Effects of geomorphology and distribution of water sources for livestock on the floristic composition and livestock receptivity of the Arid Chaco

Efecto de la geomorfología y la distribución de las fuentes de agua para el ganado en la composición florística y receptividad ganadera del Chaco Árido

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Abstract

Livestock production in semi-arid areas is possible due to the presence of permanent water sources, which create a radial pattern of grazing intensity known as the piosphere. For this reason, we predicted that permanent water sources would negatively impact the ecological conditions of plant communities, leading to variations in livestock receptivity. To test this prediction, we compared grazing gradients in two geomorphological units, using distance to water sources as an indicator of accumulated livestock pressure. We assessed variations in the botanical composition of both areas by analysis of variance and principal components analysis. Additionally, we modeled the relationship between distance to water source and livestock receptivity. Our results revealed significant differences in the contribution of different species based on their distance to water sources. Notably, a non-linear regression model provided the best fit for the relationship between water source and livestock receptivity in both geomorphological units. These findings demonstrate that the distance to permanent water sources serves as a reliable indicator of accumulated livestock pressure in semi-arid regions like the study area.

Keywords
arid Chaco • natural grasslands • piosphere • geomorphology

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Resumen

La producción de ganado en zonas semiáridas es posible debido a la existencia de fuentes de agua permanentes, lo que genera un patrón radial de intensidad de pastoreo llamada piosfera. Por tal motivo, nuestra predicción se basa en que las fuentes de agua permanente influyen negativamente en las condiciones ecológicas de las comunidades vegetales provocando diferentes receptividades ganaderas. Comparamos gradientes de pastoreo tomando la distancia a las fuentes de agua como indicador de presión ganadera acumulada en dos unidades geomorfológicas. La variación en la composición botánica de las diferentes áreas se realizó utilizando análisis de la varianza y un análisis de componentes principales. Se efectuó un modelo de la relación entre la distancia a la fuente de agua y la receptividad ganadera. Nuestros resultados mostraron diferencias significativas en la contribución de las diferentes especies en relación con la distancia a las fuentes de agua. El modelo de regresión no lineal fue el que mejor se ajustó entre la fuente de agua y la receptividad ganadera para ambas unidades geomorfológicas. La distancia a las fuentes de agua permanente es un buen indicador de la presión ganadera acumulada en regiones semiáridas como el área de estudio.

Palabras clave
Chaco árido • pastizales naturales • piosfera • geomorfología

Introduction

Like other arid and semi-arid regions, the Arid Chaco exhibits heterogeneous spatial patterns of degradation driven by the uneven distribution of drinking throughs (4, 19). The availability of permanent water sources is critical for livestock production in these areas. Consequently, a radial pattern of grazing intensity, known as 'piosphere,' develops around water sources. Analysis of piospheres allows to quantify the effects of radial attenuation of a disturbance on the system's condition (8).

Piospheres are areas around water sources that suffer from heavy grazing and trampling, making it difficult for vegetation to establish (degraded zones) (22). Management practices near these water bodies often involve continuous grazing without rest periods for the land, leading to changes in plant composition (10). As a result, plant communities near water sources are dominated by annual grasses and/or species with little grazing value (23).

Grassland dynamics can be conceptualized using a state-and-transition model (STM), which describes vegetation as existing in discrete states with transitions triggered by natural events or management practices (5, 38). Within an STM framework, each state represents a distinct plant community reflecting the current ecological conditions relative to a climax community. Transitions within a state are considered reversible, while transitions between states can be irreversible depending on disturbance severity (26, 36).

In interaction with livestock, geomorphology shapes the spatial patterns and dynamics of plant communities (27). In arid and semi-arid environments, water availability is the primary control of vegetation structure and function, surpassing even the influence of the physical and chemical characteristics of each geomorphological unit (24). Recent sedimentary environments, are particularly sensitive to the colonization strategies employed by vegetation given the specific arrangement and structures of their deposits (15).

Evaluating the impact of grazing on ecosystem integrity becomes difficult, especially in systems where the original condition is unknown given widespread and irreversible transformations of plant communities (10). Furthermore, when a system has surpassed a critical threshold and transitioned to an alternative stable state, experiments utilizing grazing exclusion methods may yield misleading interpretations (9).

An alternative approach to evaluate grazing is to interpret current vegetation assemblages in the context of accumulated livestock pressure and associated management practices. Proxy indicators such as proximity to water sources (1), livestock posts (32), and even specific plant growth forms or species abundance (13, 18) can be employed for this purpose. These approaches often provide solid information to inform management decisions, particularly when time constraints prevent reliance on long-term grazing trials (10).

