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Flora and vegetation of Lejía lagoon, a desert ecosystem of the high *Puna* in northern Chile

Flora y vegetación de la laguna Lejía, un ecosistema desértico de la puna alta en el norte de Chile

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ABSTRACT
The *puna* is an ecosystem located in the desert plateau above 3500 m elevation in the Andes Range that covers parts of north-eastern Chile, north-western Argentina, south-eastern Peru and mid-western Bolivia between 15° and 28° S latitude. Laguna Lejía is a shallow lake set in an endorheic basin, with high altitude steppe climate type, low temperatures and wide diurnal variation. Precipitation is concentrated in the summer; evaporation is very high and the relative humidity of the environment very low. The object of this study was to characterise the flora and plant associations present in this high, arid ecosystem. Intensive collecting and surveying was carried out in 2008, with the following products: (a) a catalogue of flora, including phytogeographic origin, life form, endemism and conservation state; (b) a phytosociological catalogue, and the characterization of the plant communities with their alpha and beta diversity. Thirty species of vascular plants were recorded, all native. Two plant associations were identified: *Pappostipa-Deyeuxia* (high Andean scrub) and *Puccinellia-Calandrinia*, corresponding respectively to the sub-desert steppe of the Atacama *puna* and the azonal vegetation associated with the Laguna Lejía wetland. The results justify the designation of the area as a priority conservation site for biodiversity by the government.

Key **words:** Desert vegetation, phytosociology, sub-desert steppe, wetland vegetation.

RESUMEN
La puna es un ecosistema ubicado en la meseta del desierto por encima de 3.500 msnm en la Cordillera de los Andes que cubre partes del noreste de Chile, el noroeste de Argentina, el sureste de Perú y el medio oeste de Bolivia, entre los 15 ° y 28 ° sur. Laguna Lejía es un lago poco profundo situado en una cuenca endorreica, con un clima de gran altura de estepa, con grandes variaciones de temperaturas. Las precipitaciones se concentran en el verano; la evaporación es muy alta y la humedad relativa del medio ambiente es muy baja. El objetivo de este estudio fue caracterizar la flora y las asociaciones vegetacionales presentes en este ecosistema árido. Se realizó una recolección intensiva en 2008, con los siguientes productos: (a) un catálogo de flora, de origen fitogeográfico, formas de vida, endemismo y estado de conservación; (b) un catálogo fitosociológico, y la caracterización de las comunidades de plantas con su diversidad alfa y beta. Se registraron treinta especies de plantas vasculares, todas nativas. Se identificaron dos asociaciones vegetales: Pappostipa-Deyeuxia *(matorral alto andino) y* Puccinellia-Calandrinia*; que corresponden respectivamente a la estepa subdesértico de la puna de Atacama; y la vegetación azonal está asociada con el humedal Laguna Lejía. Los resultados justifican la designación del área como un sitio prioritario para la conservación de la biodiversidad.*

Palabras clave: *Vegetación del desierto, fitosociología, estepa subdesértica; vegetación de humedales.*

Introduction

The *puna* is an ecosystem of the Central Andes of South America located in the desert plateaux above 3,500 m elevation; it covers parts of north-eastern Chile, north-western Argentina, south-eastern Peru and mid-western Bolivia. In Chile it extends from 17°30' to 28° S latitude, and westward from the country's eastern border for a width varying between 20 and 70 km. The *puna* is composed of sedimentary, volcanic and intrusive rocks, dating from the Palaeozoic to the Quaternary.

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The precipitations which fall on the Andean plateau are collected by drainage systems, characterised by an absence of perennial watercourses reaching the more depressed areas. Superficial water run-off infiltrates into fractures in the rock or clastic sedimentary material to form phreatic aquifers. Water is commonly found welling up in the form of springs (Risacher et al., 1999). At the lowest points of these basins small lakes and salt flats are formed. Paleoclimate studies show very limited recharging of the aquifers; the subterranean waters present today would be fossil waters generated at a time when the precipitation in the area was 2.5 times higher than present (Messerli *et al.*, 1997).

