Catena 149 (2017) 86–97

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Spatial patterns of soil resources under different land use in *Prosopis* woodlands of the Monte desert

Pablo A. Meglioli [a,*], Julieta N. Aranibar [a,b], Pablo E. Villagra [a,c], Cecilia Vega Riveros [a]

[a] *Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), Consejo Nacional de Investigaciones Científicas y Técnicas (CCT-CONICET, Mendoza), Av. Ruiz Leal s/n, Parque General San Martín, CP 5500, Mendoza, Argentina*
[b] *Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Ciudad Universitaria, Parque General San Martín, CP 5500, Mendoza, Argentina*
[c] *Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo, Almirante Brown 500, Chacras de Coria, CP 5505, Mendoza, Argentina*

ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 26 August 2016
Accepted 3 September 2016
Available online xxxx

Keywords:
Grazing gradient
Livestock corrals
Nutrient balance
Piosphere
Soil resource distribution
Woodland soils

ABSTRACT

Changes in the spatial distribution of resources constitute an indicator of degradation of arid grazing lands. In arid and semi-arid ecosystems, the distribution of soil resources has been commonly associated with the structure and the spatial arrangements of the vegetation. Although the formation of "fertile islands" beneath vegetation patches is well documented, much less is known about the changes induced by grazing systems on the distribution of soil resources. We examine how pastoralist settlements are affecting the spatial distribution of soil resources and the soil nutrient balance in central-western woodlands of Argentina. We analyzed the distribution of soil water, chloride, nitrate, total nitrogen, and organic matter at increasing distances from livestock corrals and in undisturbed woodlands, at different soil depths. We also calculated variation indexes of soil organic matter and total nitrogen produced by livestock settlements, as an indicator of degree of deterioration or improvement of the soils. The transects located in pastoralist settlements demonstrated an increasing centripetal gradient in availability of soil water and nutrients compared to transects outside of these disturbed areas. Livestock corrals create local hotspots of nutrient enrichment, but when we analyzed the effects of livestock settlements at a higher spatial scale, we found net losses of soil organic matter and total nitrogen. We conclude that the coupling between nutrient and patch dynamics is disrupted by the pastoralist settlements, which caused a redistribution of soil resources, controlled by the location from the livestock corrals. The processes that promote nutrient losses, such as ammonium volatilization, denitrification, nitrate leaching, organic matter oxidation, manure exports, and soil erosion, are relatively higher than the extra inputs of dung and urine. Therefore, this study emphasizes the role of grazing systems as modulators of water and nutrient fluxes, and soil nutrient balance.

1. Introduction

Semi-arid woodlands contain rich biodiversity and provide soil-mediated ecosystem services, including carbon storage and nutrient cycling (MEA, 2005). However, as a result of disturbance, woodland structure and composition are changing, affecting ecological and hydrological processes (Wilcox et al., 2003), and consequently some ecosystem services (Foley et al., 2005). Changes in land use and land cover play key roles in hydrological and biogeochemical processes, including water, carbon, and nitrogen cycles (D'Odorico et al., 2010; McLauchlan et al., 2014). Particularly, livestock grazing has been recognized as an important factor affecting ecosystem function, altering the composition and structure of plant communities, modifying accumulation and spatial distribution of soil resources, and changing nutrient balance (Adler et al., 2001; Milchunas and Lauenroth, 1993; Piñeiro et al., 2009).

Spatial heterogeneity of soil resources, at large scales, affects the distribution and productivity of plant communities and, at smaller scales, influences plant establishment, growth and survival (Maestre et al., 2003), and modulates morphological and physiological plant responses (García-Palacios et al., 2012; Meglioli et al., 2016). In semi-arid environments, the distribution and availability of soil water and nutrients are usually associated with the spatial distribution of vegetation patches and rainfall variability (Austin et al., 2004; Breshears et al., 2009; Huxman et al., 2004). Vegetation patches tend to accumulate litter and plant material, and create a particular microenvironment that enhances carbon and nutrient cycling, and soil microbial activity beneath plant canopies (Alvarez et al., 2009; Carrera et al., 2009; Facelli and Brock, 2000; Rossi and Villagra, 2003). Canopy patches lead to higher soil moisture, nitrogen, and organic matter content compared with open intercanopy patches (Schlesinger et al., 1996; Titus et al., 2002). As a consequence, changes in the structure and spatial arrangement of vegetation patches have implications for ecosystem functioning (Aguiar and Sala, 1999).

---

* Corresponding author.
E-mail address: pmeglioli@mendoza-conicet.gob.ar (P.A. Meglioli).

http://dx.doi.org/10.1016/j.catena.2016.09.002
0341-8162/

In arid ecosystems, livestock grazing around pastoralist settlements represents a typical land use that changes vegetation structure (Bertiller et al., 2002), causing different plant spatial organization and heterogeneity (Bisigato et al., 2009). Vegetation changes modify the depth and distribution of plant roots, influencing the distribution of soil resources (Jackson et al., 2000; Jobbágy and Jackson, 2000). Understanding the effects of disturbance like grazing on vegetation patterns and soil water and nutrient dynamics is useful to understand ecosystem functioning, soil erosion processes, runoff and sediment fluxes in these landscapes (Bisigato et al., 2008; Ravi et al., 2010), and has implications on management programs of semi-arid zones, where extensive grazing is the main activity developed by human populations.

In water-limited ecosystems, the spatial distribution of livestock is restricted by water availability. Livestock frequently congregate around permanent watering points, generating areas of higher animal impact called 'Piospheres' (Lange, 1969). Multiple researchers have found grazing gradients, expressed as changes in vegetation cover (Brooks et al., 2006; Landsberg et al., 2003; Todd, 2006) and in the physical and chemical properties of soil (Shahriary et al., 2012; Smet and Ward, 2006) as a function of the distance from livestock watering points. These landscape focal points can concentrate soil resources from large foraging areas, which are carried and deposited by domestic animals. Goats and cattle consume plant and litter, reducing the local input of soil organic matter in grazing sites. However, livestock can transport and return the nutrients to the soil through urine and dung depositions, modifying carbon and nitrogen cycles, and soil nutrient balances (Adler et al., 2001; Mohamed Saleem, 1998). Urine and dung lead to increase in soil nitrate and ammonium, which are soluble and volatile forms of nitrogen that can produce high nitrogen losses via leaching and volatilization (Augustine, 2003; Wachendorf et al., 2005). Grazing by domestic livestock may also exert strong influences on microbial functional communities involved in soil nutrient cycling (Patra et al., 2005).

In central-western Argentina, open woodlands support the development of local communities and their traditional production systems (Jobbágy et al., 2011; Villagra et al., 2009). The low mean annual precipitation of <200 mm in this environment is a limiting factor for agriculture, but groundwater accessibility allows extensive livestock grazing. Recent studies of the Central Monte desert (NE, Mendoza) indicated that interdune valleys, characterized by woody legumes coupled to groundwater, have higher productivity and availability of soil resources than dune crests and flanks (Aranibar et al., 2011; Guevara et al., 2010; Jobbágy et al., 2011; Villagra et al., 2011). Groundwater provision for human and domestic animal consumption influences the spatial distribution of livestock, generating disturbance gradients.

The establishment of a new settlement involves the partial removal of the vegetation in 'sacrifice areas', including shrubs and trees, which are used for the construction of corrals, wells, and households, and to decrease the abundance of poisonous animals. Although these changes have direct effects aboveground, decreasing cover of shrubs, grasses and forbs (Goirán et al., 2012; Meglioli et al., 2014), they also cause other less obvious changes belowground, which can potentially affect hydrological and biogeochemical cycling. The reduced vegetation cover in livestock stations causes greater soil water content in surface and subsurface soils compared to undisturbed woodlands. Additionally, nutrient input from livestock dung and urine may increase nutrient leaching in the sacrifice zone (Meglioli et al., 2014). Livestock grazing alters spatial heterogeneity of vegetation and, consequently, disrupts mechanisms of resource concentration in vegetation patches (Bisigato et al., 2009). Therefore, woodlands with traditional livestock systems in these ecosystems offer an opportunity to study changes in the spatial distribution and availability of soil water and nutrients as a function of the position from corrals, where manure deposition is higher.

This study examines how pastoralist settlements are affecting the spatial distribution of soil resources in the horizontal and vertical planes, and the soil nutrient balance in the Monte desert. Most studies on nutrient cycling are on the upper layers of the soil where the greatest biological activity occurs (Jobbágy and Jackson, 2001). However, we know very little about nutrient and carbon cycling from deeper soil layers of desert ecosystems (Jin et al., 2015). Soil analysis from deeper samples (up to 200 cm in depth) can be useful to identify possible rainwater percolation and nitrate leaching through the soil, depletion of soil nutrients, and redistribution of solutes.

We hypothesized that spatially heterogeneous distributions of soil resources associated with the structure and spatial arrangements of the vegetation in the central Monte desert are modified by pastoralist settlements, which redistribute soil water, nutrients, and solutes over the landscape due to centripetal transport of nutrients towards the corrals by livestock grazing and to the decreased plant demand given by the partial removal of vegetation. In addition, we proposed that the soils of livestock stations increase net losses of total nitrogen and organic matter due to increases in ammonium volatilization, nitrate leaching, organic matter oxidation, soil erosion, and the export of manure to outside areas, compared to the soil of relatively undisturbed control woodlands (Fig. 1). In order to evaluate these hypotheses, we analyzed the contents of soil water, chloride, nitrate, total nitrogen and organic matter at increasing positions from corrals and in control woodlands, at three soil intervals (shallow, intermediate and deep). Spatial patterns in soil resources were investigated comparing linear mixed models, considering the effect of land use and location of soil profiles along the transects in the interdune valleys. We expected to find edaphic changes related to the proximity to the corrals in the livestock stations (slope of regression line different from zero). However, the slope of regression line along the transects in the control woodlands should not be significantly different from zero due to natural spatial heterogeneity. We then analyzed the relationships between soil characteristics, land use, and vegetation patches, at different soil depth intervals.