This study investigates the impact of extensive livestock farming on botanical composition and livestock receptivity within distinct geomorphological units of the Arid Chaco region in San Juan, Argentina. We aim to contribute to the understanding of the ecological state of plant communities in semi-arid areas assessing livestock receptivity potential and informing sustainable management strategies. The study area exhibits diverse plant communities with varying physiognomies, shaped by the combined effects of livestock farming, forestry exploitation, and interactions with geomorphological processes.

Within this framework, our study hypothesizes that botanical composition within each geomorphological unit varies in response to distance from water sources. This prediction is based on permanent water sources negatively influencing the ecological states of plant communities, leading to differential livestock receptivity.

Materials and methods

Study area

The study area covers approximately 1000 km^2 within the Valle Fértil department, located between parallels 30°50' and 30°29' S and meridians 67°27' and 67°12' W. It is located east of the Sierras de Valle Fértil-La Huerta within the Bajo Oriental depression, bordering La Rioja to the east. This region represents a unique and characteristic expression of the Arid Chaco in San Juan, exhibiting distinctive physiographic, climatic, social, and productive features. Its climate is classified as arid (BWk) according to the Köppen-Geiger system (20), with an average annual temperature of 17.9°C. Precipitation falls within the 200-300 mm isohyets. The vegetation comprises an open forest dominated by *Aspidosperma quebracho blanco*, *Neltuma flexuosa*, and *Bulnesia retama*. A shrub layer rich in *Larrea divaricata* is present, while the herbaceous layer is well-represented by genera such as *Leptochloa*, *Setaria*, *Aristida*, and *Pappophorum*, among others.

Basin delimitation

A high-resolution (12.5-meter pixel size) Alos Palsar Digital Elevation Model (DEM) was used to delineate the basins. Flow direction derived from the DEM was employed to identify the basins associated with the main channels within the study area. GRASS GIS software, a free and open-source module linked to QGIS 3.14.15 (30), was used for the digital processing of the DEM.

Given the study area corresponds to a plain, vectors representing the mountain range were excluded from the analysis. Consequently, sampling was focused on the geomorphological units of the foothills (Piedemonte) and the river floodplain (Floodplain) (figure 1, page 15).

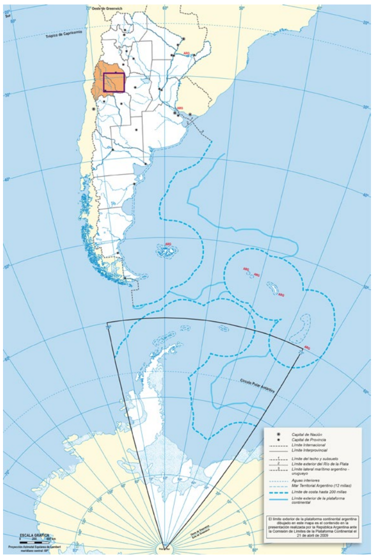
Location of livestock posts

The study area encompasses a diversity of fenced enclosures with varying surface areas. Each enclosure has a water source (dam, well, or drinker) for livestock located in the vicinity of the post. All sampled fields employed a continuous grazing regime, where cattle roam freely with unrestricted access to a central water source. During periods of extreme drought, ranchers are forced to either sell animals at a reduced price or pay to graze them in fields with superior forage availability.

This study adopts the methodology proposed by Cingolani *et al.* (2008), who emphasizes the value of distance to permanent water sources as an objective, measurable, and precise indicator for assessing the long-term effects of extensive grazing.

Establishment of distance ranges

Given the extensive grazing behavior of livestock in the Arid Chaco region (16), we categorized sampling locations according to their distance to water sources: close range (0-1000 m), intermediate range (1001-2000 m), and far range (>2001 m). This approach was applied within each geomorphological unit (Piedemonte and Floodplain). Thirty 50-meter transects were established within each unit, with readings taken at 50 cm intervals along the transects (figure 1, page 15). In the Piedemonte, ten transects were located close to water sources (within 1000 m, designated PMC), ten at intermediate distances (1001-2000 m, PMI), and ten at a far range (>2001 m, PML). Similarly, in the Floodplain, ten transects were placed near water sources (<1000 m, PLC), ten at intermediate distances (1001-2000 m, PLI), and ten at a far range (>2001 m, PLL) (figure 1).



Fuente/Source: IGN (Instituto Geográfico Nacional, República Argentina).