Gajardo (1995) places the area of Laguna Lejía in the high-Andean steppe region, high plateau and *puna* sub-region, which extends from the border with Peru and Bolivia to the Andean mountains of the Maule Region, at altitudes between 4,000 and 5,000 m. Seven plant formations are recognised in the extensive territory of this sub-region: high-Andean plateau steppe, high-Andean sub-desert steppe, pre-plateau scrub steppe, pre-*puna* scrub steppe, sub-desert steppe of the Atacama *puna*, desert steppe of the Andean salt flats and high-Andean desert of the Ojos del Salado, each with various plant communities or associations. Two large areas of endemism are recognised in the far north of Chile: one associated with the coast and the other with the Andes Range. The latter contains an endemism of 13.9% for Chile and 2.7% for the region (Squeo *et al*., 1998; Cavieres et al., 2002).

The flora and vegetation of the mountains of northern Chile are relatively well documented (e.g. Villagrán *et al.*, 1981; Arroyo et al., 1988; Teillier 1998, 2004; Teillier and Becerra, 2003); phytosociological studies have also been done (e.g., Gajardo, 1995; Luebert and Gajardo, 2005; Teillier and Becerra, 2003; Navarro and Rivas-Martínez, 2005). The highland is one of the most fragile and harsh environments of the Andean ecosystems, due to the combined effects of low temperatures and extreme aridity (Gutiérrez *et al.*, 1998). Wetlands of the highlands of northern Chile are under threat due to human activity, especially mining. The Chilean government has selected *a priori* several priority sites for conservation of biodiversity, including Laguna Lejía, so the aim of this study was to characterize the flora and vegetation associations present to assess, together with other components of biological diversity, its importance as a priority site.

Materials and methods

Study area

The study area is located in the Antofagasta Region of northern Chile (23º 30’ S; 67º 42’ W) (Fig. 1), at 4,350 m altitude in a desert depression. It lies in a hydrographic basin covering 329 km^2. The lake is shallow (1 m), covering 1.9 km^2, and endorheic (Grosjean, 1994); its hydrological parameters are controlled by subterranean springs. There is little precipitation, concentrated in summer, (< 200 mm/year), excessive evaporation (> 2,000 mm/year) and limited internal drainage (estimated at 40 l/min) (Grosjean, 1994). The lake is the remnant of a large glacial lake.

The geomorphological units form an amphitheatre, of which Laguna Lejía is the centre, surrounded by volcanoes. The average altitude of the surrounding volcanoes is 5,700 m, but their elevation from base to summit is only 800-900 m.

Methodology

Collecting and surveying was carried out in January 2008, obtaining the catalogue of flora and the phytosociological inventory (Fig. 1). Each species was identified and classified following APGIII classification (Bremer *et al.*, 2009), and its phytogeographic origin determined from specialised literature (e.g., Zuloaga *et al.,* 2008). The material collected was prepared as herbarium specimens and deposited in the collection of the Centro de Estudios Agrarios y Ambientales. The life forms were determined as proposed by Ellenberg and Mueller-Dombois (1966), and the degree of human disturbance to the place as proposed by Hauenstein *et al.* (1988), who consider the phytogeographic origin and the life forms (Raunkiaer’s biological forms) as measures of human disturbance. A catalogue of the flora was obtained, containing all the elements mentioned above and the records produced by the present study.

The phytosociological surveys (inventories) included 12 randomly selected 10x5 m plots (Table 1), using European phytosociological methodology (Braun-Blanquet, 1964). The aquatic and marsh vegetation of the wetlands associated with the area were also considered. The phytosociological tables were processed using the methodology proposed by Braun-Blanquet (1964). To name each community, generic names of the two species with the highest importance value given in inventories was used.

The table includes the frequency of each species, i.e. the number of inventories in which it is present. This frequency is indicated in absolute terms (F) and in terms of relative frequency (Fr), which indicates the percentage frequency of each species, taking the sum of all the frequencies as 100%. We also incorporated the total cover (C) and relative cover (Cr) of each species, the latter being

