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Livestock stations as foci of groundwater recharge and nitrate leaching in a sandy desert of the Central Monte, Argentina

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ABSTRACT

In arid ecosystems, evapotranspiration generally exceeds precipitation, preventing deep drainage and groundwater recharge. We propose that vegetation changes associated with the establishment of pastoralist settlements (i.e. livestock stations) can disrupt the ecological and hydrological linkages in arid groundwater-coupled ecosystems of the Monte desert (Argentina), allowing local groundwater recharge and nitrate leaching to the aquifer, affecting groundwater quality. We tested this hypothesis by analysing vegetation, land use indicators, water and nitrate dynamics in three pairs of livestock stations and relatively undisturbed control woodlands. Livestock stations had lower vegetation and dead wood but higher dung covers than control woodlands, indicating soil and vegetation changes associated to land use. Water and nitrate dynamics were also affected by land use. Soil nitrate and water contents sampled down to the water table were higher, and soil chloride and salinity were lower in livestock stations, indicating higher water percolation and N input/transport rates. Higher groundwater nitrate concentrations in livestock stations indicate that these areas behave as foci of N and water export from ecosystems to the phreatic aquifer. Our study supports the idea that vegetation in arid areas prevents downward surface–groundwater interactions, but it also indicates that human modifications of vegetation disrupt this control, reducing soil water consumption and allowing vertical movement of water and solutes to the aquifer, which can modify groundwater quality. Disruptions of ecological processes by livestock activities clearly affect the hydrological links between surface and groundwater. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS land use changes; *Prosopis flexuosa* woodlands; grazing systems; shallow groundwater; soil profiles; vegetation structure

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INTRODUCTION

Arid and semi-arid areas host an important proportion of the global human population, whose different economic activities depend mainly on surface water availability (FAO, 2011). Drylands are characterized by low and patchy precipitation, always exceeded by potential evapotranspiration (Noy-Meir, 1973; Loik *et al*., 2004; Schwinning *et al*., 2004). Without permanent surface water availability, shallow groundwater found in some areas of the Monte Desert is a key resource for plants and people, sustaining biological activity, primary productivity and human development levels above those expected from local precipitation alone (Contreras *et al*., 2011; Jobbágy *et al*., 2011). Climate projections for the next 100 years in the Monte Desert of Argentina suggest an increase in rainfall and temperatures, mostly during summertime (Labraga and Villalba, 2009). Under this scenario, groundwater may play an increasing role on the development of local communities.

In desert ecosystems, where water availability is the main limiting factor, direct evaporation and plant roots often make an exhaustive use of rainfall inputs, preventing deep percolation and local groundwater recharge. In these systems, vegetation has large root systems that exceed the canopy area and explore the unsaturated zone to great depths, controlling soil water dynamics and recharge (Noy-Meir, 1973; Wilcox *et al*., 2003; Newman *et al*., 2006). Plant roots absorb water and nutrients from the soil and exclude other ions such as chloride, which can be used as a tracer of water dynamics (Allison *et al*., 1994; Phillips, 1994). Leaching of large soil chloride stocks in desert systems subject to disturbances indicates low water uptake rates and the occurrence of deep drainage and aquifer recharge (Jackson *et al*., 2000; Jobbágy and Jackson, 2001; Scanlon *et al*., 2005). Successional changes from a non-vegetated to a fully vegetated condition may reduce groundwater recharge to a null level (Scanlon *et al*., 2006), whereas replacement of native woodland with pastures or crops has been shown to increase recharge

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rates (Santoni *et al.*, 2010; Moore *et al.*, 2012; Nosetto *et al.*, 2012).

Grazing and wood extraction in human settlements can permanently reduce vegetation cover, altering their structure and nutrient, and water cycles (Hobbs and Huenneke, 1992; Asner *et al.*, 2004; Reynolds *et al.*, 2007). Even under very low livestock and human population densities, as found in most of the Monte desert, the periodic concentration of animals close to water points and corrals, and close to human settlements may concentrate nutrients captured in a broad grazing range into highly disturbed foci. The combination of vegetation degradation and nutrient imports may couple increased deep water drainage with horizontal nutrient imports and downward transport to groundwater, modifying hydrological and biogeochemical connections and altering water resource quality (Jackson et al., 2009; Nosetto et al., 2012).

In the Central Monte desert (Argentina), *Prosopis flexuosa* D.C. (Fabaceae, Mimosoideae, 'algarrobo dulce') woodlands have provided valuable resources (i.e. fruits, wood) to rural populations since pre-Hispanic times (Roig, 1993; Prieto, 2000; Chiavazza, 2002). Huarpe descendants still live in the area and now practice subsistence livestock production, using woodland resources and groundwater (Ladio and Lozada, 2009; Inojosa *et al.*, 2010). Because a high proportion of *Prosopis* woodlands was cut down for building railroads and vineyards in the 20th century (Rojas *et al.*, 2009), the remaining woodlands are now protected by law. The rich Huarpe identity and cultural legacy of the local inhabitants have been recognized by government authorities, granting land rights to Huarpe communities (Inojosa *et al.*, 2010). A sustainable use of these woodlands depends on a good understanding and sound management of the interactions among human activities and the environment, including interactions among livestock stations, nutrients and water cycles.

Local settlers, when establishing a livestock station in the woodlands of the Central Monte, generate a set of disturbances in the environment (Villagra *et al.*, 2009). In general, new families settle near their elders' home, if groundwater and woodland resources are available. Hand-dug wells, houses and corrals are built with forest products (Torres, 2008). In these areas, relatively large numbers of free grazing livestock (predominantly goats and cattle) concentrate overnight around water wells and corrals during the entire year. As a result, clear gradients of degradation develop across the landscape, with reduced vegetation cover up to 2 km away from livestock stations (Goirán *et al.*, 2012). In addition, livestock deposit large amounts of urine and dung in these stations, likely causing a centripetal concentration of nutrients, as shown in other rangelands (Tolsma *et al.*, 1987; Smet and Ward, 2006). Nitrate leaching to the subsoil has been observed in scarcely vegetated areas, which may reach the aquifer and jeopardize water quality for human consumption, because of its negative effects on human health (Aranibar *et al.*, 2011; ATSDR, 2011).