2. Material and methods

2.1. Study area

The study area is the Telteca Natural and Cultural Reserve, located in the central plains of northeastern Mendoza River, Argentina (32–33 S; 67–68 W; 500–550 m elevation), on the alluvial plain near the lower Mendoza river. Geomorphologically, this region comprises a system of transverse dunes oriented NNW–SSE separated by discontinuous valleys. The plain is composed of Holocene deposits (Tripaldi and Forman, 2007), including soils with poorly developed horizons of recent origin (Entisols).

The climate is arid with a mean temperature of 18.5 °C and large daily and annual temperature ranges (48 °C absolute maximum and −10 °C absolute minimum). The mean annual precipitation is 156 mm (1972–2014 average), occurring almost exclusively during the spring and summer (from October to March) (Meglioli, 2015). Because rainfall is scarce and permanent rivers are not present in the region, groundwater is the most important source of water in the lowlands. The water table is located 6–15 m below the surface (Gomez et al., 2014). Shallow groundwater is used by phreatophyte vegetation in the interdune valleys, although groundwater is inaccessible to plants in dune crests and flanks (Jobbágy et al., 2011). Stable isotope composition of groundwater indicates that the aquifer is remotely recharged by precipitation in the Andes, >100 km away, with a negligible local recharge by drainage of summer rainfall (Jobbágy et al., 2011).

The vegetation is representative of the central Monte Biogeographic Province, with open woodlands of *Prosopis flexuosa* accompanied by xerophytic shrubs such as *Larrea divaricata*, *Capparis atamisquea*, *Trichomaria usillo*, *Lycium tenuispinosum*, *Atriplex lampa*, and *Suaeda divaricata* (Villagra et al., 2004). Dunes have a lower vegetation cover and are dominated by shrub species such as *T. usillo* and *L. divaricata* coexisting with small trees of *P. flexuosa*, and the grass *Panicum urvilleanum* (Villagra et al., 2004).

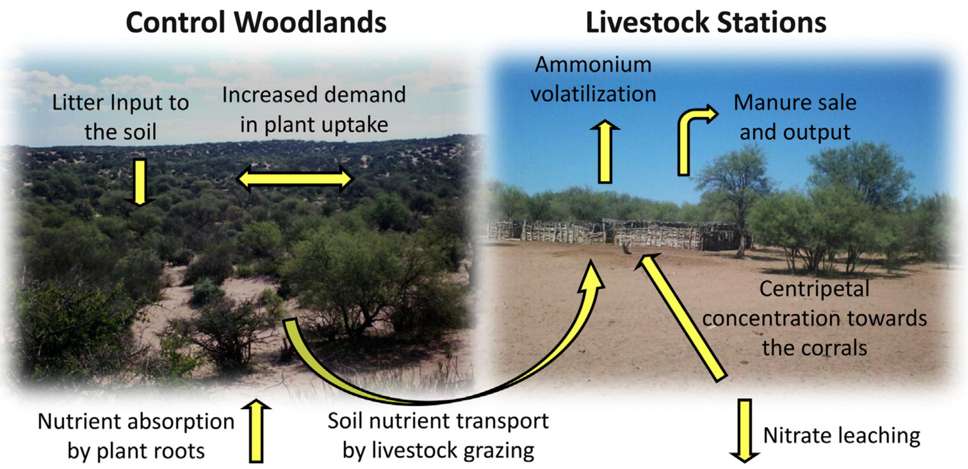

Fig. 1. Conceptual scheme of the effects of livestock stations on nutrient dynamics in the Central Monte desert. The main nutrient fluxes for both land uses are indicated with the arrows. In livestock stations, nutrients are transferred towards corrals through urine and dung depositions by animals; however, rates of processes that cause nutrient losses, such as ammonium volatilization, nitrate leaching, and manure exports, increase in disturbed sites. In control woodlands, vegetation patches contribute to the accumulation of leaf litter, enhancing nutrient cycling, and lead to soil nutrient retention despite their removal via plant uptake.

Prosopis woodlands in the central Monte have a relatively high productivity and provide valuable resources (i.e. wood, forage, fruits) to pastoralist communities (Inojosa et al., 2010). During the 19th century, trees were cut down for building railroads and vineyards in irrigated oases, causing the loss of woodlands (Rojas et al., 2009; Villagra et al., 2009). Currently, a proportion of the remaining woodlands conform a protected area of around 20.000 ha (Villagra et al., 2010) and, as permitted by law, wood can only be extracted by the local inhabitants to meet domestic fuel and construction needs (e.g. houses, wells and corrals).

Local people living in these woodlands have subsistence livestock production (predominantly goats and cattle) in permanent livestock stations (Torres, 2008). Areas with reduced plant cover associated with livestock grazing are detected up to 2 km away from livestock stations by satellite images (Goirán et al., 2012), but the main effects of vegetation removal are evident approximately 50 m around corrals and water points (Meglioli et al., 2014). In the region, environmental factors, such as the distances to rivers and old river beds, influence livestock settlements spatial distribution (Millán et al., 2015), causing a pattern of settlement aggregation around rivers and old river beds, and dispersion in the aeolian plain (densities around 0.08 settlements/km^2), far from surface water features (Goirán et al., 2013). In the aeolian plain, access to public services such as drinking water, electricity and transport to nearby cities is scarce and settlements are dispersed, in a matrix of relatively undisturbed woodlands. For this study, we selected livestock stations located in interdune valleys of the aeolian plain.

2.2. Experimental design

Soil samples were collected in February 2011, from soil profiles situated at six experimental units, including three livestock stations and their paired relatively undisturbed 'control' woodlands. The analyzed livestock stations were established >80 years ago; and vegetation structure and surface soil characterization of these paired sites (site 1: 'La Primavera'; site 2: 'Las Delicias' and site 3: 'Las Hormigas') were performed in previous studies by Meglioli et al. (2014, 2016). Although our study area includes landscapes with multiple topographic positions (dune crests, midslopes, footslopes, and interdune valleys), we only located sampling points in the interdune valleys, ensuring the same topographic relief (lowland areas), which have slopes <3% (Vega Riveros et al., *unpublished data*). At each site, we conducted one 70-m linear transect in the valley lowland, where we sampled 13 to 15 soil cores (up to 200 cm depth), every 5 m. In livestock stations, the transect was laid from a corral, running towards the woodland boundary. In control woodlands, the transect started at the bottom of the valley lowland, and was representative of natural spatial heterogeneity, including different vegetation patches (Fig. 2). We also registered the presence of trees, shrubs, forbs, grasses, bare soil, and litter in one quadrat of 1 m^2 at each sampling point.

2.3. Soil sampling and chemical analyses

Although most piosphere studies have focused on the upper layers of the soil where the greatest biological activity occurs (Shahriary et al., 2012; Smet and Ward, 2006), we decided to consider a coarser stratification because ecohydrological processes, such as water drainage and nutrient leaching, are reflected at deeper soil layers in our region of study (Aranibar et al., 2011; Jobbágy et al., 2011). The vertical distribution of the sediments is somehow homogeneous in texture, being composed of fine sands, without marked horizon changes (Gomez et al., 2014). Fine roots are better developed from surface to 50 cm depth (Aranibar et al., 2011), where plants interact with soil solutes and contribute to soil organic matter. Changes in ecohydrological indicators (soil moisture, nitrate, and chlorides) were observed at 50 cm intervals, providing a useful approach to assess vegetation activity on deep water drainage, nitrogen absorption and retention (Meglioli et al., 2014). In this sense, chloride distribution in the soil is often used as a tracer of water transport, particularly in arid and semi-arid systems (Herczeg and Leaney, 2011). Leaching of large soil chloride stocks in desert systems indicates low water uptake rates and the occurrence of deep drainage (Scanlon et al., 2006). Therefore, representative soil samples were taken at three depths of 0–50 cm (shallow), 50–100 cm (intermediate) and 150–200 cm (deep) at each sampling point, using hand soil augers. The soil intervals included several subsamples, at different depths within the interval, which were thoroughly mixed to constitute a composite soil sample. Soils were collected to determine moisture, chloride, nitrate, organic matter (SOM) and total nitrogen (TN) contents, electric conductivity (EC) and pH. A subset of samples was stored in closed plastic bags for gravimetric soil moisture determination. The rest of the samples were air dried in the field.

In the laboratory, gravimetric moisture content was determined for soil subsamples by weighing moist field samples before and after drying at 105 °C for 48 h. Chloride concentration, EC and pH were determined

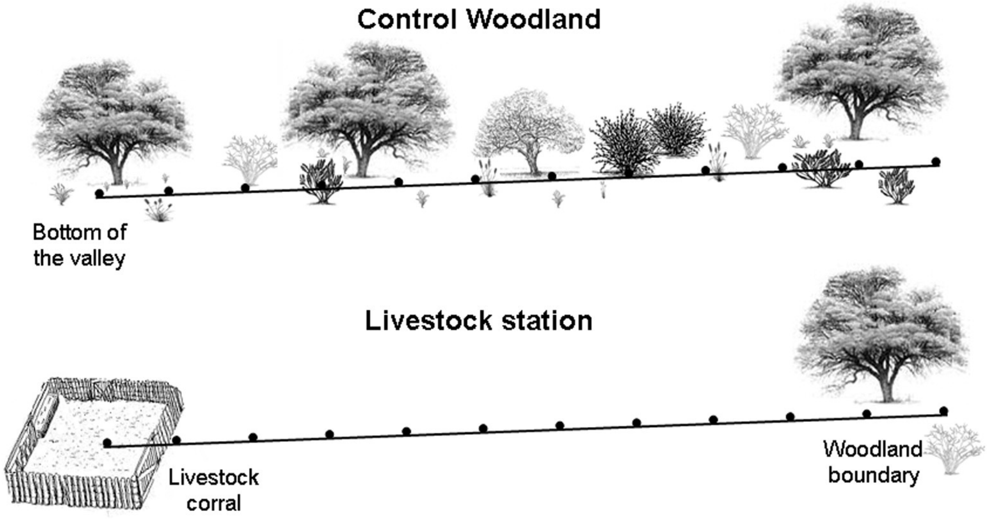

Fig. 2. Schematic representation of the sampling design. A linear transect was laid across three paired stands in relatively undisturbed (control woodland) and disturbed (livestock station) interdune valleys in the Central Monte desert. In livestock stations, the transect was laid from a corral, running towards the woodland boundary, while in control woodlands the transect started at the bottom of the valley. On each transect, we indicate the sampling points (*filled circles*), where soil cores were extracted (up to 200 cm depth), every 5 m.