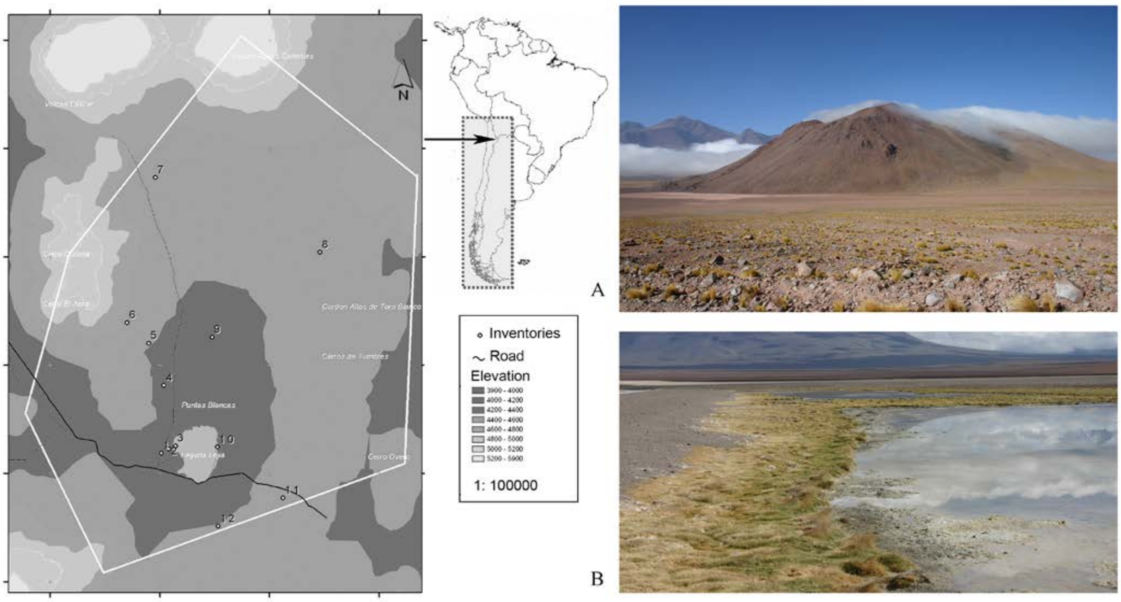

Figure 1. Study area. Numbering of inventory points in Laguna Lejía, northern Chile. A= sub-desert steppe of the Atacama puna. B= Azonal vegetation associated with the Laguna Lejía wetland.

Table 1. List and characterisation of the inventories of flora and vegetation in Laguna Lejía, northern Chile.

Inventories	coordinates (UTM)		altitude in	
	west	north	meters	plant formation
1	632049	7400753	4,361	scrub and herbaceous
2	632334	7400901	4,347	scrub and herbaceous
3	632571	7401021	4,341	herbaceous
4	632149	7403253	4,361	scrub
5	631596	7404811	4,419	herbaceous with scrub
6	630809	7405574	4,589	herbaceous with scrub
7	631843	7410930	4,563	bare soil
8	637846	7408169	4,577	herbaceous
9	633908	7405039	4,385	scrub and herbaceous
10	634099	7400972	4,350	herbaceous
11	636493	7499097	4,550	scrub and herbaceous
12	634130	7398049	4,406	scrub and herbaceous

the percentage of the total cover of the species, using the sum of all the covers as 100%. Species with little cover or only one individual are designated with the symbols + and r respectively. These symbols were replaced by the value 1 to calculate the Importance Value (IV) when the information was processed. This was determined for each species using the sums of the relative frequencies and covers (Wikum and Shanholtzer, 1978), thus reflecting the abundance and importance of each species at the study site.

The intra-environment diversity a was determined according to the Shannon-Wiener diversity index, which quantifies the total diversity of a sample and has two basic components: richness and evenness. It thus considers the importance value of each species and expresses the uniformity of the importance values across all the species in the sample. The formula for this function is: $H' = -\Sigma (p_i \times \log_2 p_i)$, where p_i is the proportion of the total number of individuals of the species in question in the sample. Its value ranges from zero, when there is only one species, to the maximum (H'max) which corresponds to $\log_2 S$, where S is the number of species. Pielou's evenness index (J) was also calculated according to the equation: $J = H'/H'max$. This index quantifies the contribution of the evenness to the total diversity observed. Its value fluctuates between 0 (minimum heterogeneity) and 1 (maximum heterogeneity, i.e. the species are equally abundant) (Magurran, 1998). The inter-environment diversity b was calculated using the Bray-Curtis Index (1957), using the BioDiversity Professional programme.

Results

Flora

The catalogue of flora is shown in Table 2, in which the 30 species recorded are characterised (two taxa were identified only to genus). The species are distributed taxonomically into 20 Eudicotyledoneae (66.7%) and 10 Monocotyledoneae (33.3%).