We hypothesize that in livestock stations, the reductions in vegetation cover and the deposition of urine and dung by livestock favour downward water and nutrient transport in the soil, increasing local recharge and nitrate leaching to the aquifer (Figure 1). We evaluate this hypothesis by comparing paired stands in relatively undisturbed (control woodlands) and disturbed (livestock stations) interdune valleys in the Central Monte desert in Argentina. We expect livestock stations to have (i) lower vegetation cover, (ii) higher soil moisture and nitrate contents, (iii) lower vadose chloride and total salt stocks than control woodlands, (iv) and higher groundwater nitrate concentrations than control woodlands.

MATERIALS AND METHODS

Study site

The study sites are located in the Telteca Natural and Cultural Reserve, in Mendoza, Argentina (32°S, 67°–68°W; 500–550 m of elevation). Biogeographically, the area corresponds to the Central Monte and is characterized by a warm arid climate, with mean annual precipitation of 156 mm, mostly concentrated in the austral summer (from October to March). Absolute extreme temperatures vary from −10 °C in winter to 48 °C in summer, with a long-term mean of 18·5 °C (Alvarez *et al.*, 2006).

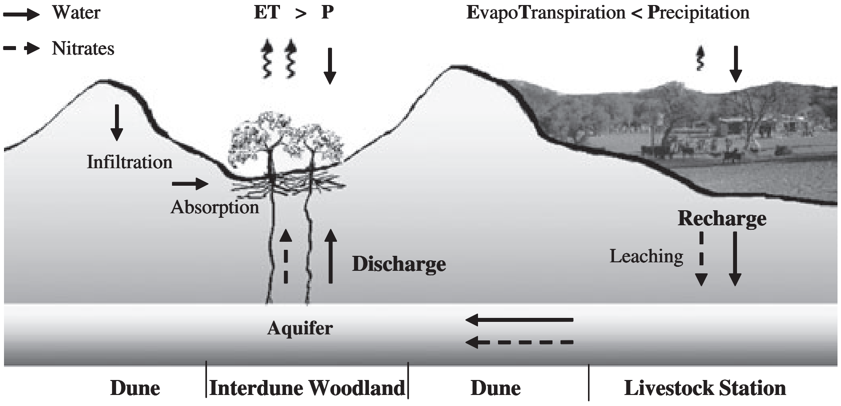

Figure 1. Hypothetical mechanisms of water and nitrate fluxes for livestock stations and relatively undisturbed woodlands in arid, groundwater-coupled ecosystems. Livestock stations facilitate water percolation and nitrate leaching to groundwater, increasing local recharge. In control woodlands, the vertical water flux down to the phreatic aquifer is interrupted by vegetation roots. In these places groundwater use, through transpiration of the phreatophyte trees, exceeds precipitation and does not allow deep drainage, determining a local discharge regime (Evapotranspiration > Precipitation).

The area is located in an aeolian plain, which was formed by fluvial and aeolian sediments that developed dune-interdune systems of NNW–SSE orientation, with active sand dunes partially stabilized by the vegetation. The region hosts discontinuous valleys with elevation gradients of 10 to 30 m (Gomez *et al.*, 2010). Livestock stations are established in interdune valleys (Figures 1 and 2), where the water table lies at depths of 6–15 m. This shallow groundwater is used by phreatophyte vegetation dominated by *P. flexuosa* trees (5–10 m tall), coexisting with small tree species, such as *Geoffroea decorticans*, and shrub species, as *Larrea divaricata*, *Bulnesia retama*, *Atriplex lampa*, and *Suaeda diva*ricata (Morello, 1958). Dune flanks are dominated by *L. divaricata*, *Tricomaria usillo*, small individuals of *P flexuosa* (lower than 4 m) and the grass *Panicum urvilleanum* (Villagra *et al.*, 2004; Alvarez *et al.*, 2006).

These woodlands have been used by human populations for several centuries and are still used today by the local inhabitants. In the past, trees were exploited for building railroads and vineyards without any management plan, causing irreversible changes in some areas where trees have been completely eliminated (Abraham *et al.*, 2009; Rojas *et al.*, 2009). Difficult access on motorized vehicles into the sand dune fields has prevented deforestation in the study region, where old *Prosopis* individuals still remain. Presently, the woodlands are protected by law, and wood can only be extracted by the local population for fuel and construction of the house, wells and corrals. The Telteca reserve hosts approximately 34 family units in an area of ~200 km^2 (Bosch, 2008). Many settlements are isolated from access roads, commercialization centres and points of public drinking water supply and have no access to electricity. Livestock, mainly goats and a lower number of horses and cattle, feed on local vegetation and rely on groundwater extracted from hand-dug wells. Most of these wells are cased with