in soil extracts of 25 g of soil and 50 ml of deionized water, using a portable multi-parameter meter with a chloride ion-selective electrode (Thermo Scientific Orion Star A329), a conductivity meter (WTW LF 91) and a pH meter (Denver Instrument UP-25), respectively. Nitrate was extracted by shaking 5 g of air dried soil in 25 ml of extracting solution, composed of 2.5 g of $CuSO_45\ H_2O$, 0.15 g of Ag_2SO_4, 0.62 g of BO_3H_3 in 1000 ml of deionized water. Nitrate concentrations were determined by spectrophotometry (HACH DR 2800 spectrophotometer) with the cadmium reduction method, after adjusting the soil extracts to pH 7 with sodium hydroxide (1%) and filtering. The SOM contents were determined by dry combustion (Davies, 1974), while TN contents were determined according to the Kjeldahl method (Pearcy et al., 1989). Although the method of loss on ignition (Davies, 1974) could overestimate the SOM values in comparison to other methods, we considered it suitable to process large numbers of soil samples at one time, and compare sites with different treatments. In addition, dry combustion method does not produce toxic wastes and correlates well with wet oxidation methods (Wang et al., 2012).

2.4. Data analyses

2.4.1. Soil water, solutes, organic matter, nutrients and pH distribution

We used linear mixed models (LMM) to evaluate whether the estimated edaphic variables differed with land use (control woodlands and livestock stations) and position along the transect for three soil depth intervals (shallow, intermediate and deep). For this purpose, we analyzed separate models, at each soil interval, using *land use* (U), *position along the transect* (P) (location of the soil profiles within the transect, in meters), and their *interaction* (U × P) as fixed factors. The LMM structures considered the sites (1, 2, 3), with soil profiles nested within each site as random factors. For each edaphic variable, we ranked models and selected the best model using Akaike information criterion (*AICc*) (Burnham and Anderson, 2002). The relative importance of each model was scored according to Akaike weights (*w*), which indicate the probability that the model is the best among the whole set of candidate models. The top ranked models that differed from the *AIC* of the best-fitting model by <4 (*dAIC* < 4) were retained for mean parameter estimation. Parameters were estimated by restricted maximum likelihood (REML) using the 'model.avg' function of the MuMIn package (Barton, 2014). The z-values were computed as the test statistic for the average parameters (intercepts and slopes). When absolute value of the z-statistic was higher that 2.0 (corresponding to a test with a significance level of $\alpha = 0.05$) the variable was significant to explain the data. All the statistical analyses were carried out by using the R program (R Development Core Team, 2013).

2.4.2. Influence of vegetation patches on soil chemical parameters

We evaluated the effects of different vegetation patches and litter found in the quadrats of each sampling point on chemical variables for each soil depth interval, using stepwise backward variable selection of the respective regression models. Regression analyses were only performed at the three control woodlands, where vegetation was formed by heterogeneous patches. This analysis could not be performed in livestock stations, where vegetation and litter were absent, and the sampling points had bare soil surface and dung depositions. We grouped the control woodland quadrats ($n = 40$) within three plant functional compositions, as follows: *Legume* (only *Prosopis*), *Mixed* (*Prosopis* with shrubs - grasses), *Non-legume* (shrubs, grasses and forbs separated or combined). Therefore, for each response variable (log-transformation of moisture, chloride, electric conductivity, nitrate, organic matter and total nitrogen) we selected the significant descriptor variables (*Legume*, *Mixed*, *Non-legume* and *Litter*) of the final model (minimum *AIC*) by stepwise regression analysis. The criterion for inclusion of a descriptor variable in the final model was $P < 0.05$.

2.4.3. Index of variation in soil nutrients produced by livestock stations

Variation indexes reflect the changes in soil nutrients as a percentage, and can indicate the degree of deterioration or improvement of soils (Wang et al., 2001). We calculated variation indexes of SOM and TN produced by livestock stations for the three soil depth intervals (shallow, intermediate, and deep), considering all sampling points along the transects. The indexes were calculated assuming that soil nutrient concentrations were similar for both land uses (livestock stations and control woodlands) before pastoralist establishments. The indexes (I) were separately calculated for TN and SOM, and expressed as percentages, as follows:

$$TNI = TNL - TN\ base.$$

$$SOMI = SOML - SOM\ base.$$

where *TNI* and *SOMI* are the indexes of variation of total nitrogen and soil organic matter, respectively, at each soil interval; *TNL* and *SOML* are the values of nitrogen total and soil organic matter, respectively, from soils of the livestock stations; and *TN base* and *SOM base* are the reference values of TN and SOM, respectively, for soils from woodlands, obtained by averaging all soil values, at each soil interval, within woodlands ($n = 40$ samples at each depth). Positive and negative values indicate enrichment and loss, respectively, of TN and SOM in the ecosystem produced by livestock stations.

2.4.4. Relationships among soil chemical parameters with land use

We performed a principal component analysis (PCA) to determine first relationships among soil chemical variables, and to establish association of soil samples grouped by soil properties variation ($n = 7$). The PCA is multivariate method for integrated assessment of collinearity of multiple parameters that can be useful to separate forest areas as a function of soil management (Sena et al., 2002). For this analysis, edaphic data were included into the PCA and log transformed, except for pH. Correlation analysis was performed with Pearson's test for linear relationships between edaphic variables. The PCA used chemical data of all soil samples collected at the three sites. Biplot with the two significant principal components was used to better interpret the relationships between the soil samples ($n = 246$) and variable spaces plotted simultaneously. In this case, we separated the soil samples considering three levels of land use intensity (control woodlands, livestock stations, and corrals) for each soil depth interval (shallow, intermediate, and deep). In livestock stations, we considered sampling points located inside the corrals or in their immediate vicinity (<10 m away), as belonging to the "corral" category, because of strong effects of dung and urine on edaphic variables.

3. Results

3.1. Soil moisture, solutes, organic matter, and nutrient distributions

Content and spatial distribution of soil water, solutes, and nutrients were affected by land use and position along the transect, showing changes in their relative importance for the different soil depths (Table 1). In general, the effects of land use and position along the transect on each edaphic variable were decreased at the intermediate and deep soil intervals (Figs. 3 and 4). Compared with control woodlands, livestock stations modified the contents of soil moisture, chloride, nitrate, and salinity (i.e., electric conductivity), generating a centripetal concentration influenced by the proximity to the corrals (first sampling points). For these edaphic variables, the linear models with interaction between main effects were significant at the shallow and intermediate intervals. For SOM, TN and pH, the models without interaction between land use and position along the transect had lower *AIC* values and were the best among the whole set of candidate models (Table 1).

In Table 2, we provide the parameters estimated from LMM for each soil depth interval, including the differences in intercepts and slopes found between both land uses; and we explain these results of LMM for each edaphic variable, highlighting their ecological significance.

Table 1
Model selection statistics of three soil depth intervals to evaluate the effect of land use (U), position along the transect (P) and their interaction (U × P) on edaphic variables, using multimodel inference. Models were ranked using Akaike information criterion (*AICc*). Plus signs indicate the fixed effects included in each model. Akaike weights (*w*) indicate the relative importance of each model. Candidate models (*dAIC* < 4) are highlighted in bold.

Edaphic variable	Rank	Shallow					Intermediate					Deep				
		AICc	*w*	U	P	U × P	*AICc*	*w*	U	P	U × P	*AICc*	*w*	U	P	U × P
Moisture	1	**234.1**	**0.99**	+	+	+	**208.2**	**0.53**	+	+	+	**208.9**	**0.56**	+	+	
	2	249.7	0.00	+			**208.7**	**0.41**	+			**210.4**	**0.26**		+	
	3	250.2	0.00	+	+		213.8	0.03				**212.4**	**0.10**	+		
	4	255.2	0.00				214.7	0.02	+	+		213.6	0.05			
	5	255.9	0.00		+		220.1	0.00		+		215.1	0.02	+	+	+
Chloride	1	**970.3**	**0.97**	+	+	+	**954.4**	**0.90**	+	+	+	**918.4**	**0.44**	+	+	+
	2	978.2	0.02	+			959.7	0.06	+	+		**918.6**	**0.40**	+	+	
	3	980.3	0.00	+	+		960.8	0.03	+			**920.5**	**0.16**	+		
	4	984.9	0.00				971.2	0.00		+		942.4	0.00		+	
	5	987.0	0.00		+		972.2	0.00				944.4	0.00			
EC	1	**1166.0**	**0.99**	+	+	+	**1176.1**	**0.78**	+	+	+	**1173.1**	**0.64**	+	+	+
	2	1186.1	0.00	+	+		**1180.0**	**0.11**	+	+		**1175.5**	**0.19**	+		
	3	1187.9	0.00	+			**1180.1**	**0.10**	+			**1175.7**	**0.17**	+	+	
	4	1195.6	0.00		+		1193.5	0.00		+		1192.8	0.00			
	5	1197.3	0.00				1193.6	0.00				1192.8	0.00		+	
Nitrate	1	**582.2**	**0.80**	+	+	+	**532.9**	**0.78**	+	+		**490.1**	**0.97**	+		
	2	**586.0**	**0.12**	+			**536.3**	**0.14**	+			498.6	0.01	+	+	
	3	586.9	0.08	+	+		538.9	0.04	+	+	+	499.1	0.01			
	4	595.4	0.00				539.7	0.03		+		505.1	0.00	+	+	+
	5	596.5	0.00		+		543.1	0.00				507.4	0.00		+	
SOM	1	**56.7**	**0.86**				**−71.9**	**0.86**				**−81.6**	**0.76**			
	2	**60.4**	**0.13**	+			**−68.2**	**0.14**	+			**−79.2**	**0.24**	+		
	3	65.0	0.01		+		−57.5	0.00		+		−68.2	0.00		+	
	4	68.9	0.00	+	+		−53.8	0.00	+	+		−65.8	0.00	+	+	
	5	80.1	0.00	+	+	+	−40.3	0.00	+	+	+	−52.3	0.00	+	+	+
TN	1	**−496.1**	**0.89**				**−661.9**	**0.89**				**−692.7**	**0.99**			
	2	**−491.9**	**0.11**	+			**−657.9**	**0.11**	+			−680.8	0.01	+		
	3	−478.1	0.00		+		−640.1	0.00		+		−671.1	0.00		+	
	4	−473.5	0.00	+	+		−635.8	0.00	+	+		−659.1	0.00	+	+	
	5	−456.2	0.00	+	+	+	−619.1	0.00	+	+	+	−642.5	0.00	+	+	+
pH	1	**132.3**	**0.68**		+		**184.7**	**0.45**				**197.2**	**0.71**			
	2	**135.1**	**0.17**				**185.4**	**0.31**	+			**199.7**	**0.21**	+		
	3	**135.7**	**0.12**	+	+		**187.0**	**0.14**		+		202.2	0.06		+	
	4	138.4	0.03	+			**187.7**	**0.10**	+	+		204.6	0.02	+	+	
	5	146.8	0.00	+	+	+	198.1	0.00	+	+	+	214.8	0.00	+	+	+

