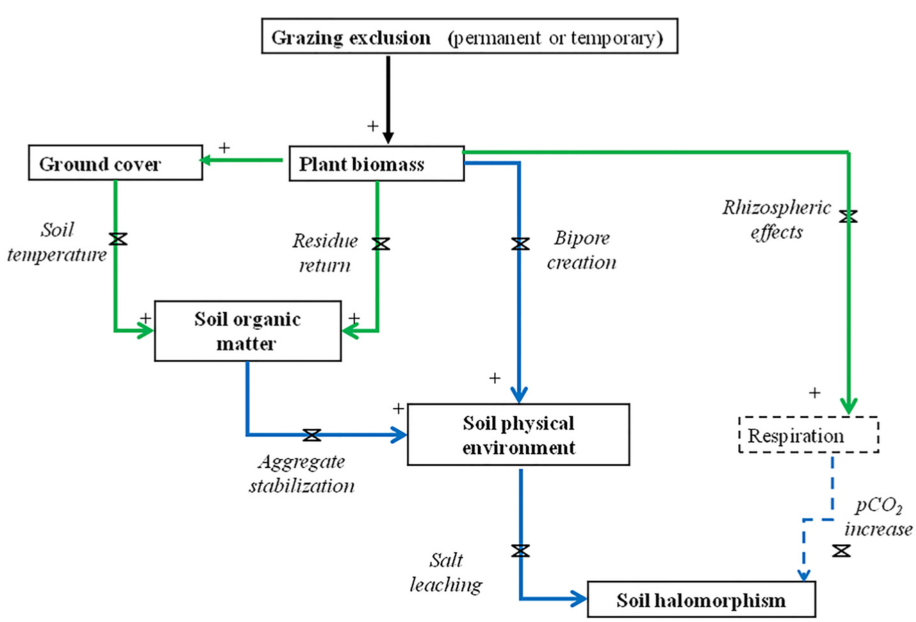

Figure 6. Biotic and abiotic factors and processes determining soil halomorphism. Factors are linked by arrows with a sign indicating the type of effect of each factor on the following (positive or negative). In italics is consigned the factor or process involved in the interaction represented by the arrow.

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dissolution of calcite ($CaCO_3$), releasing calcium (Ca^{2+}) that replaces sodium (Na^+) absorbed into the soil colloids and promoting pH decreases (Semple et al., 2003; Qadir et al., 2007). Also, the slight pH decrease under grazing exclosure may be an incipient process of soil desalinization in this halomorphic soil.

Conceptual Model

Our results of soil halormorphism, soil physical properties, soil organic carbon concentration, and stock are highly consistent. They show important improvements in soil function because of permanent grazing exclosure or periodic (rotational) grazing exclusion, as compared with continuous grazing. Changes in soil properties mainly impacted the first 10 cm of soil, suggesting the influence of increases in ground cover by vegetation after continuous grazing was terminated (Sala et al., 1986). Despite the fact that most studied properties reacted positively after rotational grazing, the magnitude of reaction was not the same. Soil organic carbon contents and stocks increased with increasing time of grazing exclosure, while some physical properties (e.g., structural instability, infiltration rate, and bearing capacity) only differed between the grazing exclusion treatments, and soil halomorphism reacted only weakly to changes in grazing management, as shown by only slight pH decreases and little or null effects on topsoil salinity and sodicity.

We propose a conceptual model integrating all the previously mentioned reported changes (Fig. 6). Permanent or temporary grazing exclosure changed plant canopy structure, increasing significantly vegetation biomass and ground cover (Sala et al., 1986). This increased organic carbon storage in soil because of both increased fresh plant residue returns and decreased carbon losses by mineralization in a cooler soil (Taboada et al., 2011). Both vegetation and soil organic matter improve topsoil physical environment because of the process of aggregate stabilization by rhizopheric effects and the creation of biopores by grass roots, worms, and other soil biota (Oades, 1984; Dexter, 1988). These beneficial changes are responsible for increased infiltration, which favors an incipient process of salt leaching and pH decreases.

The proposed conceptual model establishes a sequence of paths leading to soil recovery in this halophytic steppe community. A similar sequence of paths was also found by Otondo et al. (2015) in a nearby place because of the sowing of warm season grasses. Both studies indicate that the process of recovery is not dependent on salt leaching, but by soil organic carbon increase and the improvement of soil physical environment. The decrease in soil halomorphism as a consequence of the small decreases in pH that we hypothesize is the end of the recovery process. These results suggest temporary grazing exclusion and periodic grazing break periods are plausible and inexpensive management options that can be recommended to farmers in this highly limiting environment.

Implications

The implementation of grazing exclosure and periodic grazing break periods by rotational grazing are process technologies, cheap in inputs but expensive in knowledge by technicians and farmers. These technologies have proven to be effective in farms of the same region, with a mosaic of more and less saline-alkaline soil patches (Jacobo et al., 2006). However, despite their effectiveness, they were not yet massively adopted. Rural extension is needed for governmental and nongovernmental agencies to promote the adoption of these and other management practices that improve the conditions of fragile natural grasslands all around the word.

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