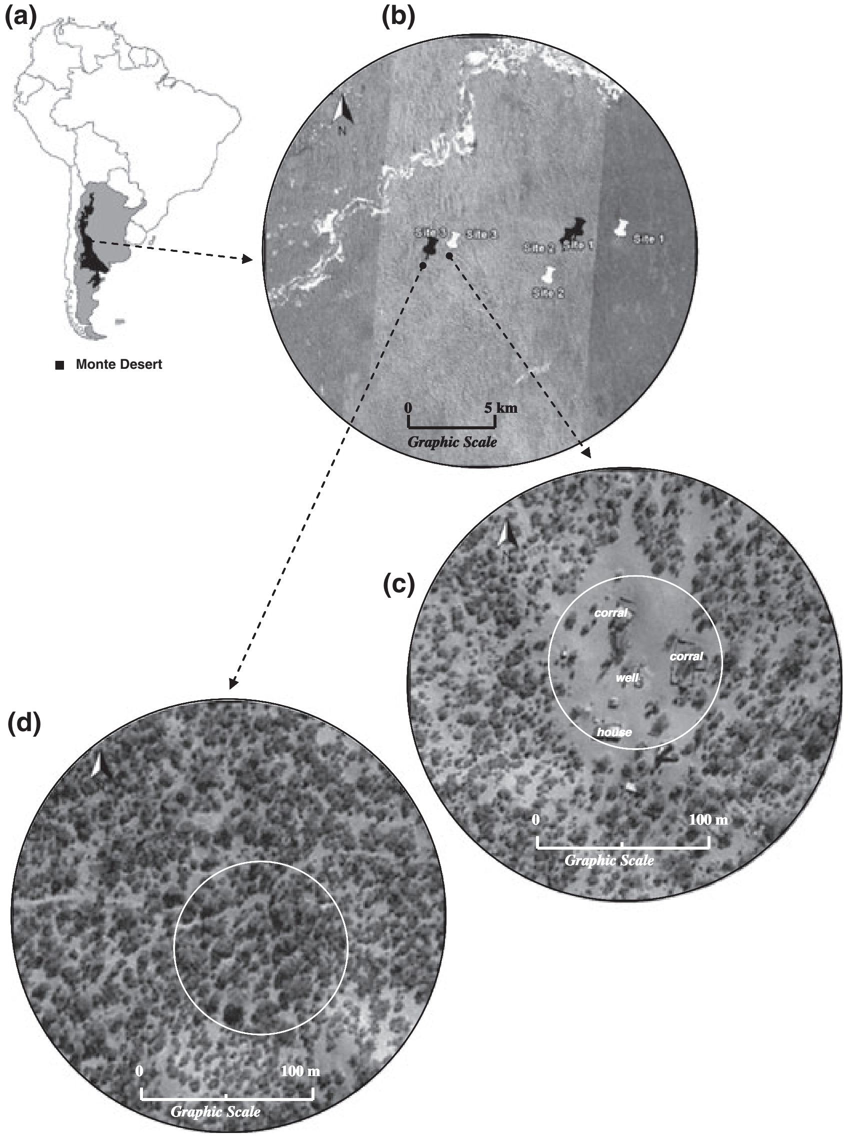

Figure 2. Map of South America with the extension of the Monte Desert (a). A satellite image marks the location of the livestock stations (white mark) and control woodlands (black mark) in the Telteca Reserve (Lavalle-Mendoza) (b). Satellite images with zoom of a livestock concentration area, where land use intensity is greater (c), and of paired relatively undisturbed woodlands (d). In these images, we highlighted with a circle the area where we analyzed soils and vegetation. Source for the satellite images was Google Earth http://earth.google.es.

wooden frames, and water is extracted by hand or with animal-powered devices.

Experimental design

To assess the effects of livestock stations (i.e. nutrient deposition and vegetation removal) on water and nutrient dynamics, we compared soils and vegetation in three pairs of livestock stations and relatively undisturbed 'control' woodlands (Figure 2). Livestock stations and paired control woodland stands were in the same geomorphological setting (interdune valleys), 1·5–2·0 km from each other (Table I). All three paired sites were considered independent replicates.

Field observations

Because there is no information about livestock densities and their spatial distribution on our study sites, we evaluated the differences in livestock and human activities through several variables that are typically considered good indicators of land use intensity. With higher livestock density, we expect higher dung deposition and *Prosopis* pod consumption (Bertiller *et al.*, 2009), lower cover of biological soil crusts (Gómez *et al.*, 2012) and enhanced germination rates of *Prosopis* seeds (Campos and Ojeda, 1997). Low abundance of *Prosopis* pods may also indicate human activity, because local inhabitants use them as a source of food (seed flour and pod sugar) and forage (Inojosa *et al.*, 2010). Similarly, low abundance of dead wood on the ground may reflect its use for fuel or construction (Alvarez and Villagra, 2009; Vázquez *et al.*, 2011). We visually estimated the cover/abundance of domestic animal dung, biological soil crusts, woody debris >5-cm diameter, and the density of *Prosopis* pods and seedlings in 15 plots of 9 m^2 at each stand. We distributed five plots every 20 m, along three randomly located 100-m-long transects. For each land cover indicator, we used the mean of the 15 square plots of each site for statistical analysis.

We determined vegetation structure with the point-quadrat method using three 30-m linear transects randomly distributed on each experimental site. We sampled 100 points per transect, every 30 cm (Passera *et al.*, 1983). In each point, we registered the presence of bare soil, litter, trees, shrubs, forbs and grasses and calculated the percentage cover of each soil cover type in each transect. Final results were an average of the three transects per each stand.

Soil sampling and chemical analyses

To characterize soil nutrient and water stocks and their vertical distribution, we measured moisture, chloride and nitrate contents, electric conductivity and pH along soil profiles down to the water table. Chloride is often used as a tracer of water transport, particularly in arid and semi-arid systems, because it is highly mobile in water, its source is mainly atmospheric and roots tend to exclude it during water absorption (Allison *et al.*, 1994; Phillips, 1994). Therefore, chloride concentration and distribution in the soil are indicators of water dynamics, including drainage and evapotranspiration (Scanlon *et al.*, 2006; Jobbágy *et al.*, 2011). Soil nitrate, which also has high mobility, is affected by animal transport and deposition (horizontal transport towards livestock stations) and vegetation activity (drainage control and nitrogen absorption and retention).

We obtained soil samples from deep soil profiles in each of the six experimental units, at intervals of 0·25 m for the first 0·5 m and 0·5 m down to the water table, which was located at a depth of 8·3 to 9·6 m. We collected soil samples with a hand soil auger (10-cm diameter) and applied a PVC casing to avoid borehole collapse. Soil subsamples were weighed in the field (100 g) for later determination of gravimetric soil moisture, after drying at 100 °C for 24 h. Soil samples for chemical analysis were immediately homogenized, stored in plastic bags, air dried in the field and oven-dried at 60 °C for 24 h before chemical analyses.

Chloride concentration, pH and electric conductivity were measured on soil extracts (25 g of soil and 50 ml of deionized water) using a solid state ion-selective electrode (Denver Instrument UP-25), a pH electrode (Denver Instrument UP-25) and a conductimeter (HACH, Session5), respectively. Soil extracts were shaken mechanically during 30 min, filtered and frozen until analysis. Total salt content of soil

Table I. Location of study sites in the Telteca reserve and their characteristics.