Livestock stations had greater soil moisture than undisturbed woodlands, and also exhibited decreasing moisture contents with increasing soil depth and position to corrals (Fig. 3a). Soil moisture, at the shallow and intermediate intervals, showed a negative linear response to increasing the position along the transect in livestock stations, which was insignificant in control woodlands. These differences between land uses decline towards deeper soil layers (Table 2).

Chloride concentrations in livestock stations were lower than in control woodlands, and showed changes in the regression lines at different soil depth for both land use (Fig. 3b). As a consequence, the best models (lower *AICc* values) indicated that spatial distributions were determined by the integration of main effects. Compared to control woodlands, chloride contents in livestock stations declined with increasing the position along the transect at the shallow interval, but did not show changes in the slope of regression lines at the deeper soils (Table 2).

Salinity, indicated by electric conductivity, in livestock stations showed a significant decrease at the deeper soil layers (Fig. 3c). The best-fitting model for electric conductivity included the interaction of fixed effects (U × P), decreasing their relative importance with soil depth (w) (Table 1). The comparison of the regression lines indicated that electric conductivity had significantly negative responses to increasing position along the transect in livestock stations at the shallow and intermediate intervals (Table 2).

Nitrate contents were higher in livestock stations for all three soil layers, with significantly higher concentrations in the shallow soils of corrals and surroundings than in undisturbed woodlands (Fig. 3d). In livestock stations, soil nitrates significantly decreased along the transect at the shallow intervals, compared with control woodlands. We observed a negative relationship to the position along the transect at the intermediate intervals, which was insignificant at the deep layers, in both land uses (Table 2).

Soil organic matter decreased with increasing soil depth for both land uses, and contents were significantly lower in the deep interval from livestock stations than in that from undisturbed woodlands (Fig. 4a). Although the null models had lower *AIC* values from set of models, the second model, with a *dAIC* < 4, included land use as an explaining variable (Table 1). The slopes of the regression lines for SOM were not significantly different from zero for the three soil layers (Table 2).

Compared with undisturbed woodland soils, livestock stations had lower levels of total nitrogen, except at deep soil interval where contents increased (Fig. 4b). The parameters estimated (coefficients) for both land uses showed significant differences in intercepts, but not in the slopes of regression lines (Table 2). This analysis suggested that variations in TN at the different soil depths were dependent on land use.

Soil pH was alkaline, with lower values in shallow samples than in intermediate and deep samples for both land uses (Fig. 4c). Several candidate models had similar empirical support to explain the changes in soil pH (Table 1). We found significant positive relationships between pH and the position along the transect, at the shallow and intermediate intervals, for both land uses (Table 2).

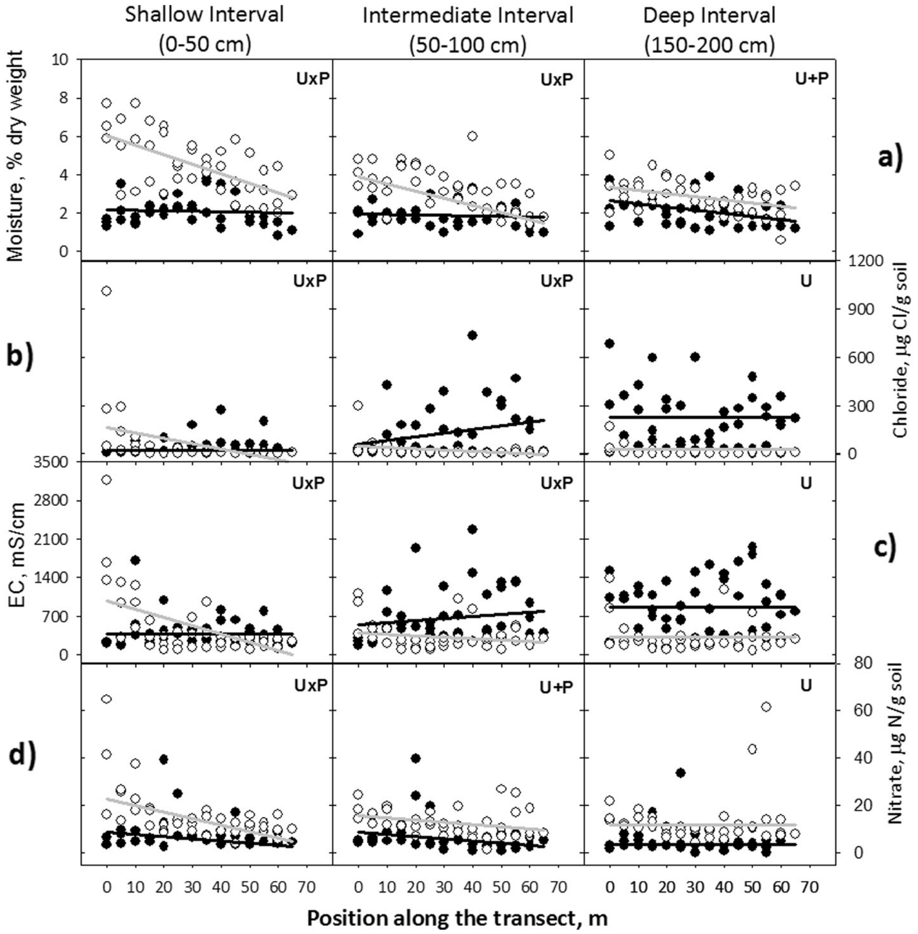

Fig. 3. Distribution of soil moisture (a), chloride (b), electric conductivity (c), and nitrate (d) in control woodlands (*filled circles*) and livestock stations (*open circles*) for the shallow (*first column*), intermediate (*second column*) and deep (*third column*) soil intervals. Each symbol (*circles*) represents a single measurement. Letters inside each plot show the significant fixed effects (U: land use, P: position along the transect, U + P: additive effect, U × P: interactive effect) affecting each edaphic variable. Solid lines correspond to the linear regressions for control woodlands (*black*) and livestock stations (*gray*). Horizontal lines indicate the effect of U, but not P; while dotted lines indicate only influence of P.

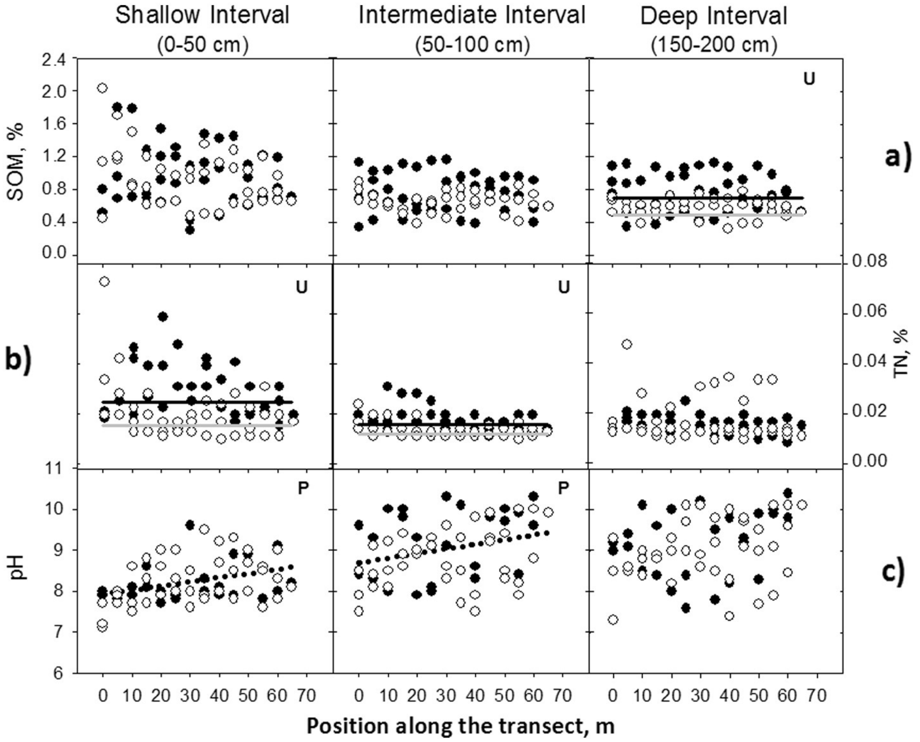

Fig. 4. Distribution of soil organic matter (a), total nitrogen contents (b), and pH (c) in control woodlands (*filled circles*) and livestock stations (*open circles*) for the shallow (*first column*), intermediate (*second column*), and deep (*third column*) soil intervals. Each symbol (*circles*) represents a single measurement. Letters inside each plot show the significant fixed effects (U: land use, P: position along the transect, U + P: additive effect, U × P: interactive effect) affecting each edaphic variable. Solid lines correspond to the linear regressions for control woodlands (*black*) and livestock stations (*gray*). Horizontal lines indicate the effect of U, but not P; while dotted lines indicate only influence of P.