The best represented families are Poaceae (six genera – nine species) and Asteraceae (four genera – four species). The biological spectrum (Table 2) shows the presence of 18 hemicryptophytes (perennial herbaceous plants) (60.0%); 8 chamaephytes (sub-shrubs) (26.6%); 2 cryptophytes (geophytes and hydrophytes) (6.7%) and 2 therophytes (6.7%), including annual and biannual plants. The phytogeographic origins are shown in Table 2, which indicates that 27 species are native (90.0%) and 3 are endemic (10.0%). No allochthonous species were recorded for the study area, which is therefore categorised as "without intervention" and pristine.

Phytosociology

The conglomerates analysis distinguished two groups, with no species in common. Table 3 shows the phytosociological results which confirm these groupings, identifying two plant communities: *Puccinellia-Calandrinia* (A) and *Pappostipa-Deyeuxia* (B).

Puccinellia-Calandrinia is an herbaceous community (inventories 3 and 10). It is poor in species (only six); the principal ones are *Puccinellia frigida, Calandrinia compacta, Xenophyllum incisum* and *Arenaria rivularis*. The community is hygrophilous in type, since its component species are typical of marshland or the verge zone of water bodies, representing the wetland vegetation of Laguna Lejía.

Pappostipa-Deyeuxia is an herbaceous and low shrub community (inventories 1, 2, 4 to 9, 11 and 12), with 24 species, notably *Pappostipa frigida, Nassella nardoides, Deyeuxia cabrerae*, *D. antoniana*, *Junellia pappigera, Mulinum crassifolium, Pycnophyllum bryoides* and *P. macropetalum*. The importance values of the species, in decreasing order, were: *Pappostipa frigida, Deyeuxia cabrerae*, *Junelliapappigera, Puccinellia frigida* and *Mulinum crassifolium*.

Diversity

Table 4 shows the alpha diversity analysis. The high Andean scrub *Pappostipa-Deyeuxia* (S= 24) presents greater species richness than the azonal hygrophilous community *Puccinellia-Calandrinia* (S= 6); the Shannon-Wiener evenness index of the latter is higher, in other words its species, however, few in number, are better represented than those of the high Andean scrub, where a small number of species predominate. Comparison of the two communities shows that they are completely dissimilar (100%), and therefore present maximum beta diversity.

Discussion

The vegetation recorded around Laguna Lejía coincides with that expected in ecosystems located in captive salt flat depressions of the pre-plateau, with isolated, intermontane, saline lacustrine basins dominated by a high-altitude steppe climate. The best represented families, Poaceae and Asteraceae, contain species adapted to xeric environments and steppe communities. All these life forms present both structural and physiological adaptations to the climatic conditions of the area (Montenegro et al., 1979). Chamaephytes with their

Table 2. Catalogue and life forms of the zonal and azonal flora of Laguna Lejía.

Taxonomic Group / Species	Family	Common Name	Fv[1]	Of[2]
Zonal Flora				
Angiosperms				
Eudicotyledoneae				
Adesmia subterranea Clos	Fabaceae	cuerno de cabra	Cr[3]	N[7]
Calceolaria stellariifolia Phil.	Calceolariaceae	capachito	Ca[4]	E[8]
Chaetanthera revoluta (Phil.) Cabrera	Asteraceae	chinita revoluta	Te[5]	N
Junellia pappigera (Phil.) N.O'Leary & P. Peralta	Verbenaceae	sn[9]	Ca	N
Junellia tridactylites (Lag.) Moldenke	Verbenaceae	sn	Ca	N
Lenzia chamaepitys Phil.	Montiaceae	lenzia	Hc[6]	N
Menonvillea virens (Phil.) Rollins	Brassicaceae	sn	Hc	N
Moschopsis monocephala (Phil.) Reiche	Calyceraceae	sn	Te	N
Mulinum crassifolium Phil.	Apiaceae	zucunco	Ca	N
Nototriche auricoma (Phil.) A.W.Hill	Malvaceae	nototriche	Hc	E
Nototriche sp. 1	Malvaceae	nototriche	Ca	N
Nototriche sp. 2	Malvaceae	nototriche	Ca	N
Oxalis erythrorrhiza Gillies ex Hook. & Arn.	Oxalidaceae	culle	Hc	N
Perezia atacamensis (Phil.) Reiche	Asteraceae	marancel	Hc	N
Pycnophyllum bryoides (Phil.) Rohrb.	Caryophyllaceae	k'ota	Hc	N
Pycnophyllum macropetalum Mattf.	Caryophyllaceae	sn	Hc	N
Senecio puchii Phil.	Asteraceae	sn	Ca	N
Monocotyledoneae				
Deyeuxia antoniana (Griseb.) Parodi	Poaceae	champa	Hc	N
Deyeuxia cabrerae (Parodi) Parodi	Poaceae	champa	Hc	N
Deyeuxia curvula Wedd.	Poaceae	champa	Hc	N
Festuca chrysophylla Phil.	Poaceae	paja brava	Hc	N
Hordeum pubiflorum Hook. f. subsp. *halophilum* (Griseb.) Baden & Bothmer	Poaceae	sn	Hc	N
Pappostipa frigida (Phil.) Romasch.	Poaceae	keiruichu, paja	Hc	N
Nassella nardoides (Phil.) Barkworth	Poaceae	chac'ke	Hc	N
Azonal Flora (Laguna Lejía)				
Angiosperma				
Eudicotyledoneae				
Arenaria rivularis Phil.	Caryophyllaceae	arenaria	Hc	N
Calandrinia compacta Barnéoud	Montiaceae	quiaca	Hc	N
Xenophyllum incisum (Phil.) V.A. Funk	Asteraceae	pupusa de agua	Ca	N
Monocotyledoneae				
Carex maritima Gunnerus	Cyperaceae	pasto de lavega	Cr	N
Festuca deserticola Phil.	Poaceae	waylla	Hc	E
Puccinellia frigida (Phil.) I. M. Johnst.	Poaceae	sn	Hc	N