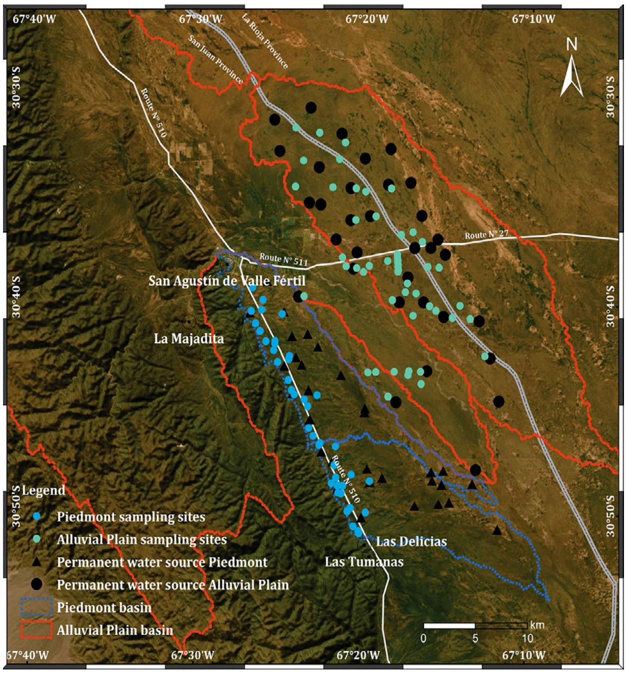


Figure 1. Location of study sites on the Arid Chaco phytogeographic province of San Juan and La Rioja, Argentina. Projection: Posgar 2007; Argentina/2; EPSG: 5344.

Figura 1. Ubicación de los sitios de estudio en la Provincia Fitogeográfica del Chaco Árido de la provincia de San Juan y La Rioja, Argentina. Proyección: Posgar 2007; Argentina/2; EPSG: 5344.

Determination of botanical composition

Botanical composition was quantified at peak growing season using the modified Point Quadrat method (28) in April and May, following the rainy season. The resulting data were then used to calculate percent coverage and specific contribution per contact (CSC) for each species.

$$CSC = \frac{C}{\sum C} * 100$$

where:
C = Contacts of a species
ΣC= Sum of the contacts of all species

Determination of field forage receptivity for bovine cattle

Livestock receptivity refers to the amount of forage required to sustain an Equivalent Cow Unit (EV). An EV is defined as a 400 kg cow that gestates and raises a calf to 6 months old (weighing 160 kg), including the forage consumed by the calf (Passera, C.P.Q.). One EV can be supported by 100 Pastoral Value (VP) units.

Plant species for calculating Pastoral Value (VP) were selected based on established criteria for determining specific quality indices (19, 29). Table 1 (page 16-19), presents their classification according to livestock preference: Preferential (P) - readily consumed species without selection; Good (G) - species initially rejected compared to Preferential ones; Regular (R) - species presenting some difficulty in consumption.

Table 1. Contribution of each species, total coverage, and diversity indices in each sector considered for sampling within each Geomorphological Unit separately.

Tabla 1. Aporte de cada especie, cobertura total e índices de diversidad en cada uno de los sectores considerados para el muestreo en cada Unidad Geomorfológica por separado.

	Geomorphological Units								
	Piedemonte				**Floodplain**				
	PML	**PMI**	**PMC**	**C**	**PLL**	**PLI**	**PLC**	**C**	**S**
Species	**Perennial Grasses**								
Leptochloa pluriflora	11.03c	-	2.48b	0.54	15.25d	10.36d	-	0.63	P
Gouinia paraguayensis	2.49b	0.63a	0.52a	0.54	1.34e	2.45d	2.78d	-0.48	P
Setaria lachnea	5.23b	5.99b	0.16c	0.5	1.21d	0.54d	-	0.62	P
Setaria leucopila	5.93b	6.73b	3.84a	0.32	6.96d	6.00d	-	0.49	P
Setaria cordobensis	0.64	-	-	0.44	-	-	-	-	P
Digitaria californica	1.71b	2.16b	0.47a	0.41	0.60d		0.52d	0.19	P
Cenchrus ciliaris	-	0.16	-	0.04	-	-	-	-	P
Cottea pappophoroides	1.63b	0.68a	1.60b	-0.09	-	-	-	-	G
Setaria hunzikeri	1.9	-	-	0.55	-	-	-	-	P
Pappophorum philippianum	1.32a	4.85b	11.12b	-0.48	-	-	-	-	P
Neobouteloua lophostachia	0.87a	2.41b	4.06b	-0.43	0.92d	2.34d	10.75e	-0.59	R
Leptochloa crinita	16.34a	1.73b	0.53b	0.56	1.13d	1.84d	-	0.33	P
Leptochloa dubia	0.34	-	-	0.56	-	-	-	-	P
Chloris parvispicula	0.79	-	-	0.34	-	-	-	-	P
Aristida medocina	-	-	0.18	-0.58	11.14d	1.14e	2.78e	0.71	P
Setaria sp	-	-	-		0.81	-	-	0.65	P
Sporobolus pyramidatus	0.17a	0.31a	-	0.29	0.40d	-	1.08d	-0.3	G

Different letters indicate significant differences (P < 0.05). The column labeled C represents the correlation of each species, total coverage, and diversity indices with respect to the distance from water sources. Significant correlations (P < 0.05) are indicated by grayed cells.

