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ZOOPLANKTON IN LAGUNA LEJÍA, A HIGH-ALTITUDE ANDEAN SHALLOW LAKE OF THE PUNA IN NORTHERN CHILE

BY

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ABSTRACT

The Puna is a high altitude ecosystem of the Central Andes located in the desert plateaus above 3500 m a.s.l. that covers parts of north-eastern Chile, north-western Argentina, south-eastern Peru and mid-western Bolivia. It is characterised by the presence of endorheic basins. Laguna Lejía is an oligohaline shallow lake with alkaline pH, located in the Atacama Puna above 4000 m a.s.l. It is surrounded by volcanoes and enclosed in a secluded basin that is of great scientific interest, due to its ecological insularity. It has been designated by the government as a priority site for biodiversity conservation. The object of this study was to analyse the specific composition and the structure of the zooplankton community in this shallow, high altitude lake. In March 2012, zooplankton samples were taken for qualitative and quantitative analysis from 13 sampling stations in the lake and two adjacent pools. The bodies of water were characterised in the field using portable equipment, with the following parameters being measured: pH, water temperature, conductivity, and dissolved oxygen. The results indicate that the type of zooplankton community matches relatively well that observed in other low salinity, high Andean wetlands, although no calanoid copepods were found. The species found have been reported for high Andean zones and shallow lakes in countries bordering Chile. The absence of species with wide geographical distribution specific for low salinity, high Andean environments, is presumably due to the presence of geographical and environmental barriers that prevent colonization by those species.

Key words. — High altitude wetland, *Macrothrix palearis*, *Alona* sp., *Diacyclops andinus*

RESUMEN

La Puna es un ecosistema de gran altitud de los Andes Centrales que se encuentra en las mesetas del desierto por encima de los 3500 msnm, que cubre partes del noreste de Chile, el noroeste de Argentina, el sudeste de Perú y medio oeste de Bolivia. Se caracteriza por la presencia de cuencas endorreicas. Laguna Lejía es un lago somero, oligohalino, con pH alcalino, que se encuentra

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en la puna de Atacama por encima de 4000. Está rodeada de volcanes, en una cuenca cerrada de alto interés científico por su insularidad ecológica que ha sido designado por las autoridades gubernamentales sitio prioritario para la conservación de la biodiversidad. El objetivo de este estudio es analizar la composición específica y estructura del zooplancton de este lago somero. Se muestreó en marzo de 2012 (verano septentrional) en 13 estaciones abarcando el lago y dos cuerpos de agua adyacentes, extrayéndose muestras de zooplancton para el análisis cuali y cuantitativo. En terreno se caracterizaron los cuerpos de agua y se midieron los parámetros pH, temperatura del agua, conductividad y oxígeno disuelto, con equipo portátil. Los resultados indican que el tipo de ensamble zooplanctónico se ajustaría relativamente a lo observado para otros humedales altoandinos de baja salinidad, no obstante no se encontraron copépodos calanoideos. Las especies encontradas han sido reportadas para zonas altoandinas y lagos someros altoandinos de países limítrofes a Chile. La ausencia de especies de amplia distribución geográfica que son propias de ambientes altoandinos de baja salinidad se debería presumiblemente a que la presencia de barreras geográficas y ambientales evitarían su colonización por otras especies.

INTRODUCTION

The Puna is an ecosystem of the Central Andes located on the desert plateaus above 3500 m a.s.l. (Marquet et al., 1998), and it covers parts of north-eastern Chile, north-western Argentina, south-eastern Peru, and mid-western Bolivia. It is a region of high peaks and recent volcanic activity. In Chile, it extends from 17°30′ to 28° south, and westward from the eastern border of the country, with a width of 20-70 km (Garcia, 1967; Troll, 1968; Luebert & Gajardo, 2000).

Laguna Lejía is a shallow lake set in the Atacama Puna, in an endorheic basin. This watershed, located in the highland climate zone, has seasonal runoff, and a pluvio-nival regime with a moderate slope (Klohn, 1972; Ferrando, 1992-1993; Grosjean, 1994). Like other secluded basins of the Andean plateau, it is characterised by the presence of more depressed areas towards its western edge, where surface and subterranean waters collect. The precipitation that falls on the Andean plateau is collected by drainage systems, which are characterized by the absence of perennial watercourses that can reach the more depressed areas. The run-off watercourses which flow across impermeable rocks then infiltrate into fractured rocks or clastic sedimentary material to form phreatic aquifers. The water commonly is welling up in the form of springs (Risacher et al., 1998).