Site	Land use	Location	Groundwater depth (m)	Corrals (*n*)	Animals (*n*) [a]	Distance of wells to corral (m) [b]
1-La Primavera	Livestock station	32°24′45.1″ (S), 67°54′53·8″ (W)	9·6	2	80 goats 80 cattle	31·0
1-La Primavera	Control woodland	32°34′47·8″ (S), 67°56′31·4″ (W)	8·3	—		
2-Las Delicias	Livestock station	32°26′22·6″ (S), 67°57′32·5″ (W)	8·3	3	90 goats 70 cattle	24·6
2-Las Delicias	Control woodland	32°25′05·6″ (S), 67°56′54·6″ (W)	9·5	—		
3-Las Hormigas	Livestock station	32°25′26·4″ (S), 68°01′08·7″ (W)	9·5	3	150 goats 30 cattle	28·6
3-Las Hormigas	Control woodland	32°25′43·2″ (S), 68°01′59·9″ (W)	9·5	—		

[a] Because there are no agricultural data for these areas, the number of animals was visually estimated during field studies, indicating approximate values.
[b] Distance of wells to corrals is equal to the distance from soil sampling point to perimeter of the nearest corral.

extracts was estimated using a conversion factor of 0·491 ppm $\mu s\,cm^{-1}$, which assumes that all solutes are NaCl (Bresler *et al.*, 1982). Chloride concentrations and soil salinity ($g\,m^{-3}$ of soil) were calculated using a bulk density value of 1·47 $g\,cm^{-3}$, previously obtained for interdune valleys of the Telteca reserve (Guevara *et al.*, 2010). Nitrate concentration was determined in soil extracts of 5 g of soil and 25 ml of extracting solution, composed of 2·5 g of $CuSO_45$ H_2O, 0·15 g of Ag_2SO_4 and 0·62 g of BO_3H_3 in 1000 ml of deionized water. Soil extracts were shaken during 1 h, filtered, adjusted to pH 7 with sodium hydroxide (1%) and frozen until analysis. Nitrate concentrations were determined by spectrophotometry (HACH DR 2800) with the cadmium reduction method. We also determined nitrate concentration, electric conductivity and pH in groundwater samples with the same methods as in the soil extracts. Groundwater samples were obtained from the bottom of each soil profile, refrigerated in the field and immediately analysed in the laboratory after return from the field.

Data analysis

Differences in vegetation structure (grass–forbs, shrubs and trees), bare soil and litter among livestock station and woodland sites were analysed using Kruskal–Wallis test with non-parametric comparisons, because of the high heterogeneity of variances (Zar, 1984). Indicators of livestock and human activity (dung, woody debris, soil crusts, seedlings and pods) were analysed using generalized linear mixed model (GLMM) fit by the Laplace approximation, considering land use (livestock stations vs control woodlands) as a fixed factor and site (1, 2 and 3) as a random factor. The indicators had Poisson distributions.

We also used GLMM to analyse soil variables, considering land use with two levels (livestock stations vs control woodlands) and soil depth as fixed factors, and site as a random factor with three levels. We conducted the GLMM analyses using the 'lmer' function of the 'lme4' package (Bates and Maechler, 2009) with R statistical software (R Development Core Team, 2009). We ran models with and without the interaction (models 2 and 1, respectively) between land use and soil depth. In the analysis, we only considered samples of the vadose zone, excluding those from the saturated zone, to avoid the influence of groundwater. We selected the best model using Akaike's information criterion (dAIC > 2). We estimated significance of fixed factors with Markov Chain Monte Carlo simulations ($n = 100000$), using the 'pvals.fnc' function of the 'languageR' package for R (Baayen, 2008), which estimates p-values for GLMM parameters, considering $p < 0{\cdot}05$ as significant. Moisture, chloride, nitrate and salinity were log-transformation to approximate normality.

Soil water content (% dry weight), chloride concentration ($g\,m^{-3}$), nitrate concentration ($g\,m^{-3}$), pH and salinity ($g\,m^{-3}$) were plotted with depth. We also constructed curves of cumulative chloride and nitrate ($g\,m^{-2}$) versus cumulative water ($m^3\,m^{-2}$) for each soil profile, using a bulk density of 1·47 $g\,cm^{-3}$ (Guevara *et al.*, 2010). Different cumulative chloride : water slopes indicate concentration shifts and therefore changes in the drainage regimes (Phillips, 1994; Santoni *et al.*, 2010).

RESULTS

Land use intensity indicators and vegetation structure

Livestock stations had higher bare soil and dung cover, lower plant litter and dead wood cover, and *Prosopis* pod density than their neighbouring control woodlands. Control woodlands had higher covers of all vegetation groups (grasses, shrubs and trees) than livestock stations, although differences in tree cover were not significant (Table II). Livestock stations were very poor in grass and forb species, with their vegetation being characterized by the presence of a few large *P. flexuosa* trees. In control woodlands, the tree layer was dominated by *P. flexuosa* as well but also included individuals of *Geoffroea decorticans*. The most frequent shrub species were *Capparis atamisquea*, *Lycium tenuispinosum* and *Suaeda divaricata*. The grass layer was characterized mainly by *Trichloris crinita*, with a lower cover of *Bouteloua aristidoides*, *Aristida mendocina* and *Setaria leucophila*.

Soil water and solutes

Compared with control woodlands, livestock stations had higher soil moisture, nitrate concentrations and lower chloride in the unsaturated zone (Figure 3).

Soil water content in the unsaturated zone was higher in livestock stations than in control woodlands, showing a sharp increase in both cases when the water table was approached. Moisture differences were greatest between 3·25 and 6·75-m depth (Figure 3(a–c)). The effects of land use and soil depth showed significant differences (Markov Chain Monte Carlo simulations) in model 1 (Table III).

Table II. Vegetation structure and surface soil characterization in control woodlands and livestock stations, expressed in percent cover, except in *Prosopis* seedlings and pods, which are expressed as number per plot.

Variable/indicators	Livestock Station	Control Woodland	p
Forbs–grasses [a]	0·33 (1·0)	22·44 (15·91)	**0·0023**
Shrubs [a]	1·56 (3·13)	33·89 (9·8)	**<0·0001**
Trees [a]	19·78 (19·7)	31·67 (17·56)	0·1754
Total vegetation [a]	21·67 (22·27)	88·00 (19·86)	**<0·0001**
Bare soil [a]	62·22 (16·4)	20·11 (13·52)	**0·0001**
Litter [a]	2·22 (3·67)	47·44 (21·21)	**<0·0001**
Dung [b]	12·27 (2·18)	4·12 (0·71)	**<0·0001**
Soil wood [b]	1·11 (0·25)	10·23 (1·56)	**<0·0001**
Biological Soil crusts [b]	0·24 (0·22)	2·00 (1·44)	0·214
Prosopis pods [b]	0·38 (0·18)	12·51 (4·8)	**0·0169**
Prosopis seedlings [b]	1·56 (0·57)	0·73 (0·2)	0·1870

Data represent mean values ±1 standard error of the mean between brackets.