[1]Life form, [2]Phytogeographic origin, [3]Cryptophyte, [4]Chamaephyte, [5]Therophyte, [6]Hemicryptophyte, [7]Native, [8]Endemic, [9]No common name.

Table 3. Phytosociological table with importance values and flora structure in Laguna Lejía, Chile.

	A[1]		B[2]														
Species / Inventories	**3**	**10**	**1**	**2**	**4**	**9**	**11**	**7**	**8**	**5**	**6**	**12**	**F[3]**	**Fr[4]**	**C[5]**	**Cr[6]**	**IV[7]**
Deyeuxia cabrerae			1	1							35	15	4	4.7	52	14.4	**19.1**
Deyeuxia curvula			1	1									2	2.4	2	0.6	3.0
Nassella nardoides			1	1	1	1				3			5	5.9	7	1.9	7.8
Pappostipa frigida			8	3		3	3	1	15	40	10	3	9	11	86	23.8	**34.4**
Lenzia chamaepitys			1										1	1.2	1	0.3	1.5
Moschopsis monocephala			1	1	1					1		1	5	5.9	5	1.4	7.3
Mulinum crassifolium			7							3	2	8	4	4.7	20	5.5	10.2
Nototriche auricoma			1	1	1					1	1		5	5.9	5	1.4	7.3
Nototriche sp.1			1	1									2	2.4	2	0.6	2.9
Nototriche sp.2			1	1	1								3	3.5	3	0.8	4.4
Senecio puchii			1									1	2	2.4	2	0.6	2.9
Junellia pappigera			2	6	3	6	7			6	1	2	8	9.4	33	9.1	**18.6**
Adesmia subterranea				1						1	4		3	3.5	6	1.7	5.2
Carex maritima	1												1	1.2	1	0.3	1.5
Puccinellia frigida	10	30											2	2.4	40	11.1	**13.4**
Festuca deserticola	1												1	1.2	1	0.3	1.5
Arenaria rivularis	10												1	1.2	10	2.8	3.9
Calandrinia compacta	30												1	1.2	30	8.3	9.5
Xenophy llu mincisum	15												1	1.2	15	4.2	5.3
Festuca chrysophylla										1		1	2	2.4	2	0.6	2.9
Chaetanthera revoluta										1	1		2	2.4	2	0.6	2.9
Pycnophyllum bryoides										1	2	2	3	3.5	5	1.4	4.9
Perezia atacamensis										1	1	1	3	3.5	3	0.8	4.4
Junellia tridactylites											1		1	1.2	1	0.3	1.5
Oxalis erythrorrhiza											1		1	1.2	1	0.3	1.5
Pycnophyllum macropetalum									5				1	1.2	5	1.4	2.6
Hordeum pubiflorum												1	1	1.2	1	0.3	1.5
Deyeuxia antoniana												20	1	1.2	20	5.5	6.7
Calceolaria stellariifolia												1	1	1.2	1	0.3	1.5
Menonvillea virens												1	1	1.2	1	0.3	1.5

[1]Life form, [2]Phytogeographic origin, [3]Cryptophyte, [4]Chamaephyte, [5]Therophyte, [6]Hemicryptophyte, [7]Native, [8]Endemic, [9]No common name.