3.2. Influence of vegetation patches and litter on soil chemical parameters

We found that *Litter* presence within the sampling plots was a descriptor variable with significant and positive influences on all chemical variables of shallow soils. Different vegetation patches did not produce significant changes on soil moisture, but significantly affected values of chloride and electric conductivity in the shallow, with lower values than intermediate and deep intervals. The presence of plants from the *Legume* group decreased nitrate concentration in deeper soils. We also found that the presence of *Prosopis* (in the *Legume* and *Mixed group*), in addition to *Litter*, increased organic matter in shallow soils. All plant functional groups were descriptor variables retained in the final model of total nitrogen, positively influencing nitrogen contents in shallow soils, when compared to intermediate and deep soils (Table 3).

3.3. Variation in soil nutrients produced by livestock settlements

Indexes of change in SOM and TN in response to land use were negative, indicating decreasing nitrogen and organic matter caused by livestock activity, except for TN at the deep soil interval. The SOM index indicated increasing deterioration with soil depth, reaching a 25% decrease in the deeper soils. The TN index showed a higher depletion in the shallow and intermediate layers, with up to 30% and 20% decrease, respectively, but an enrichment at the deeper soil interval (Fig. 5).

Table 2

Parameters estimated from linear mixed models for each soil depth interval considering the effect of land use (intercept) and position along the transect (slope) on each edaphic variable. Parameters were obtained averaging top ranked models with $\delta AIC < 4$, using the 'model.avg' function of the MuMIn, the multi-model inference package (Barton, 2014) by using the R program (R Development Core Team, 2013). For each edaphic variable, significant differences ($P > |z|$ value) in intercepts and slopes of regression models are included, considering the control woodland as a reference. Significance codes: $P < 0.01$ '***'; $P < 0.05$ '**'; $P < 0.1$ '*'; n.s. = not significant.

Soil interval	Parameter	Land use	Moisture		Chloride		EC		Nitrate		SOM		TN		pH	
			Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value
Shallow	Intercept	Woodland	2.18	***	20.9	n.s.	378.4	***	8.80	***	0.96	***	0.025	***	7.97	***
		Livestock	3.88	***	144.6	*	602.7	**	14.02	***	−0.05	n.s.	−0.009	***	−0.01	n.s.
	Slope	Woodland	0.00	n.s.	0.6	n.s.	−0.2	n.s.	−0.02	n.s.	0.00	n.s.	0.000	n.s.	0.01	***
		Livestock	−0.05	***	−4.0	***	−15.3	***	−0.27	***	0.00	n.s.	0.000	n.s.	0.00	n.s.
Intermediate	Intercept	Woodland	1.95	***	62.6	n.s.	549.4	***	8.90	***	0.72	***	0.015	***	9.04	***
		Livestock	1.93	**	−14.2	n.s.	−141.3	n.s.	6.71	***	−0.13	n.s.	−0.004	***	−0.48	n.s.
	Slope	Woodland	0.00	n.s.	2.2	*	3.8	n.s.	−0.09	*	0.00	n.s.	0.000	n.s.	0.01	***
		Livestock	−0.03	***	−3.1	**	−6.7	**	0.00	n.s.	0.00	n.s.	0.000	n.s.	0.00	n.s.
Deep	Intercept	Woodland	2.66	***	225.1	***	871.6	***	3.59	***	0.70	***	0.016	***	9.07	***
		Livestock	0.69	*	−198.4	***	−547.4	**	8.41	**	−0.20	*	0.002	n.s.	−0.16	n.s.
	Slope	Woodland	−0.02	***	−0.6	n.s.	3.3	n.s.	−0.01	n.s.	0.00	n.s.	0.000	n.s.	0.01	n.s.
		Livestock	0.00	n.s.	0.3	n.s.	−5.4	n.s.	−0.05	n.s.	0.00	n.s.	0.000	n.s.	0.00	n.s.

Table 3
Dependence of different soil chemical properties on the presence of vegetation with three plant functional compositions and litter. The coefficients of the multiple regressions refer to the final accepted model, using stepwise backward variable selection. We only included the effects of the significant variables ($P < 0.05$). Edaphic variables were log transformed.

Descriptor variable	Soil interval	Moisture		Chloride		EC		Nitrate		SOM		TN	
		Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value
	Intercept	0.25	<0.001	1.71	<2e−16	2.72	<0.001	0.77	<0.001	−0.15	<0.001	2.23	<0.001
Litter	Shallow	0.13	0.002	0.40	0.036			0.23	0.014	0.11	<0.001	0.11	0.012
	Intermediate			0.48	0.012					0.13	0.005		
	Deep					0.17	0.040						
Legume	Shallow			−0.45	0.049	−0.24	0.006			0.09	0.046	0.16	0.002
	Intermediate												
	Deep							−0.20	0.031				
Mixed	Shallow			−0.53	0.047					0.14	0.012	0.18	0.003
	Intermediate												
	Deep												
Non-legume	Shallow			−0.58	0.012	−0.24	0.005					0.15	0.005
	Intermediate												
	Deep												

3.4. Relationships among soil chemical properties and land use

We found multiple linear relationships among edaphic variables, considering their log-transformation. Pearson correlation analysis showed that soil pH was negatively and significantly ($P < 0.0001$) correlated with moisture, nitrate, organic matter, and total nitrogen content ($r = -0.22$; $r = -0.28$; $r = -0.38$; $r = -0.34$, respectively). Electric conductivity and chloride concentrations showed a strong positive correlation ($r = 0.80$; $P < 0.0001$). Chloride and electric conductivity were directly proportional to SOM ($r = 0.35$; $P < 0.0001$) and TN ($r = 0.19$; $P < 0.002$); and inversely proportional to nitrate contents ($r = -0.28$; $r = -0.17$; $P < 0.006$, respectively). Soil moisture had positive correlations with nitrate ($r = 0.32$; $P < 0.0001$) and organic matter contents ($r = 0.22$; $P < 0.006$).

The PCA of the soil chemical properties summarized the variation of the data on the two major independent principal components, which together explained 59% of the total variance in the data. Component 1 was primarily affected by electric conductivity, chloride, and SOM (0.54; 0.53 and 0.48 eigenvectors, respectively), accounting for 33% of the variation in the data. Component 2 was primarily weighed by nitrate, pH and moisture (0.55; −0.50; and 0.41 eigenvectors, respectively), explaining 26% of the variation (Fig. 6a).

Results from the PCA visually separated three groups of soil samples. Group 1 dominated samples taken from distinct soil layers in livestock stations, which had lower values of electric conductivity, chloride and SOM. Group 2 combined samples taken from subsoils (intermediate and deep intervals) in control woodlands, which were characterized by increased pH values and decreased nitrate and moisture contents.

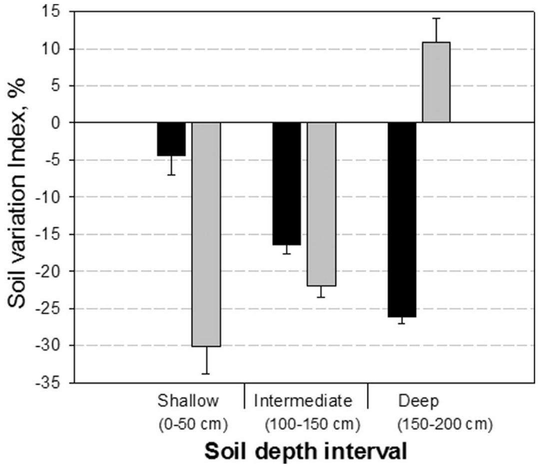

Fig. 5. Variation indexes of soil organic matter (*black bars*) and total nitrogen (*gray bars*) produced by livestock stations. Reference value of control woodlands is indicated by the horizontal line at zero.

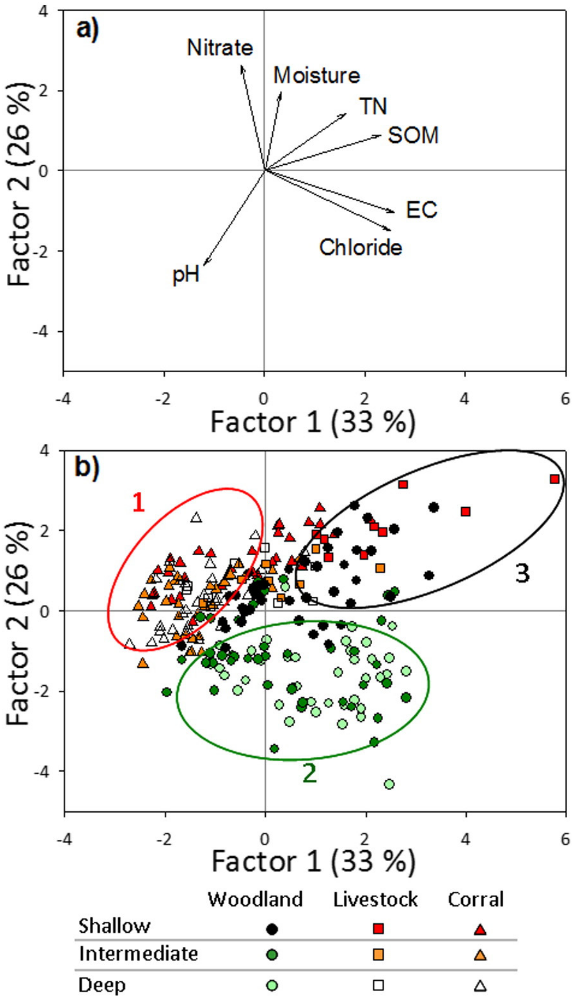

Fig. 6. Principal component analysis (PCA). (a): Visualization of relationships between edaphic variables (arrows) for the first two principal components. Soil chemical parameters are moisture, chloride, nitrate, electric conductivity (EC), organic matter (SOM), total nitrogen (TN), and pH. (b): Representation of relationships between the soil samples ($n = 246$) and variable spaces plotted simultaneously. Each symbol represents a single measurement for sampling soils in control woodlands (*circles*), livestock stations (*triangles*), and corrals (*squares*) at the shallow, intermediate, and deep intervals. *Numbers* inside plots indicate groups of soil samples.