[a] Data obtained with the point-quadrat method for vegetation structure. p-values are significance levels obtained with Kruskal–Wallis test. Significant test statistics $\alpha = 0{\cdot}05$ are highlighted in bold.

[b] Data obtained with the square plot method for indicators of livestock and human activity. p-values are significance levels by fixed factor obtained with generalized linear mixed model.

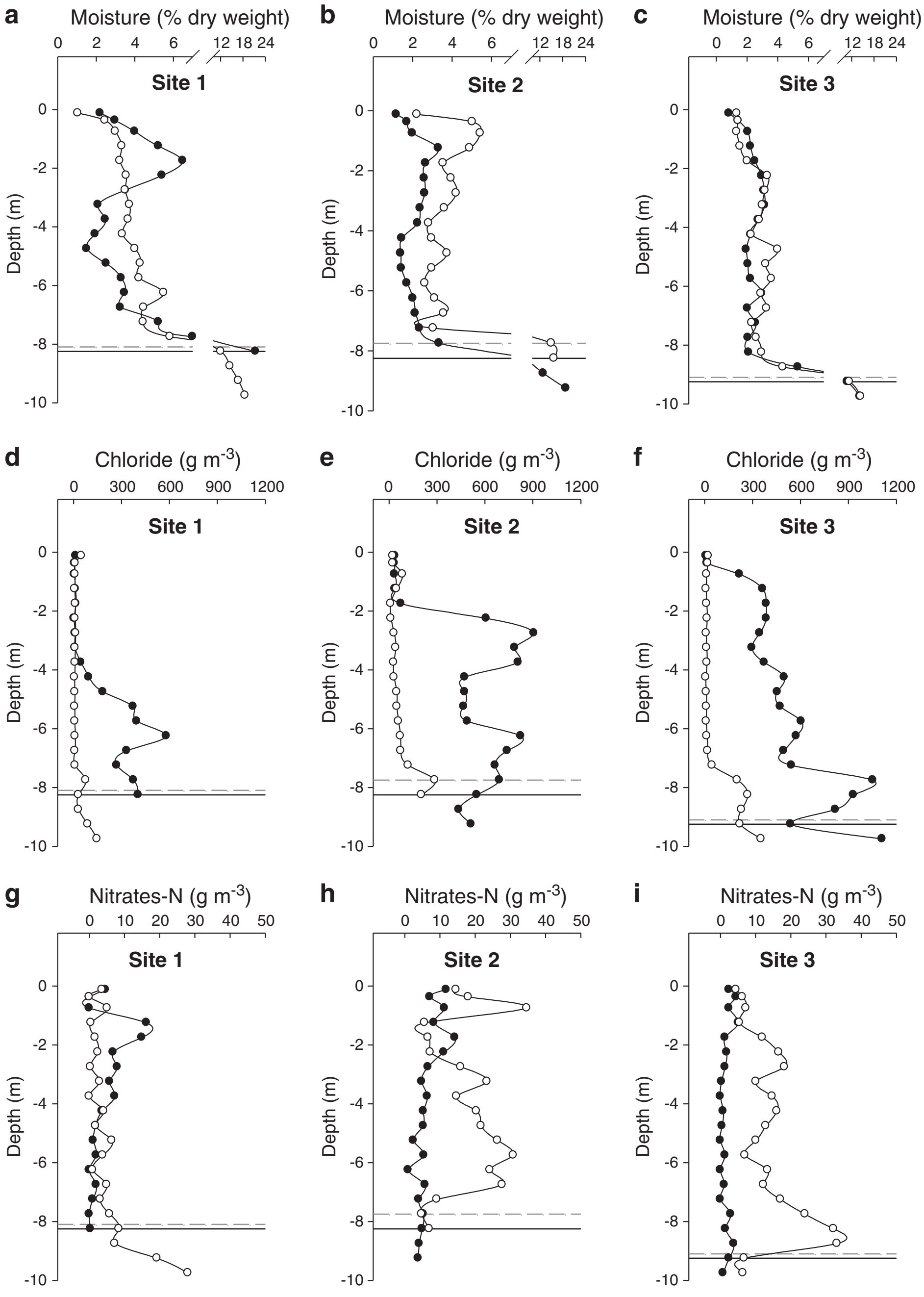

Figure 3. Vertical distribution of moisture content (a–c), chloride concentration per cubit metre of soil (d–f) and nitrate-N concentration per cubit metre of soil (g–i) in control woodlands (*filled circles*) and livestock stations (*open circles*). Each symbol represents a single measurement. The horizontal solid and dotted lines indicate the water table level for control woodlands and livestock stations, respectively.

Chloride concentrations had contrasting vertical distributions in livestock stations and control woodlands, with higher stocks and increasing concentrations with soil depth in the latter. Chloride accumulation increased dramatically below 4, 2 and 1 m depth in control woodlands at sites 1, 2 and 3, respectively (Figure 3(d–f)). Model 2 had a lower AIC value than model 1 and showed a significant interaction (Table III).

Nitrate concentrations were higher in livestock stations than in control woodlands, with the exception of site 1. Maximum nitrate contents were found at 5·75 and 8·25 m of depth in livestock stations at sites 2 and 3, respectively (Figure 3(g–i)).We observed increasing nitrate concentrations with soil depth in livestock stations and the opposite trend in control woodlands, which is also indicated by the significance of the interaction between land use and soil depth (Table III).

Soil pH indicated alkaline conditions at all sites, which varied markedly with soil depth but not with land use (Figure 4(a–c)). The model without interaction between fixed factors had lower AIC values. Markov Chain Monte Carlo simulations only showed a marginal significance for land use effect (Table III).

Soil salinity values were slightly higher in control woodlands than in livestock stations and increased with

Table III. Results for all soil variables from linear mixed effect models, including Akaike's information criterion (AIC) index and Markov Chain Monte Carlo (MCMC) *p*-values.