Letras diferentes indican diferencias significativas (P<0,05). La columna indicada con C representa la correlación de cada especie, cobertura total e índices de diversidad, respecto de la distancia con las fuentes de agua. Las correlaciones significativas (P<0,05) se indican con los casilleros pintados de gris.

Geomorphological Units									
	Piedemonte				Floodplain				
	PML	PMI	PMC	C	PLL	PLI	PLC	C	S
Annual Grasses									
Bouteloua aristoides	7.21a	19.85b	31.13b	-0.55	-	-	-	-	R
Eragrostis mexicana var. virescens	0.84b	-	0.38b	0.34	-	-	-	-	G
Aristida adscensionis	0.13a	0.81a	1.28a	-0.49	2.36d	-	0.36d	0.38	R
Tripogon spicatus	2.03	-	-	0.55	-	-	-	-	R
Shrubbery									
Larrea divaricata	9.05a	17.86b	20.26b	-0.75	30.82d	33.97d	55.71e	-0.74	-
Lippia turbinata	0.48b	-	0.38b	0.16	-	-	-	-	-
Mimozyganthus carinatus	1.30a	5.92a	1.26a	0.05	4.54	-	-	-	R
Cordobia argentea	0.60ab	0.68b	0.16a	0.43	5.60d	16.51e	8.65d	-0.24	G
Capparis atamisquea	0.48	-	-	0.55	-	-	-	-	R
Senna aphyla	1.95a	7.49b	0.49c	0.17	0.46d	5.65e	1.20d	-0.1	R
Pithecoctenium cynanchoides	0.67	-	-	0.56	-	-	-	-	-
Lantana fucata	1.74a	0.54b	-	0.67	-	-	-	-	-
Senegalia gilliesii	0.12a	-	0.57a	-0.35	-	-	-	-	R
Lippia integrifolia	1.00a	-	1.88a	-0.24	1.38	-	-	0.56	-
Ximenia americana	-	0.51a	0.65a	-0.58	-	3.57	-	-0.02	-
Aloysia gratissima	1.05a	0.16b	-	0.72	-	-	-	-	-
Condalia microphylla	0.51	-	-	0.56	-	0.54	-	-0.06	R
Tillandsia sp	0.13a	-	0.16a	-0.18	-	-	-	-	R
Lantana grisebachii	-	2.93a	5.00a	-0.67	-	-	-	-	-
Strombocarpa torquata		2.38a	0.47b	-0.1	0.44d	5.66e	8.34e	-0.74	R
Salvia gilliesii	-	-	-	-	0.23	-	-	0.56	-
Cereus aethiops	-	-	-	-	0.23	-	-	0.56	-
Ephedra triandra	-	-	-	-	0.21	-	-	0.45	G
Lycium chilensis var. filifolium	1.02c	0.33a	0.34a	0.53	0.23	-	-	0.56	R
Justicia gilliesii	2.89a	-	0.38b	0.55	-	-	-	-	G

Different letters indicate significant differences (P<0.05). The column labeled C represents the correlation of each species, total coverage, and diversity indices with respect to the distance from water sources. Significant correlations (P<0.05) are indicated by grayed cells.

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	Geomorphological Units								
	Piedemonte				Floodplain				
	PML	PMI	PMC	C	PLL	PLI	PLC	C	S
Mimozyganthus carinatus	1.30a	5.92a	1.26a	0.05	4.54	-	-	0.66	R
Lantana xenica	-	-	0.18	-0.58	-	0.31d	3.31e	-0.68	-
Tricomaria usillo	-	-	0.18	-0.58	1.38d	3.92e	0.96d	0.07	G
Forestry									
Parkinsonia praecox var praecox	3.53a	2.55a	3.65a	3.00E-03	0.42e	1.92d	-	0.06	R
Celtis tala	0.66a	0.16a	-	0.36	-	-	-	-	R
Neltuma flexuosa	8.27a	0.33b	1.30b	0.53	2.11d	2.01d	3.13d	-0.26	G
Geoffroea decorticans	-	-	-		6.75d	1.18d	0.52e	0.81	G
A quebracho blanco	-	2.44b	0.19b	0.01	-	-	-	-	-
Bulnesia retama	0.51a	4.39b	0.16a	0.06	-	-	-	-	-
Dicotyledonous herbaceous plants									
Bidens subalternans	0.29b	-	0.38b	-0.06	-	-	-	-	-
Pseudabutilon virgatum	0.25a	0.18a	0.95a	-0.37	-	-	-	-	-
Zinnia pruviana	0.25a	-	0.19a	0.1	-	-	-	-	-
Talinum polygaloides	-	-	0.18	-0.58	-	-	-	-	-
Gaya parvifolia	0.46a	0.16a	-	0.72	0.69d	-	0.52d	0.14	-
Amaranthus standleyanus	0.26	-	-	0.34	-	-	-	-	-
Gomphrena pulchella	0.34a	-	0.19a	0.27	-	-	-	-	-
Tribulus terrestris	0.12	-	-	0.56	-	-	-	-	-
Parthenium hysterophorus	0.13a	0.18a	-	0.25	-	-	-	-	-
Euphorbia catamarcensis	0.67	-	-	0.56	-	-	-	-	-
Sphaeralcea miniata	0.56a	1.88a	1.90a	-0.29	-	-	-	-	-
Allionia incarnata	0.13a	1.93b	1.14ab	-0.27	-	-	-	-	-
Heliotropium mendocinum	-	0.18	-	0.03	-	-	-	-	-
Porophyllum lanceolatum	-	0.16	-	0.04	-	-	-	-	-
Portulaca grandiflora	-	-	0.18	-0.58	-	-	-	-	-
Solanum elaeagnifolium	-	-	0.18	-0.58	-	-	0.52	-0.5	-