Group 3 included heterogeneous samples taken from the shallow interval of control woodlands and from the corrals, which had higher values of SOM and TN (Fig. 6b).

4. Discussion

4.1. Spatial patterns of soil resources

Land use and land cover change constitute the major factors affecting water and energy fluxes and nutrient cycling within ecosystems (D'Odorico et al., 2010; Ravi et al., 2010). This study shows that spatial patterns of soil water, nutrients, and solutes across woodlands in the central Monte desert are dependent upon a complex group of factors, including land use, soil depth, vegetation, and distance to corrals. Soil water and nutrients were heterogeneous and affected by the presence of litter and multi-species patches in relatively undisturbed woodlands, in agreement with other studies (Abril et al., 2009; Alvarez et al., 2009). Our findings indicate that spatially heterogeneous distributions of soil water and nutrients created by vegetation patches in interdune valleys were modified by land use for pastoralist settlements. High grazing pressure causes losses of the vegetation's spatial arrangement, relocating soil resources as a function of distance from the corrals. We found that local sinks, as SOM and nutrients, were located in corrals. However, when the effects of livestock settlements on soil nutrient status were viewed in the context of all the ‘sacrifice area’, including soils collected inside and outside corrals, we observed net nutrient losses at a landscape level. This was indicated by greater SOM and TN losses relative to inputs at different soil depth intervals. A trend to increasing total nitrogen in deeper soils of livestock stations is likely due to more mobile forms of nitrogen leaching (e.g. nitrates) from shallow soils. Soil organic matter and nutrient losses are ecological indicators of change in soil nutrient status that may increase soil erosion and degradation processes (Carter, 2002; Lal, 1997).

Our results are consistent with the proposed hypothesis that pastoralist settlements affect the spatial distribution of soil resources in the central Monte desert. Vegetation removal in disturbed sites generated different plant spatial organization, which favors increases in deep water drainage and solute leaching through the soil layer, as described in previous studies (Jobbágy et al., 2011; Meglioli et al., 2014). In addition, the location of corrals within livestock stations leads to the creation of centripetal gradients of soil nutrients towards the corrals (Fig. 1). Compared to undisturbed woodlands, the spatial patterns of soil resources were notorious in livestock stations, where the slopes of the regression line along the transects were negative for soil water, chloride, salinity, and nitrate at the shallow and intermediate intervals (Fig. 3; Table 2). Such spatial distribution was controlled by the distance from corrals where accumulation of dung and urine are considerably higher. Other studies report nonlinear relationships in the spatial patterns, indicating that reciprocal distance may better represent grazing intensity along grazing gradients (Manthey and Peper, 2010). Therefore, our linear regressions, using the distance as explaining variable in livestock stations, might underestimate strong changes in the vicinity of the grazing hotspots.

Grazing animals redistribute most of consumed nutrients into the soil through their defecation and urination, altering the proportion of nutrients returned via excreta and leaf litter in the woodland. Deposition patterns by livestock could be randomly distributed within a landscape; however, domestic animals congregate around corrals during the entire year, generating the difference in nutrient deposition seen in these specific areas. Corrals of our studied area create hotspots of nutrient enrichment within arid woodlands, as proposed by Augustine (2003) for African rangelands. In other arid lands, several authors also found changes in plant species composition and cover, and in the spatial distribution of solutes, nutrients, and water in the soils along grazing gradients from watering points (Brooks et al., 2006; Fernandez-Gimenez and Allen-Diaz, 2001; Shahriary et al., 2012; Todd, 2006; Tongway et al., 2003).

On the other hand, the distributions of soil resources were not related to position along the transect in control woodlands (Table 2). The results for undisturbed woodlands are not surprising given that transects within interdune valleys are representative of natural heterogeneity, including canopy spaces and bare inter-canopy spaces (Bisigato et al., 2009; Rossi and Villagra, 2003). Vegetation patch types determine the amount and composition of leaf litter produced, which exerts an important control on decomposition processes and nutrient availability in soils (Abril et al., 2009; Carrera et al., 2009). However, contrary to our expectation, some response variables, such as pH (at the shallow and intermediate intervals) and chloride (at the intermediate interval), had a linear positive response along the transect laid out in control woodlands (Fig. 4). This edaphic gradient for control sites might be caused by our sampling design that included linear transects starting from the bottom of the valley lowlands, with topographical slopes close to 3% (Vega Riveros et al., *unpublished data*). Subtle vegetation changes are observed in vegetation along interdune valleys, given by differential access to groundwater and subsurface water, which in turn affect shading, evaporation, and organic matter contributions to the soil. Lower reliefs, where transects started, generally have taller trees and more dense vegetation, where shading may prevent surface soil evaporation and chloride accumulation, and dense root systems may lower soil pH through organic matter decay and root respiration.

4.2. Influence of vegetation patches and litter on soil resources

Subsequent stepwise analyses in control woodlands suggested that leaf litter was a significant predictor of all soil chemical parameters, producing an increase in nutrient content in shallow soils compared to deeper soils (Table 3). Spatial distributions of soil nutrients in woodlands are influenced by the presence of leaf litter on above ground and vegetation patches, suggesting processes such as water uptake, litter fall, and litter decomposition, which maintain a heterogeneous environment (Abril et al., 2009; Alvarez et al., 2009; Rossi and Villagra, 2003), which is probably useful for invertebrates and other animals. A recent study in the same area indicates that vascular plants offer microsites within the aeolian plain, favoring biological soil crust development (Garcia et al., 2015), which may determine important nitrogen inputs in arid lands (Belnap, 2002). Desert plants have different soil exploration strategies through extensive superficial and depth root systems, which modify soil nutrient availability (Villagra et al., 2011) and efficiency of resource use (Aranibar et al., 2014). On the other hand, stepwise analysis for soil chlorides demonstrates that concentrations were also influenced by three plant functional compositions, which determined lower chloride accumulation in shallow zones than in deeper layers. Because roots tend to exclude chloride during water uptake by plants, high chloride concentrations in the soil profile might be related to the activity of fine roots. The zone of maximum root distributions, which occurs near the surface (Guevara et al., 2010; Villagra et al., 2011), exerts a greater influence on water uptake, possibly increasing chloride concentrations below the fine rooting zone (Moore et al., 2010).

4.3. Variation in soil nutrients produced by livestock settlements

Soils under woodland vegetation represent the largest pools for organic matter and nutrients (Bonino, 2006; Jackson et al., 2000; Jobbágy and Jackson, 2000); thus, our data indicates net losses of SOM and TN by livestock settlements. Even though domestic animals consume biomass in woodlands and transport it to corrals, the nutrient balance was negative in livestock settlements at different soil depth intervals, indicating depletion of soil nutrient stocks (Fig. 5). Based on these results, we suggested that the processes that cause losses, such as ammonium volatilization, denitrification, nitrate leaching, organic matter oxidation, meat and manure exports, and soil erosion, are relatively higher than the extra inputs of dung and urine (Fig. 1). In addition, local inputs by litter fall and root decay are reduced because of the sparse vegetation of disturbed sites. The negative variation indexes of SOM and TN in soils mostly devoid of vegetation for livestock settlements highlights how maintaining heterogeneous vegetation mosaics in undisturbed woodlands leads to soil nutrient retention, despite their removal via plant uptake. Higher reference values of TN in control woodlands might also reflect a greater biological activity and litter decomposition under vegetated patches (Carrera et al., 2009).

Analyzing soil nitrates (Fig. 3), we found high accumulation of nitrates in intermediate and deep soils of livestock stations compared to control woodlands. Such results may lead us to opposite conclusions about the nutrient balance. However, soil nitrate enrichment in disturbed sites demonstrates that not all nitrates in the soil profile are taken up by the roots of remaining plants, determining a potential source of nitrogen available for leaching losses from the vadose zone to groundwater (Meglioli et al., 2014). Nitrates are highly mobile in sandy soils (Brady and Weil, 1999). In other deserts a large reservoir of soil nitrate is attributed to leaching into the deeper soil layer (Jin et al., 2015), although low precipitation and high temperature of semiarid ecosystems tend to prevent nutrient leaching. Greater leaching of solutes under livestock stations and dune crests were found in previous studies by interpretation of soil water and chloride profiles (Jobbágy et al., 2011; Meglioli et al., 2014). The lower chloride and higher moisture content in soils from livestock stations (Fig. 3) reinforce the idea that inputs of chloride into the soil, by atmospheric deposition, may have leached downward under livestock stations due to water not used by plants and the low water holding capacity of sandy soils.