Soil variable	Models	AIC	MCMC *p* [a]		
			Land use	Soil depth	Land use * soil depth
Chloride	1	274·3	**0·0000**	**0·0000**	—
	2	244·6	0·1400	**0·0000**	**0·0000**
Soil moisture	1	38·96	**0·0037**	**0·0074**	—
	2	45·28	0·5381	0·2837	0·2449
Nitrate	1	217·1	**0·0000**	0·2974	—
	2	209·0	0·8772	**0·0004**	**0·0002**
pH	1	195·6	0·0562	0·4806	—
	2	201·6	0·3096	0·6086	0·9827
Salinity	1	164·8	**0·0025**	**0·0000**	—
	2	164·7	0·6403	**0·0000**	**0·0119**

[a] MCMC *p*-values, considering land use and soil depth as fixed factors (model 1 = without interaction, model 2 = with interaction). $p < 0{\cdot}05$ were considered significant and are highlighted in bold.

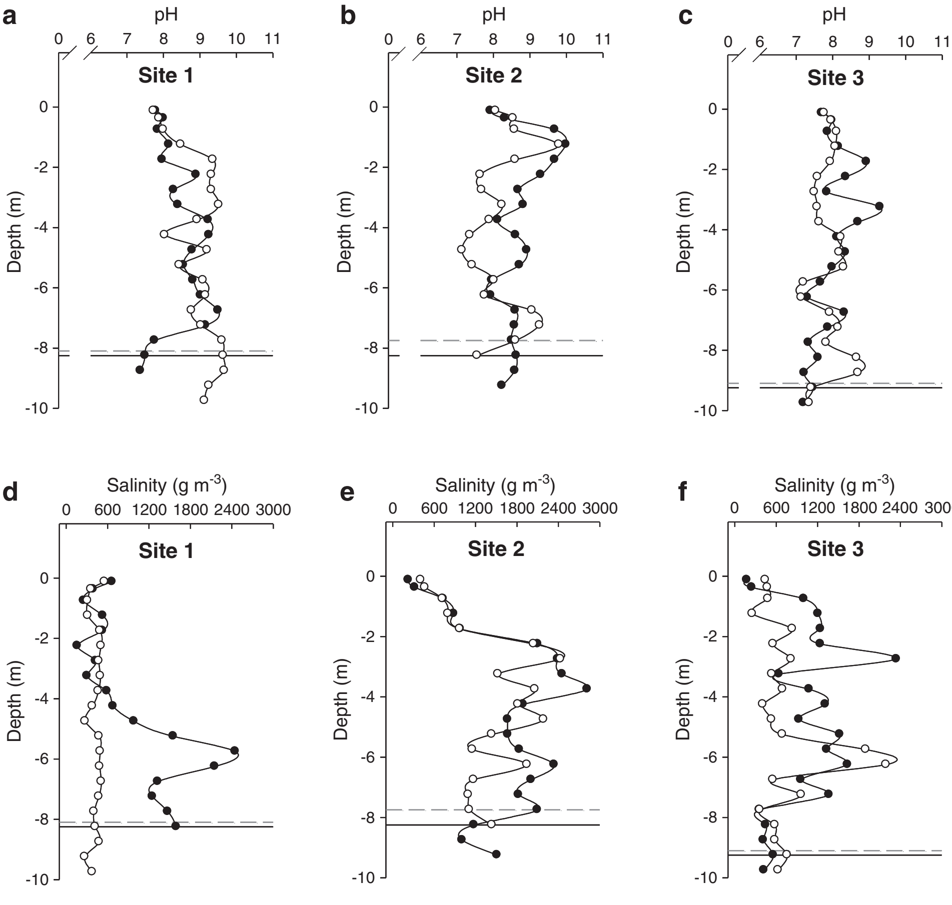

Figure 4. Vertical distribution of soil pH (a–c) and salt content per metre cubic of soil (d–f) in control woodlands (*filled circles*) and livestock stations (*open circles*). Each symbol represents a single measurement. The horizontal solid and dotted lines indicate the water table level for control woodlands and livestock stations, respectively.

soil depth in both land uses. At site 1, deep soils of the control woodland had greater values than in the paired livestock station. Sites 2 and 3 showed different variations with depth for both land uses (Figure 4(d–f)). Model 1 for soil salinity showed a significant effect of land use and soil depth. Model 2 had a significant interaction between fixed factors, indicating a different response of salinity with soil depth for the two land uses. AIC values were similar for the two models analysed (Table III).

Cumulative chloride concentration down to the water table ranged from 1560 to 5240 g m^{-2} in control woodlands and from 270 to 760 g m^{-2} in livestock stations, indicating strong net losses in the latter. In control woodlands, the slope of the curve changed at two depths: near the surface, where chloride accumulation begins, and above the saturated zone, where chloride accumulation does not increase further with depth. Cumulative nitrate concentrations at the maximum sampling depth varied from 16 to 60 g m^{-2} for control woodlands and from 55 to 150 g m^{-2} for livestock stations. At site 1, cumulative nitrate concentrations for both land uses were similar, whereas at sites 2 and 3, these values were higher in livestock stations (Figure 5).

We found considerable variations among the different sites analysed for most variables, with the random factor explaining from 16·0% to 46·3% of the total variability for different response variables (Table IV). Groundwater measurements of nitrate concentrations were higher in the three livestock stations than in their paired control woodlands, salinity showed variations among the different sites analysed and pH had similar values at paired sites, except for site 2' (Table V).

Table IV. Results of generalized linear mixed model for soil variables from models (1 = without, 2 = with interactions), including variance of the random effects 'site', standard deviation (SD) and percentage of the variance explained by 'site' for each response variable (%).

Variable	Models	Variance	SD	%
Chloride	1	0·499	0·706	38·12
	2	**0·412**	**0·642**	**37·45**
Soil moisture	**1**	**0·012**	**0·112**	**15·98**
	2	0·0125	0·112	16·05
Nitrates	1	0·2854	0·534	43·09
	2	**0·2873**	**0·536**	**46·39**
pH	**1**	**0·1144**	**0·338**	**24·54**
	2	0·114	0·338	24·32
Salinity	1	0·179	0·424	41·97
	2	**0·180**	**0·424**	**43·53**

[a] The data of model with lower Akaike's information criterion index are highlighted in bold.