Different letters indicate significant differences (P<0.05). The column labeled C represents the correlation of each species, total coverage, and diversity indices with respect to the distance from water sources. Significant correlations (P<0.05) are indicated by grayed cells.

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	Geomorphological Units								
	Piedemonte				Floodplain				
	PML	PMI	PMC	C	PLL	PLI	PLC	C	S
Diversity Coverage and Indexes									
Coverage	94.89a	88.96b	70.37c	-0.21	73.14d	67.78d	53.45e	0.63	
Shannon - Weaver	2.92a	2.54b	2.23c	0.68	2.21d	2.07d	1.58e	0.78	
Simpson	0.08a	0.12a	0.2b	-0.57	0.16c	0.19c	0.34d	-0.73	

The Pastoral Value (VP) is calculated by the following formula:

$$VP = 0.1 * (CSC * Is)\, Cf$$

where:
0.1 = constant coefficient
CSC = Specific Contribution per Contact
Cf = Forage Coverage
Is (Specific Quality Index) = ranging from 1 to 10, representing the classification of species based on their suitability and potential as forage.

Statistical analysis

Variation in botanical composition across different areas was explored using principal component analysis (PCA) based on a correlation matrix among all present species and their respective contact-specific contributions (CSC) within the community.

The influence of distance to water sources on botanical composition, diversity (Shannon-Weaver and Simpson), and total cover was assessed using analysis of variance (ANOVA) with a completely randomized design. Separate ANOVAs were conducted for each geomorphological unit (Piedemonte and Floodplain), treating distance categories (PMC, PMI, PML and PLC, PLI, PLL) as fixed effects. Additionally, a Pearson correlation analysis was performed to explore relationships between plant species, diversity indices, and total coverage. Data were square root transformed to address non-homoscedasticity and normality violations. Means were compared using Tukey's test. Data results are presented using untransformed means for ease of interpretation.

Visual exploration of the data involved plotting livestock receptivity against distance to water sources for each geomorphological unit. This analysis revealed a negative correlation up to a certain distance, followed by a plateau effect. Consequently, non-linear models were fitted for each unit to account for this observed pattern (12).

Results

Botanical composition

A total of 26 families were recorded, with *Poaceae* being the best-represented family, comprising 22 species. *Fabaceae*, *Verbenaceae*, and *Asteraceae* followed in abundance, with 7, 6, and 4 species, respectively.

The Piedemonte plant community is dominated by *Leptochloa crinita*. Additionally, *Leptochloa pluriflora*, *Bouteloua aristoides*, *Setaria leucopila*, *Setaria lachnea*, and *Gouinia paraguayensis* are present in PML sectors. In PMI and PMC sectors, the *Bouteloua aristoides* contribution increases, while the contributions of other grass species (except *Setaria leucopila* and *Setaria lachnea*, which maintain their presence in the PMI sector) decrease.

The Piedemonte shrub layer is dominated by *Larrea divaricata*, accompanied by *Mimosiganthus carinatus,* and *Senna aphylla*. The forest layer exhibits a distinct zonation: *Prosopis flexuosa* dominates in PML sectors, *Bulnesia retama* in PMI sectors, and *Aspidosperma quebracho blanco* occurs at low densities across all sectors.

Within the Floodplain, shrub communities dominate the vegetation structure. *Larrea divaricata* is the most abundant species, with accompanying species *Cordobia argentea* and *Mimozyganthus carinatus* in PLL sectors. In PLI sectors, shrub species with increased contributions include *Cordobia argentea*, *Senna aphyla*, and *Prosopis torquata*. Similarly, *Larrea divaricata* shows a significant increase in contribution within PLC sectors, accompanied by *Prosopis torquata*, *Lantana xenica*, and *Cordobia argentea*.

Following the shrub layer, grasses contribute significantly to the Floodplain community. *Aristida mendocina* and *Leptochloa pluriflora* are the most prominent grasses, with *Setaria leucopila* present to a lesser extent in PLL sectors. However, in PLC sectors, *Leptochloa pluriflora* disappears, and *Aristida mendocina* abundance declines significantly. Conversely, *Neobouteloua lophostachia* becomes the dominant grass species.