High mountain wetlands are of great scientific interest due to their ecological insularity, their pristine condition, and are also difficult to access (Locascio de Mitrovich et al., 2005). In shallow lakes located on the Andean plateau of northern Chile and Peru, endemic species of zooplankton have been recorded (Bayly, 1992; Villalobos, 1994, 2006). The crustacean zooplankton assemblages in water bodies of the Atacama Puna are characterized by low species richness and an inverse relation between species number and salinity (De los Ríos-Escalante, 2010).

The object of this study is to analyse the specific composition and the structure of the zooplankton of Laguna Lejía as a priority site for biodiversity conservation in northern Chile.

MATERIAL AND METHODS

Study area

The study area is located 103 km south-east of the town of San Pedro de Atacama, in the Antofagasta Region (fig. 1), northern Chile (23°30′S 67°42′W). The area ranges above 4350 m a.s.l. and is located in a desert depression. It lies in a hydrographical basin covering 193 km^2, in which the bodies of water cover 1.9 km^2 (Grosjean, 1994; Risacher et al., 1998). The lake is shallow (1 m) and its hydrological parameters are controlled by subterranean springs. There is little precipitation (<200 m year^{-1}), excessive evaporation (>2000 mm year^{-1}), a run-off coefficient (ratio between the amount of precipitation that falls on the drainage basin and that which enters the lake) of 0.089, and limited internal drainage (estimated at 40 l min^{-1}) (Grosjean et al., 1994, 1995; Risacher et al., 1998).

The lake is the remnant of a large glacial lake, and lies 15 km south of the Láscar volcano, formed in a tectonic depression related with the Miscanti-Callejón de Varela fault.

The geo-morphological units form an amphitheatre, of which Laguna Lejía is the centre. It is surrounded by the Láscar volcano to the northwest (the most active in the central volcanic zone of the Andes), the Aguas Calientes volcano to the north, the Chiliques volcano to the south, and the Lena and Lejía mountains to the south west, which form part of the Puntas Negras range (Gardeweg et al., 1998). The average height of the surrounding volcanoes is 5700 m a.s.l., but their elevation from base to summit is only 800-900 m. To the north-east of the lake is the Altos de Toro Blanco range, which forms the watershed between the Lejía and Salar de Aguas Calientes basins. It forms a low range between the two wetlands, with average height 4300 m a.s.l.

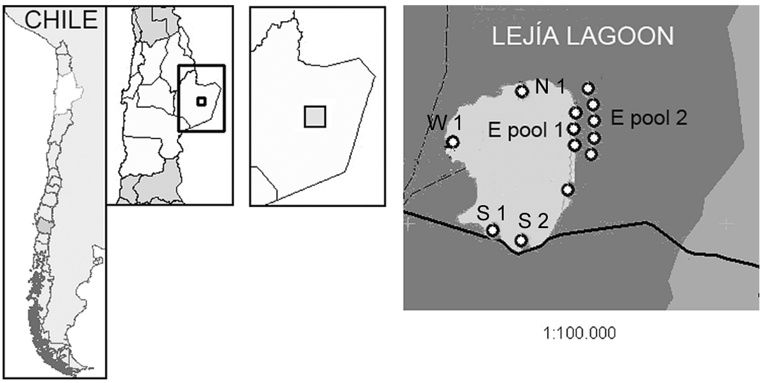

Fig. 1. Study area and sampling stations in the Laguna Lejía, northern Chile. S, south; N, north; E, east; W, west.

The climate according to Köppen's classification is high altitude steppe (BSH) (Di Castri & Hajek, 1976) with low temperatures presenting wide daily oscillation and precipitations concentrated in summer (50 to 150 mm year^{-1}), with strong annual variation and series of very dry or very wet years (three times the precipitation of a dry year) which exceed the capacity of the poorly developed drainage network and produce torrential water flows which have modelled the morphology. Evaporation from water and soil surfaces is very high (1500-2500 mm year^{-1}) and the relative humidity is very low ($<$20%), all of which explain the high aridity of the site (Luebert & Pliscoff, 2006).