DISCUSSION

Land use indicators support our assumption of high-use intensity near livestock station. These results may be caused by the combined effects of grazing and logging, which are difficult to separate in our study site (Villagra *et al.*, 2009). Livestock (mainly goats) consume vegetation and disturb the soil through trampling, leading to increased bare soil and dung deposition, and reduced litter and pod abundance. In addition, local settlers remove and use wood and pods for different purposes, maintaining lower densities near livestock stations. Acting as the centres of animal concentration, pastoralist settlements and watering points have been shown to strongly modify nutrient cycles in other areas (Tolsma *et al.*, 1987; Bisigato and Bertiller, 1997; Bisigato *et al.*, 2005). Grazing may also promote establishment of woody seedlings (Asner *et al.*, 2004) by consumption and posterior deposition of hard seeds. Our results suggest that this effect is unimportant in our study

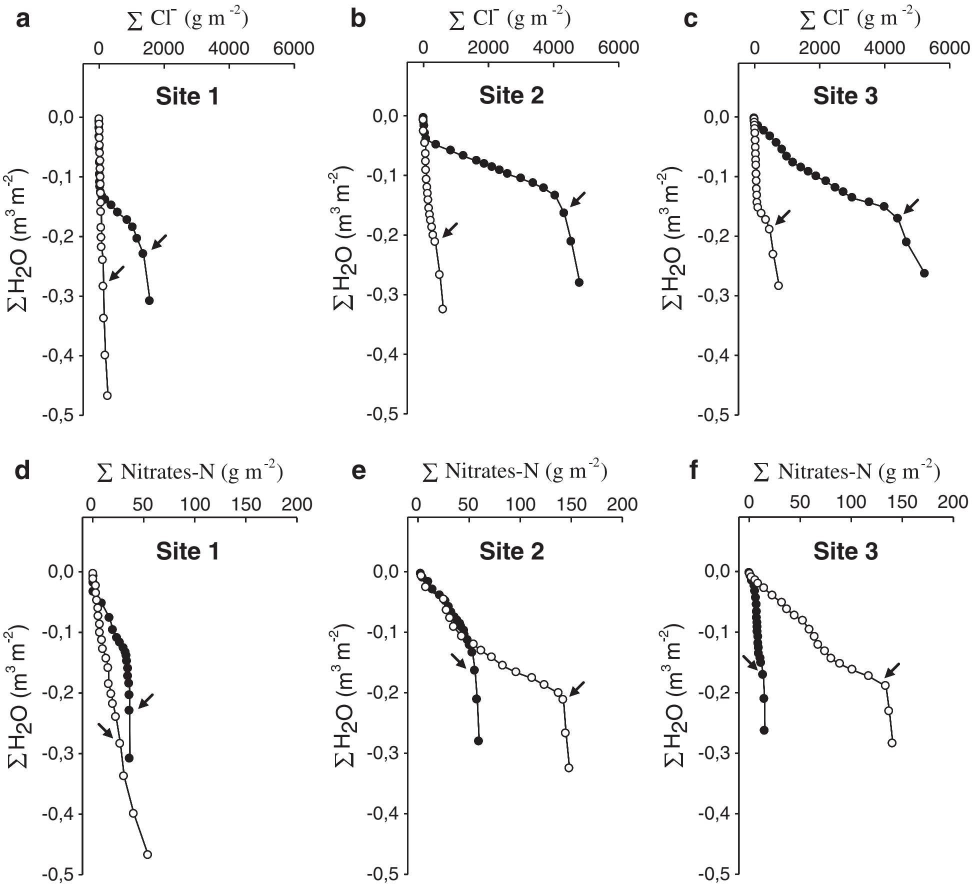

Figure 5. Cumulative chloride versus cumulative water content (a–c) and cumulative soil nitrate versus cumulative water content (d–f) in control woodlands (*filled circles*) and livestock stations (*open circles*). Each symbol represents a single measurement. Arrows indicate the beginning of the saturated zone.

Table V. Groundwater characteristics, including nitrate concentration, electric conductivity and pH.

Land use	Site	Nitrate ($mg\,l^{-1}$)	Electric conductivity ($ms\,cm^{-2}$)	pH
Livestock station	1	23·0	3·43	7·69
Control woodland	1	0·2	6·07	7·83
Livestock station	2	8·6	7·34	7·52
Control woodland	2	4·9	3·58	9·03
Livestock station	3	38·7	4·03	8·66
Control woodland	3	0·4	4·32	8·17

area (Table II). Perhaps the high intensity of livestock and human activities in the station prevents the successful establishment of *Prosopis* seedlings in the area.

Our results indicate a significant change in vegetation structure and composition with the establishment of livestock stations, as described for other arid areas (Asner *et al.*, 2004; Reynolds *et al.*, 2007). The lower vegetation strata (shrubs and grasses) were the most affected ones, whereas tree cover showed lower contrasts, possibly as a result of increasing tree size compensating for reduced density in livestock stations. Noticeably, large individuals of *P. flexuosa* are still present in stations, likely preserved by settlers as a source of shade and fruits for humans and livestock (Alvarez and Villagra, 2009). Because large trees are the most remarkable feature of vegetation in the area, common remote sensing indices and perception of local inhabitants may suggest a low effect of livestock stations on vegetation. However, total plant cover was lower in livestock stations, highlighting the importance of shrubs and grasses on the structure and composition of the woodland (Table II). At the Telteca Reserve sites, vegetation changes were also detected by soil-adjusted total vegetation index, showing gradients of landscape degradation, which decrease gradually with increasing distances to the pastoralist settlements (Goirán *et al.*, 2012). As a result, vegetation changes by livestock alter the belowground structure of plants (Milchunas and Lauenroth, 1993). In arid areas, woody species tend to be more deeply rooted than grasses and herbaceous plants (Bucci *et al.*, 2009; Villagra *et al.*, 2011). Vegetation shifts, such as a decrease in shrub and grass cover in livestock stations, may change vertical and horizontal root distributions and consequently modify the absorption of soil resources (Jackson *et al.*, 2000; Moore *et al.*, 2010).