The forest layer plays a minor role in the Floodplain, with *Geoffroea decorticans* being the most prevalent species in PLL sectors, while *Prosopis flexuosa* dominates in PLI and PLC sectors (table 1, page 16-19).

Across both geomorphological units, total coverage and the Shannon-Weaver diversity index exhibit a significant rise with increasing distance from water sources. Conversely, Simpson's dominance index shows a significant positive correlation with proximity to water sources (table 1, page 16-19).

Principal Component Analysis (PCA) revealed a variation pattern in botanical composition across the sampled geomorphological units. The first two principal components explained 61% of the total species variance, effectively separating sectors within the Floodplain from those in the Piedmont. Within the Piedmont, sectors located close and halfway to water sources (PMC and PMI) were distinct from those situated further away (PML) (figure 2).

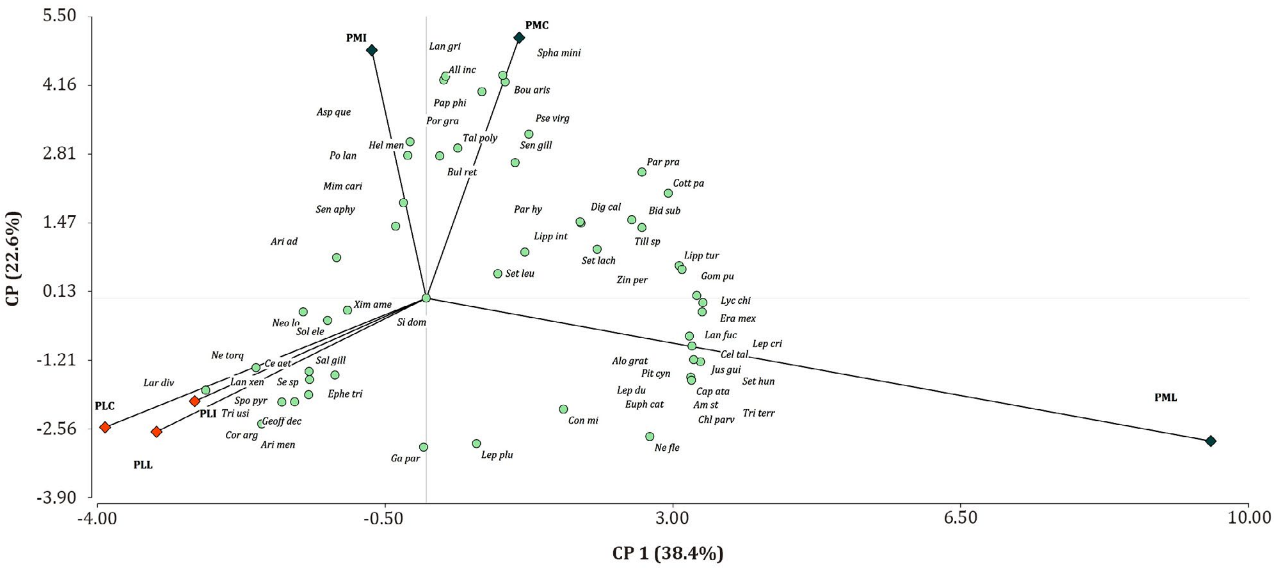

Figure 2. Principal Component Analysis (PCA) ordination diagram of sampling sectors (PMC, PMI, PML, PLC, PLI, PLL) and associated plant species.

Figura 2. Diagrama de la ordenación del Análisis de Componentes Principales (ACP) de los sectores seleccionados para los muestreos (PMC, PMI, PML, PLC, PLI, PLL) y las especies asociadas.

Within the alluvial plain, CP1 and CP2 displayed the most negative values for *L. divaricata* (Lar div), *C. argentea* (Cor arg), *T. usillo* (Tri usi), and *G. paraguayensis* (Ga par). In contrast, within the floodplain and specifically PML sectors, CP1 exhibited the most positive values for *J. gilliesii* (Jus gui), *L. chilensis var. filifolium* (Lyc chi), *S. cordobensis* (Set cor), *L. crinita* (Lep cri), *C. tala* (Cel tal), *N. flexuosa* (Ne fle), and *L. pluriflora* (Lep plu). Similarly, positive values in CP2 were associated with PMI and PMC sectors for *B. aristoides* (Bou aris), *A. quebracho blanco* (Asp que), *S. miniata* (Spha mini), *A. incarnata* (All inc), *L. grisebachii* (Lan gri), *P. philippianum* (Pap phi), *H. mendocinum* (Hel men), and *P. lanceolatum* (Po lan) (figure 2, page 20).