4.4. Relationships among soil chemical properties and land use

The characterization of degraded soils using chemical parameters is useful for planning suitable soil management practices (Sena et al., 2002; Wang et al., 2001). Thus, through the multivariate techniques we revealed relationships among chemical properties, land use, and soil depth (Fig. 6). The PCA axis 1 described a gradient of salinity from soils with low electric conductivity and chloride concentrations (group 1: samples collected in livestock stations) to soils with high salt contents (samples extracted in corrals and undisturbed soils). Therefore, axis 1 was useful to visually discriminate in the complete dataset the disturbed condition (livestock station) from control woodland stands, separating samples that differ in soil salt pools. Soil nitrate and pH were the most important parameters to characterize the PCA axis 2. The soils of the intermediate and deep layers in control woodlands (group 2) were distinguished by their lower nitrate and higher pH levels compared to other soil samples. The higher availability of nutrients in the shallow soils could be due to the increased microbial and root activity, which have a strong influence on soil properties (Brady and Weil, 1999). Curiously, there were no clear differences in some soil chemical variables between corral soils and the shallow soils of control woodlands, which were included within group 3 (Fig. 6). High soil salinity levels and nutrient status of corrals, similar to undisturbed soils, may be a result of livestock depositions, slow decomposition of SOM, and waterlogging in such sites. The integrated evaluation of other chemical, physical and biological soil properties may be relevant to discriminate sources of soil degradation (Sena et al., 2002).

5. Conclusions

This research highlights that livestock settlements redistribute water, nutrients, and solutes in the soil across sandy landscapes in the Monte desert. Spatial heterogeneity of soil resources, generally associated with 'fertility islands' under vegetation canopies in arid woodlands (Bisigato et al., 2009; Rossi and Villagra, 2003), was disrupted in the livestock stations by modifying the structure and spatial arrangement of the vegetation pattern, and by the creation of a resource gradient towards livestock corrals. Changes in the spatial distribution of resources constitute an indicator of degradation of arid grazing lands, which also occurs in Patagonian Monte shrublands (Bisigato et al., 2008).

We have shown that soils extracted from the corrals were local hotspots of nutrient accumulation compared to their surroundings. However, analyzing the effects of livestock settlement at a higher spatial scale, we found net losses of SOM and TN. This suggests that nutrient transfer towards corrals and manure depositions by domestic animals (nitrogen inputs) were not enough to compensate nitrogen losses over time since the settlements establishment. Therefore, soil organic matter and nitrogen inputs and outputs were not balanced, and nutrient losses increased in livestock stations. Nitrate leaching, ammonium volatilization, organic matter oxidation, meat and manure exports, and soil erosion are probably major causes of the decline in soil nutrients in disturbed interdune valleys. However, there are few studies about the effect of pastoralist settlements on nutrient balance in the Monte desert in Argentina. Future research must focus on the relative importance of various nutrient depleting processes to achieve a nutrient balance in this arid ecosystem.

Role of the funding source

Field work and laboratory analyses of this research were funded by the Agencia Nacional de Promoción Científica y Tecnológica of Argentina (PICT-01222-2007, Villagra), by the Banco Interamericano de Desarrollo (PICT-2703, Aranibar PBID), and by the Universidad Nacional de Cuyo (SECTyP, PID 2013-2015 given to Aranibar and Villagra).

Acknowledgements

We are most grateful to the local people for their warm hospitality during the field work. To the Telteca Park rangers and authorities of the Dirección de Recursos Naturales Renovables of Mendoza Province for giving us permission to sample. We thank Florencia Spirito, Aranzazú Guevara, Bruno Del Olmo and Alisa Alvarez for their help in the field, Victoria Garcia, Enrique Mas and Mario Medero for their laboratory assistance, Anabela Bonada and Hayes Fountain for their assistance with English version of this manuscript, Silvana Goirán, Juan Alvarez, Carlos Passera and Erica Cesca for their constructive comments. We are grateful to Markus Egli (editor) and two anonymous reviewers for their valuable and helpful suggestions.

References

Abril, A., Villagra, P., Noe, L., 2009. Spatiotemporal heterogeneity of soil fertility in the Central Monte desert (Argentina). J. Arid Environ. 73, 901–906.

Adler, P.B., Raff, D.A., Lauenroth, W.K., 2001. The effect of grazing on the spatial heterogeneity of vegetation. Oecologia 128, 465–479.

Aguiar, M.R., Sala, O.E., 1999. Patch structure, dynamics and implications for the functioning of arid ecosystems. Trends Ecol. Evol. 14, 273–277.

Alvarez, J.A., Villagra, P.E., Rossi, B.E., Cesca, E., 2009. Spatial and temporal litterfall heterogeneity generated by woody species in the Central Monte desert. Plant Ecol. 205, 295–303.

Aranibar, J.N., Villagra, P.E., Gomez, M.L., Jobbágy, E.G., Quiroga, M., Wuilloud, R.G., Monasterio, R.P., Guevara, A., 2011. Nitrate dynamics in the soil and unconfined aquifer in arid groundwater coupled ecosystems of the Monte desert, Argentina. J. Geophys. Res. 116, G04015.

Aranibar, J.N., Goirán, S.B., Guevara, A., Villagra, P.E., 2014. Carbon and nitrogen dynamics in a sandy groundwater-coupled ecosystem in the Monte desert, indicated by plant stable isotopes. J. Arid Environ. 102, 58–67.

Augustine, D.J., 2003. Long-term, livestock-mediated redistribution of nitrogen and phosphorus in an east African savanna. J. Appl. Ecol. 40, 137–149.

Austin, A.T., Yahdjian, L., Stark, J.M., Belnap, J., Porporato, A., Norton, U., Ravetta, D.N.A., Schaeffer, S.M., 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141, 221–235.

Barton, K., 2014. MuMIn: Multi-model Inference. R Package Version 1.10.0.

Belnap, J., 2002. Nitrogen fixation in biological soil crusts from southeast Utah, USA. Biol. Fertil. Soils 35, 128–135.

Bertiller, M.B., Ares, J.O., Bisigato, A.J., 2002. Multiscale indicators of land degradation in the Patagonian Monte, Argentina. Environ. Manag. 30, 704–715.

Bisigato, A.J., Laphitz, R.M., Carrera, A.L., 2008. Non-linear relationships between grazing pressure and conservation of soil resources in Patagonian Monte shrublands. J. Arid Environ. 72, 1464–1475.

Bisigato, A., Villagra, P.E., Ares, J., Rossi, B.E., 2009. Vegetation heterogeneity in Monte desert ecosystems: a multi-scale approach linking patterns and processes. J. Arid Environ. 73, 182–191.

Bonino, E.E., 2006. Changes in carbon pools associated with a land-use gradient in the dry Chaco, Argentina. For. Ecol. Manag. 223, 183–189.

Brady, N.C., Weil, R.R., 1999. The Nature and Properties of Soils. Twelfth ed. Upper Saddle River, Prentice Hall, New Jersey, United States of America.

Breshears, D.D., Myers, O.B., Barnes, F.J., 2009. Horizontal heterogeneity in the frequency of plant-available water with woodland intercanopy–canopy vegetation patch type rivals that occuring vertically by soil depth. Ecohydrology 2, 503–519.

Brooks, M.L., Matchett, J.R., Berry, K.H., 2006. Effects of livestock watering sites on alien and native plants in the Mojave Desert, USA. J. Arid Environ. 67, 125–147.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-theoretic Approach. Second ed. Springer, New York.

Carrera, A.L., Mazzarino, M.J., Bertiller, M.B., Del Valle, H.F., Martínez Carretero, E., 2009. Plant impacts on nitrogen and carbon cycling in the Monte Phytogeographical Province, Argentina. J. Arid Environ. 73, 192–201.

Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron. J. 94, 38–47.

D'Odorico, P., Laio, F., Porporato, A., Ridolfi, L., Rinaldo, A., Rodriguez-Iturbe, I., 2010. Ecohydrology of terrestrial ecosystems. Bioscience 60, 898–907.

Davies, B., 1974. Loss-on-ignition as an estimate of soil organic matter. Soil Sci. Soc. Am. Proc. 38, 150–151.

Facelli, J.M., Brock, D.J., 2000. Patch dynamics in arid lands: localized effects of *Acacia papyrocarpa* on soils and vegetation of open woodlands of south Australia. Ecography 23, 479–491.

Fernandez-Gimenez, M., Allen-Diaz, B., 2001. Vegetation change along gradients from water sources in three grazed Mongolian ecosystems. Plant Ecol. 157, 101–118.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., et al., 2005. Global consequences of land use. Science 309, 570–574.

Garcia, V., Aranibar, J., Pietrasiak, N., 2015. Multiscale effects on biological soil crusts cover and spatial distribution in the Monte desert. Acta Oecol. 69, 35–45.

García-Palacios, P., Maestre, F.T., Bardgett, R.D., de Kroon, H., 2012. Plant responses to soil heterogeneity and global environmental change. J. Ecol. 100, 1303–1314.

Goirán, S., Aranibar, J.N., Gomez, M.L., 2012. Heterogeneous spatial distribution of traditional livestock settlements and their effects on vegetation cover in arid groundwater coupled ecosystems in the Monte desert (Argentina). J. Arid Environ. 87, 188–197.

Goirán, S., Tonolli, A., Aranibar, J.N., Villagra, P.E., Millán, E., Forconesi, L., Bringa, E.M., 2013. Factores que determinan el uso del espacio y los recursos en zonas áridas no irrigadas del noreste de Mendoza (Argentina). In: Lara, A, Laterra, P., Manson, R., Barrantes, G (Eds.), Servicios ecosistémicos hídricos: estudios de caso en América Latina y el Caribe, pp. 97–110, Valdivia, Chile.

Gomez, M.L., Aranibar, J.N., Wuilloud, R., Rubio, C., Martinez, D., Soria, D., Monasterio, R., Villagra, P.E., Goirán, S., 2014. Hydrogeology and hydrogeochemical modeling in phreatic aquifer of NE Mendoza, Argentina. J. Iber. Geol. 40, 521–538.

Guevara, A., Giordano, C.V., Aranibar, J.N., Quiroga, M., Villagra, P.E., 2010. Phenotypic plasticity of the coarse root system of *Prosopis flexuosa*, a phreatophyte tree, in the Monte desert (Argentina). Plant Soil 330, 447–464.

Herczeg, A., Leaney, F.W., 2011. Review: environmental tracers in arid-zone hydrology. Hydrogeol. J. 19, 17–29.

Huxman, T.E., Snyder, K.A., Tissue, D., Leffler, A.J., Ogle, K., Pockman, W.T., Sandquist, D.R., Potts, D.L., Schwinning, S., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 141, 254–268.