Table 4. Diversity indices of the two plant communities in Laguna Lejía, northern Chile.

Index	High Andean scrub *Pappostipa-Deyeuxia*	Azonal flora *Puccinellia-Calandrinia*
Species Richness (S)	24	6
N[1]	264	97
Shannon H'	3.167	1.941
Shannon Hmax	4.524	2.585
Shannon J'	0.70	0.751

[1]Total frequency

pulviniform shape and small size resist the cold, the strong winds and the weight of the snow; cryptophytes, in this case geophytes – plants with lasting subterranean organs – represent this type of arid climate very well; the survival of therophytes is based on their short life cycles. Hemicryptophytes are well adapted to these environments.

The two plant associations identified – the sub-desert steppe of the Atacama *puna* and the high Andean wetland vegetation associated with the lake – are completely dissimilar. The *Pappostipa-Deyeuxia* community is related to that described by Gajardo (1995) as *Stipa chrysophylla*, characteristic of the highest sectors of the Andes Range, which generally indicates the highest limit of vegetation. Caespitose plants are the predominant life form. According to Teillier (2004), who studied the flora and vegetation of the mid-upper basin of the Loa River, this plant community corresponds to high Andean scrub. This unit is classified taxonomically in the *Urbanio pappigerae-Stipion frigidae* association.

The diversity of vascular plants is that expected for the type of habitat. The wetland verge zone is important for its ecological role in maintaining the assemblage of aquatic birds and invertebrates present in the lake (Muñoz-Pedreros *et al.* unpubl.).

The plant diversity recorded in Laguna Lejía (30 spp.) is comparable to that documented by Gutiérrez *et al.* (1998) for the Salado river (3,108 m with 31 species) and higher than that recorded by Gutiérrez *et al.* (op. cit.) in the Coya stream (3,782 m with 18 species), and by Teillier and Becerra (2003) for the Ascotán salt flat (3,800 m with 21 species). This salt flat was explored on several occasions between 1993 and 1998 based on 46 plots in eight patches of vegetation, each associated with a different lake with completely dissimilar azonal and zonal flora, as was found in Laguna Lejía. Teillier and Becerra (2003) suggested that the absence of zonal species in the salt flat is probably due to osmotic and/or nutritional problems produced by the high concentrations of salts. Conversely, the low water availability in the surrounding slopes might determine the absence of wetland species (salt flat and Laguna Lejía) in these habitats (Schat and Scholten, 1986; Shumway and Bertness, 1992).

Our results agree with the findings of Navarro and Rivas-Martínez (2005) in a transect from Calama (2,260 m) to the south-eastern slopes of Licancabur volcano (5,600 m); although their stations are not geo-referenced, we assume that from their inventory 3 they would be within our study area. Their inventory 20 might be outside, but its inclusion makes sense ecologically and would add only two species to the inventory, *Deyeuxia deserticola* and *D. crispa*.

The study area is an extremely fragile ecosystem, like all the puna, highly sensitive to human disturbance like water extraction for use in mining, although there is still no such activity in the study area. Both plant communities are therefore important: the high Andean scrub for its high proportional species richness (S= 25) (e.g. compared to S= 21 of the saltmarsh vascular flora in Ascotán, also in the Antofagasta region at 3,800 m (Teillier and Becerra, 2003)) and the azonal hygrophilous community for its high evenness index (all the species are well represented). Its importance also lies in its highly pristine condition and its ecological role in maintaining the assemblage of aquatic birds (e.g. flamingos *Phoenicopterus chilensis*, *Phoenicoparrus* spp., piuquén *Choephaga melanoptera*) and invertebrates (Muñoz-Pedreros *et al.*, 2013).

Conclusions

Both plant communities in Laguna Lejía show highly pristine condition. The conservation of this ecosystem is important given the high proportional species richness of the high Andean scrub and the ecological role of the azonal hygrophilous community associated with the lake in maintaining the assemblage of aquatic birds. This is sufficient justification to consider Laguna Lejía a priority site for the conservation of biodiversity in northern Chile by the government.

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