Livestock receptivity and distance to water sources

Non-linear regression analysis proved the best fit between livestock receptivity (Ha.EV^{-1}) and distance to water sources (DP), for both the Piedemonte (PM) and Floodplain (PL) units (figure 3).

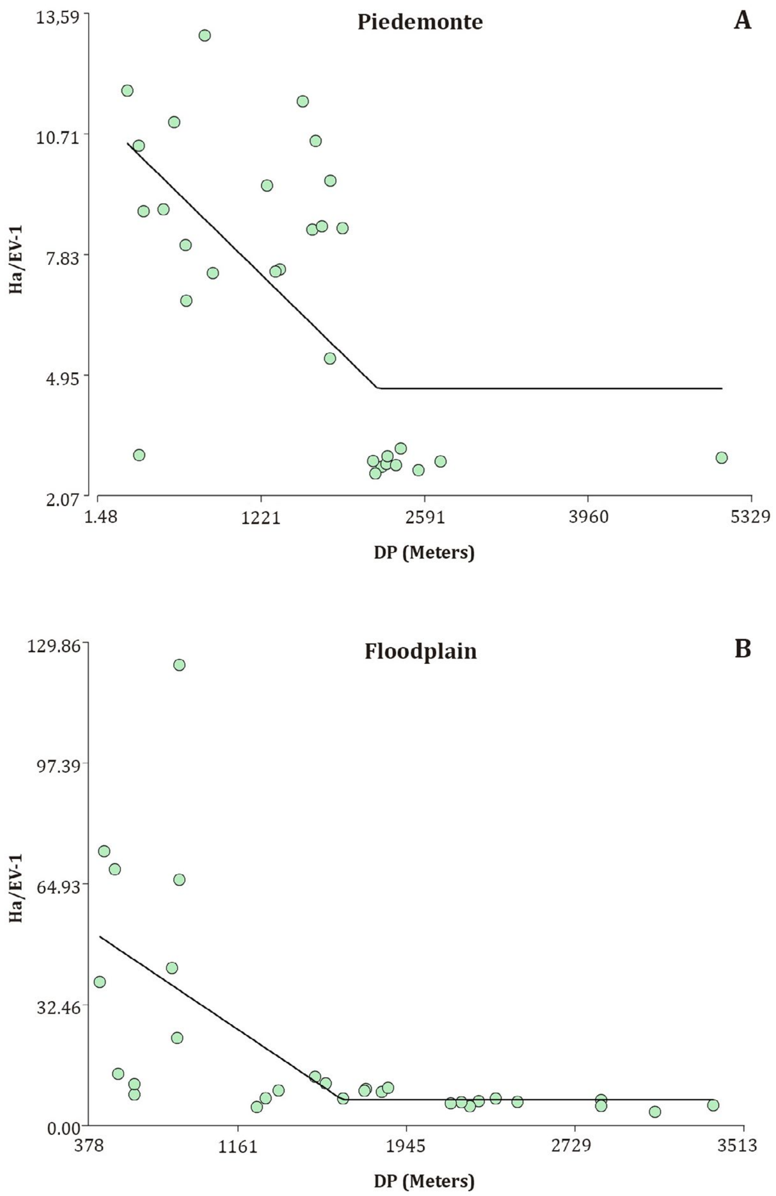

Figure 3. Non-linear regression model between livestock receptivity (Ha.EV^{-1}) and distance to water source (DP) in the Piedemonte (A) and Floodplain (B).

Figura 3. Modelo de regresión no lineal entre la receptividad ganadera (Ha.EV^{-1}) y la distancia a la fuente de agua (DP) en el Piedemonte (A) y en la Planicie de inundación (B).

Discussion

Our findings reveal changes in floristic composition across both geomorphological units, with distance to water sources playing a significant role (figure 2, page 20 and table 1, page 16-19). The study area is characterized by fenced fields of varying sizes and shapes, along with an irregular distribution of watering holes, dams, and/or livestock shelters. This heterogeneity contributes to a highly diverse botanical composition within plant communities. Szymañski *et al.* (2022) attribute similar variations primarily to livestock management practices. Specifically, our results indicate the presence of plant communities dominated by perennial forage grasses and others dominated by non-forage annual grasses. In such cases, the potential for transition towards improved ecological conditions exists due to the presence of seed sources from desirable species, facilitating the natural rehabilitation of nearby degraded areas (10).

The results align with established patterns of overgrazing documented by Briske *et al.* (2006), where plant communities near water sources (PMC and PLC) are dominated by annual grasses and/or non-forage species (table 1, page 16-19). While grazing responses vary among species, when grazing pressure alters biotic structures and interactions changes in species coverage can be attributed to underlying biotic mechanisms of grazing impact. Several studies support this notion, demonstrating that grazing pressure favors plant traits associated with rapid growth, regeneration, annual life cycles, and a ruderal strategy (11, 14, 32).