Inojosa, M., Meglioli, P.A., Karlin, U.O., 2010. Nuestra Identidad Huarpe. In: Montani, M.C., Vega RiverosC, C. (Eds.), Raíces Huarpes: Uso medicinal de plantas en la comunidad de Lagunas del Rosari 17–32 Mendoza, Argentina.

Jackson, R.B., Schenk, H.J., Jobbágy, E.G., Canadell, J., Colello, G.D., Dickinson, R.E., Field, C.B., Friedlingstein, P., Heimann, M., Hibbard, K., Kicklighter, D.W., Kleidon, A., Neilson, R.P., Parton, W.J., Sala, O., Sykes, M.T., 2000. Belowground consequences of vegetation change and their treatment in models. Ecol. Appl. 10, 470–483.

Jin, Z., Zhu, Y., Li, X., Dong, Y., An, Z., 2015. Soil N retention and nitrate leaching in three types of dunes in the Mu Us desert of China. Sci. Report. 5, 14222.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436.

Jobbágy, E.G., Jackson, R.B., 2001. The distribution of soil nutrients with depth: global patterns and the imprint of plants. Biogeochemistry 53, 51–77.

Jobbágy, E.G., Nosetto, M.D., Villagra, P.E., Jackson, R.B., 2011. Water subsidies from mountains to deserts: their role in sustaining groundwater-fed oases in a sandy landscape. Ecol. Appl. 21, 678–694.

Lal, R., 1997. Degradation and resilience of soils. Philos. Trans. R. Soc. Lond. B Sci. 352, 997–1010.

Landsberg, J., James, C.D., Morton, S.R., Müller, W.J., Stol, J., 2003. Abundance and composition of plant species along grazing gradients in Australian rangelands. J. Appl. Ecol. 40, 1008–1024.

Lange, R.T., 1969. The piosphere: sheep track and dung patterns. J. Range Manag. 22, 396–400.

Maestre, F.T., Cortina, J., Bautista, S., Bellot, J., Vallejo, R., 2003. Small-scale environmental heterogeneity and spatiotemporal dynamics of seedling establishment in a semiarid degraded ecosystem. Ecosystems 6, 630–643.

Manthey, M., Peper, J., 2010. Estimation of grazing intensity along grazing gradients – the bias of nonlinearity. J. Arid Environ. 74, 1351–1354.

McLauchlan, K.K., Higuera, P.E., Gavin, D.G., Perakis, S.S., Mack, M.C., Alexander, H., Battles, J., Biondi, F., Buma, B., Colombaroli, D., et al., 2014. Reconstructing disturbances and their biogeochemical consequences over multiple timescales. Bioscience 64, 105–116.

MEA, 2005. Millennium Ecosystem Assesment: Ecosystems and Human Well-being: Desertification Synthesis. World Resource Institute, Washington, D.C.

Meglioli, P.A., 2015. Efectos de los disturbios provocados por puestos ganaderos sobre el complejo agua-suelo-vegetación en ecosistemas áridos acoplados al acuífero freático Thesis, Universidad Nacional del Cuyo, Mendoza, Argentina 158 pp.

Meglioli, P.A., Aranibar, J.N., Villagra, P.E., Alvarez, J.A., Jobbágy, E.G., 2014. Livestock stations as foci of groundwater recharge and nitrate leaching in a sandy desert of the Central Monte, Argentina. Ecohydrology 7, 600–611.

Meglioli, P.A., Villagra, P.E., Aranibar, J.N., 2016. Does land use change alter water and nutrient dynamics of phreatophytic trees in the Central Monte desert? Ecohydrology 9, 738–752.

Milchunas, D.G., Lauenroth, W.K., 1993. A quantitative assessment of the effects of grazing on vegetation and soils over a global range of environments. Ecol. Monogr. 63, 327–366.

Millán, E.N., Goirán, S., Aranibar, J.N., Forconesi, L., García Garino, C., Bringa, E.M., 2015. Evaluating the Importance of Environmental factors on the spatial distribution of livestock settlements in the Monte desert with a Monte Carlo based model: Settlement Dynamics in Drylands (SeDD) arXiv:1507.07886.

Mohamed Saleem, M.A., 1998. Nutrient balance patterns in African livestock systems. Agric. Ecosyst. Environ. 71, 241–254.

Moore, G.W., Barre, D.A., Owens, M.K., 2010. Changes in soil chloride following shrub removal and subsequent regrowth. Geoderma 158, 148–155.

Patra, A.K., Abbadie, L., Clays-Josserand, A., Degrange, V., Grayston, S.J., Loiseau, P., Louault, F., Mahmood, S., Nazaret, S., Philippot, L., Poly, F., Prosser, J.I., Richaume, A., Le Roux, X., 2005. Effects of grazing on microbial functional groups involved in soil N dynamics. Ecol. Monogr. 75, 65–80.

Pearcy, R.W., Ehleringer, J.R., Mooney, H.A., Rundel, P.W., Binkley, D., Vitousek, P., 1989. Soil Nutrient Availability, Plant Physiological Ecology. Springer, Netherlands, pp. 75–96.

Piñeiro, G., Paruelo, J.M., Jobbágy, E.G., Jackson, R.B., Oesterheld, M., 2009. Grazing effects on belowground C and N stocks along a network of cattle exclosures in temperate and subtropical grasslands of South America. Glob. Biogeochem. Cycles 23, GB2003.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ravi, S., Breshears, D.D., Huxman, T.E., D'Odorico, P., 2010. Land degradation in drylands: interactions among hydrologic-aeolian erosion and vegetation dynamics. Geomorphology 116, 236–245.

Rojas, J.F., Prieto, M.R., Alvarez, J.A., Cesca, E., 2009. Procesos socioeconómicos y territoriales en el uso de los recursos forestales en Mendoza desde fines del siglo XIX hasta mediados del XX. Proyección 7, 1–33.

Rossi, B.E., Villagra, P.E., 2003. Effects of *Prosopis flexuosa* on soil properties and the spatial pattern of understory species in arid Argentina. J. Veg. Sci. 14, 543–550.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M., Simmers, I., 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol. Process. 20, 3335–3370.

Schlesinger, W.H., Raikes, J.A., Hartley, A.E., Cross, A.E., 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77, 364–374.

Sena, M.M., Frighetto, R.T.S., Valarini, P.J., Tokeshi, H., Poppi, R.J., 2002. Discrimination of management effects on soil parameters by using principal component analysis: a multivariate analysis case study. Soil Tillage Res. 67, 171–181.

Shahriary, E., Palmer, M.W., Tongway, D.J., Azarnivand, H., Jafari, M., Mohseni Saravi, M., 2012. Plant species composition and soil characteristics around Iranian piospheres. J. Arid Environ. 82, 106–114.

Smet, M., Ward, D., 2006. Soil quality gradients around water-points under different management systems in a semi-arid savanna, South Africa. J. Arid Environ. 64, 251–269.

Titus, J.H., Nowak, R.S., Smith, S.D., 2002. Soil resource heterogeneity in the Mojave Desert. J. Arid Environ. 52, 269–292.

Todd, S.W., 2006. Gradients in vegetation cover, structure and species richness of Nama-Karoo shrublands in relation to distance from livestock watering points. J. Appl. Ecol. 43, 293–304.

Tongway, D.J., Sparrow, A.D., Friedel, M.H., 2003. Degradation and recovery processes in arid grazing lands of central Australia. Part 1: soil and land resources. J. Arid Environ. 55, 301–326.

Torres, M.L., 2008. Hilos de agua, lazos de sangre: enfrentando la escasez en el desierto de Lavalle (Mendoza, Argentina). Ecosistemas 19, 46–59.

Tripaldi, A., Forman, S.L., 2007. Geomorphology and chronology of Late Quaternary dune fields of western Argentina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 251, 300–320.

Villagra, P.E., Cony, M.A., Mantován, N.G., Rossi, B.E., González Loyarte, M.M., Villalba, R., Marone, L., 2004. Ecología y Manejo de los algarrobales de la Provincia Fitogeográfica del Monte. In: Arturi, M., Frangi, J., Goya, J. (Eds.), Ecología y Manejo de Bosques Nativos de Argentina. Editorial UNLP, Argentina, p. 32.

Villagra, P.E., Defossé, G., Del Valle, H., Tabeni, M.S., Rostagno, C.M., Cesca, E., Abraham, E.M., 2009. Land use and disturbance effects on the dynamics of natural ecosystems of the Monte desert. Implications for their management. J. Arid Environ. 73, 202–211.

Villagra, P.E., Cesca, E., Alvarez, J.A., Rojas, F., Bourguet, M., Rubio, C., Mastrángelo, P., 2010. Documento de Ordenamiento de Bosques Nativos de la Provincia de Mendoza. Secretaría de Medio Ambiente. Dirección de Recursos Naturales Renovables, Mendoza, p. 51.

Villagra, P.E., Giordano, C., Alvarez, J.A., Cavagnaro, J., Guevara, A., Sartor, C., Passera, C., Greco, S., 2011. Ser planta en el desierto: estrategias de uso de agua y resistencia al estrés hídrico en el Monte Central de Argentina. Ecol Austral 21, 29–42.

Wachendorf, C., Taube, F., Wachendorf, M., 2005. Nitrogen leaching from 15 N labelled cow urine and dung applied to grassland on a sandy soil. Nutr. Cycl. Agroecosyst. 73, 89–100.

Wang, J., Fu, B., Qiu, Y., Chen, L., 2001. Soil nutrients in relation to land use and landscape position in the semi-arid small catchment on the loess plateau in China. J. Arid Environ. 48, 537–550.

Wang, X., Wang, J., Zhang, J., 2012. Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China. PLoS One 7, e44334.

Wilcox, B.P., Breshears, D.D., Allen, C.D., 2003. Ecohydrology of a resource conserving semiarid woodland: effects of scale and disturbance. Ecol. Monogr. 73, 223–239.