The establishment of livestock stations affected biogeochemical and hydrological transport between the ecosystem and groundwater. The lower chloride, and higher moisture and nitrate contents in soils from livestock stations support our hypothesis that water and solute transport from the surface to the phreatic aquifer is facilitated in these areas, which function as foci of local deep drainage, nitrate leaching and groundwater pollution. Chloride concentration in soils, which is inversely proportional to the downward water flux (Scanlon, 1991; Phillips, 1994), indicated higher water percolation rates in livestock stations, similar to those reported for bare lowlands in a nearby active dune field (Jobbágy *et al.*, 2011). In control woodlands, chloride profiles (Figure 3) indicate that progressive evaporation and water extraction by plant roots are likely consuming all precipitation inputs, preventing recharge (Allison *et al.*, 1994; Phillips, 1994). In agreement with chloride concentrations, livestock stations showed the expected pattern of slightly lower soil salinities, probably given by solute transport to groundwater. Salts accumulated in the soils may also be transported to the aquifer with increasing local recharge and probably decrease groundwater quality.

The differences in water dynamics found between both land uses are likely caused by differences in plant biomass both aboveground and belowground. In woodlands, plant root systems can exhaustively absorb soil resources (water and nutrients) with their horizontally extended root system (Breshears and Barnes, 1999; Bucci *et al.*, 2011; Villagra *et al.*, 2011). Under the sparse vegetation of livestock stations, rainfall inputs have a better chance to escape root uptake and percolate to deep soil layers (deep drainage) (Seyfried *et al.*, 2005). Changes from native woodlands to pastures in semi-arid rangelands of southern Texas also modified water dynamics, decreasing chloride concentrations in the soil profile. Aquifer recharge was estimated to increase in root-plowed areas by about 2·6 mm $year^{-1}$ (Moore *et al.*, 2012), but the effects of these changes in groundwater quality were not considered.

Domestic animals seem to mediate the increased nitrate concentrations in soil profiles that we found in livestock stations (Figure 3). Biomass consumption in nearby woodlands, and transport and deposition of its associated nutrients as dung and urine in livestock settlements could change the vertical and horizontal distribution of nutrients at different scales (Tolsma *et al.*, 1987; Rossi, 2004). The observed variability of nitrate contents with depth in the different profiles may be related to spatial variability in vegetation (e.g. the presence of a tree near the profile), vegetation history (livestock station age and use), livestock behaviour (e.g. there might be preferential resting areas at different distances from each soil profile) and previous precipitation events at the different sites (Walvoord *et al.*, 2003; Jackson *et al.*, 2004). Nitrates accumulated in the soils of livestock stations are not completely absorbed by the scarce vegetation and may be leached to deep soils during intense rainfall events, forming underground nitrate reservoirs, as shown in other deserts of the world (Walvoord *et al.*, 2003; Austin, 2011). These nitrate reservoirs can reach groundwater with successive deep drainage events, affecting groundwater quality, as shown in the wells of our study sites and in other wells of the area (Aranibar *et al.*, 2011). If there are no mechanisms for the surrounding vegetation to recapture groundwater nitrates, this nitrate movement may represent net nitrogen losses from the ecosystem. However, groundwater flow, with estimated velocities from 0·1 to 0·25 m per day (Gomez *et al.*, 2010; Aranibar *et al.*, 2011), may transport this nitrate to neighbouring woodlands, where phreatophyte vegetation could absorb it and return it to the surface environment. Further studies are needed to determine the final fate of groundwater nitrate.

The curves of cumulative chloride versus water content (Figure 5) showed slope changes under both land uses. In control woodlands, maximum slope was approximately an order of magnitude higher than in livestock stations, whereas the same curves for nitrate versus water content showed an opposite pattern, with slopes being less than half of those found in livestock stations at two study sites. These contrasts suggest higher water drainage fluxes with higher nitrate contents along the soil profile of livestock stations. The combined effect of higher nitrate content in soil water and faster downward water fluxes suggests even faster nitrate transport rates beneath livestock stations compared with woodlands. A rough estimate of this increased transport can be achieved by comparing soil at intermediate depths (4·25–4·75 m) where little effects of both root uptake and capillary rise can be expected. The nitrate-N : chloride ratio is a good indicator of the nitrate transport difference increase and approached 20, 50 and 1100-fold increases at sites 1, 2 and 3, respectively. The extremely high value of site 3 suggests that nitrate flux in the control woodland is virtually nil. Accompanying this trend, groundwater nitrate concentrations in the three livestock stations were higher than in their paired control woodlands (Table V). None of the groundwater samples exceeded the recommended local drinking water standards ($45\,\mathrm{mg\,l^{-1}}$; Código Alimentario Argentino, 2007), but two of them exceeded those accepted in the USA ($10\,\mathrm{mg\,l^{-1}}$; Environmental Protection Agency, United States, 2009). In the region, domestic wells for human and animal use are often found a few metres from corrals or livestock gathering areas.

Traditional, subsistence livestock production is the main economic activity in this challenging environment (Torres, 2008; Guevara *et al*., 2009). Because government authorities are granting land rights and providing some basic services (e.g. drinking water supply in access roads and installation of solar panels in settlements) to Huarpe communities, density of livestock stations in the reserve and surrounding areas may increase in the near future. Therefore, management programs are crucial to maintain or improve forests and groundwater quality (Alvarez *et al*., 2006). For example, new livestock stations should consider these observations to locate wells in upstream and directions from corrals, to avoid groundwater pollution with nitrate. In addition, the practice of leaving adult *P. flexuosa* trees standing in livestock stations should be encouraged, to provide shade and fruits for domestic animals and reduce nitrate leaching.

Other arid and semi-arid systems may be similarly vulnerable to land use changes. Although vegetation removal has been shown to increase groundwater recharge in arid areas (Moore *et al*., 2012), nitrate, salt and surface contaminants may also be transported to the aquifer, decreasing groundwater quality. Our and previous studies (Jobbágy *et al*., 2011) show that vegetation activity prevents the downward movement of water and solutes, protecting groundwater from surface pollution.

CONCLUSION

This research reinforces the idea of a strong vegetation control over water and nitrogen cycles in arid lands and shows how human activities, even in low density grazing systems, can disrupt the interactions among vegetation, water and nutrients in the soil–plant–groundwater system. Disruptions of ecological processes by livestock activities clearly affect the hydrological links between surface and groundwater. The removal of vegetation by humans and domestic animals in livestock stations allows deeper water percolation, which transports nitrate deposited as dung and urine, an increasing groundwater nitrate concentration.

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