Across the geomorphological units, perennial grasses exhibited a significant trend of increased colonization away from water sources (table 1, page 16-19). Conversely, annual grasses and species with low forage value showed the opposite pattern. This aligns with established knowledge on grazing pressure inducing species turnover, favoring some species while hindering others (10). Briske *et al.* (2006), further suggests that heterogeneous livestock use is common in homogeneous landscapes (*i.e.*, within a single geomorphological unit). This heterogeneity contributes to an increase in landscape physiognomic diversity. However, increased livestock density can lead to a decline in unused areas (37). While maintaining some level of unused sites is important for overall community coexistence (10), excessively large paddocks with few water sources or shelters may allow even high livestock densities to coexist with unused areas (21, 26).

Total coverage and Shannon-Weaver diversity in the geomorphological units exhibited a significant decrease near water sources (table 1, page 16-19). Conversely, Simpson's dominance index shows a positive trend in these areas. This pattern aligns with observations in other semi-arid African grasslands, where grazing-sensitive forage species are replaced by those more resistant to grazing. However, this replacement may not fully compensate for diversity losses, potentially leading to environments dominated by a few resilient species. In this context, grazing regimes exceeding the historical range experienced by the ecosystem are likely to induce a significant decline in overall diversity (16).

The observed variations in floristic composition may be explained by mechanisms of resilience to harsh conditions proposed by Cingolani *et al.* (2008) for arid and semi-arid grasslands. These mechanisms, such as reduced sprouting and production of long-lived seeds, can confer some resistance to short periods of intense grazing. However, this resilience is insufficient to withstand continuous grazing for extended periods, particularly under moderate to high grazing pressure. A study evaluating intensity versus grazing strategies in perennial forage grasses of the Arid Chaco region found that while increased defoliation intensity may maximize short-term biomass yield, it negatively impacts long-term sustainability and produces detrimental residual effects on grasslands (31). Importantly, the study identified continuous grazing combined with high defoliation intensity as the least sustainable management practice for this ecosystem (31).

In these systems, continuous grazing by introduced herbivores without proper stocking management is highly likely to cause widespread extinctions and/or significant declines of specific plant species (10, 21, 25). However, a contrasting recovery trajectory may emerge when degradation and/or extinction of desirable species occurs homogenously across large areas (several square kilometers) and grazing pressure is subsequently relieved (10, 21). An alternative stability perspective for degraded ecosystems emphasizes persistence relative to the livelihood needs of ecosystem users. If the timeframe for ecosystem recovery surpasses user tolerance, typically a few years to a decade, the degraded state can be considered persistent from a practical viewpoint. Therefore, a 'persistent decline' of an ecosystem service may not always be associated with a critical threshold and a shift to a new ecological state. Slow recovery within a single stability domain can also lead to persistent declines (23).

Livestock receptivity values in this study range from 47.02 to 2.86 $Ha.EV^{-1}$ (figure 3, page 21). These values are consistent with observations from other arid and semi-arid regions in Patagonia (23), Puna, Monte, and the driest parts of the Arid Chaco, where reported livestock receptivities typically exceed 6 $Ha.EV^{-1}$ (3). Nevertheless, the value of 8.92 $Ha.EV^{-1}$ measured in the PMC sector deviates from historical data for degraded foothills, which reported values around 24 $Ha.EV^{-1}$ (33). This discrepancy may be attributed to interannual precipitation variations, known to cause substantial differences (>300%) in grassland productivity within degraded areas of the Arid Chaco (11).

Despite using the same model for both geomorphological units, the estimated values and rates of change differed (figure 3, page 21). These non-linear relationships align with the findings of Sasaki *et al.* (2008), who highlight the non-linear nature of ecological patterns and processes in response to grazing pressure. Furthermore, the estimated values from our models are consistent with other studies conducted in the region (2, 7, 11). Additionally, the observed spatial patterns of vegetation change correspond to documented livestock grazing behavior in the Arid Chaco (16). This distribution pattern of livestock receptivity informs spatial dynamics within grazing plots, allowing for the establishment of criteria for plot size and water source distribution.

Conclusions

Across both geomorphological units, distance to water sources significantly influences floristic composition, which in turn affects livestock receptivity. Areas closer to water sources are dominated by annual grasses and/or non-forage species, resulting in lower livestock receptivity. Conversely, areas farther from water sources are dominated by perennial grasses with higher forage value, leading to increased livestock receptivity.

A long history of domestic grazing has shaped the heterogeneity of plant communities, influencing species diversity and dominance. This translates to a landscape with varying ecological conditions (good, fair, and bad) distributed in different proportions. Quantifying the extent of each condition is crucial for optimizing water source distribution and achieving biologically and economically sustainable grazing management strategies. Notably, non-linear models provided the best fit between distance to water sources and livestock receptivity for both geomorphological units under study (figure 3, page 21).

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