The vegetation surrounding Laguna Lejía has been studied by Muñoz-Pedreros et al. (unpubl.) and is characterized by the presence of two communities: one, set in the lake, is a *Stipa-Deyeuxia* community consisting of some 23 species of herbaceous plants and low shrubs, including *Stipa frigida* Phil., *Stipa nardoides* (Phil.) Hackel ex Hitchc., *Deyeuxia cabrerae* (Parodi) Parodi, *Deyeuxia antoniana* (Griseb.) Parodi, *Pycnophyllum bryoides* (Phil.) Rohrb., *Pycnophyllum macropetalum* Mattf., *Mulinum crassifolium* Phil. and *Junellia pappigera* (Phil.) N. O'Leary & P. Peralta. It is a community characteristic of the highest sectors of the Andes, generally marking the upper limit of vegetation. The other community, in the eastern area of the lake, is a *Puccinellia-Calandrinia* community with six herbaceous species (e.g., *Puccinellia frigida* (Phil.) I. M. Johnst., *Calandrinia compacta* Barnéoud, *Xenophyllum incisum* (Phil.) V. A. Funk and *Arenaria rivularis* Phil.). This is a hygrophilous community typical of the borders of water bodies, representing the azonal vegetation of this lacustrian wetland, and owes its existence to springs of subterranean water to the east of the lake which generate small, parallel pools adjacent to it.

Methodology

Samples were collected in March 2012 at the four cardinal points around Laguna Lejía, with special emphasis on sampling in the eastern sector, both in the lake itself and in two parallel pools adjacent to the lake (fig. 1). Samples of zooplankton were taken at the 13 stations (5 replicates for the lake, 3 for pool 1 and 5 for pool 2) for qualitative and quantitative analysis, by filtration of 30 litres of superficial water per station, using a conventional conical net with 50 μm mesh, and following the methods described by Soto & De los Ríos (2006). The material was fixed in situ with alcohol at 75%.

Observation, taxonomic identification and measurement of the specimens were done under optical microscope and stereoscopic microscope, using specialist literature for identification (e.g., Araya & Zúñiga, 1985; Reid, 1985; Bayly, 1992; González, 2003). Counts were based on Cassie's formula (Edmonson & Winberg, 1971), with 10% error, in 1 and 5 cm^3 samples Sedgwick Rafter chambers for microzooplankton (crustacean nauplia and rotifers) and macrozooplankton (Cladocera, copepodites and adult copepods) respectively, or total counts when the abundance was very scarce. The water bodies were characterised in the field, measuring pH, water temperature, conductivity and dissolved oxygen, using WTW 3400i multi-parameter equipment, fitted with: WTA temperature sensor (precision 0.1°C); Tetra-con 325 conductivity sensor (precision 0.2 μS); CellOx 325 for oxygen (sensitivity 0.1 mg/l); and pH Sentix 20 (0.1 sensitivity pH units).

The data were analysed first by a correlation analysis of the abundances of the species reported and the parameters considered in the present study. Next, a hierarchical agglomerative clustering analysis using the Bray-Curtis index was applied to determine possible similarities between the groups. For both these analyses, Biodiversity Pro version 2.0 software (Mc Aleece et al., 1997) was used. The next step was to calculate a Checkerboard score (C-score), which is a quantitative index of occurrence that measures the extent to which species co-occur less frequently than expected by chance (Gotelli, 2000). One can consider that a community is structured by competition when the C-score is significantly larger than expected by chance (Gotelli, 2000). Thirdly, co-occurrence patterns with null expectations were compared via simulation. Gotelli & Etsminger (2007) and Gotelli (2000) suggest the following robust statistical null models: (1) Fixed-Fixed: in this model the row and column sums of the matrix are preserved. Thus, each random community contains the same number of species as the original community (fixed column), and each species occurs with the same frequency as in the original community (fixed row). (2) Fixed-Equiprobable: in this algorithm only the row sums are fixed, and the columns are treated as equiprobable. This null model considers all the samples (column) as equally available for all species. (3) Fixed-Proportional: in this algorithm the species occurrence totals are maintained as in the original community, and the probability of a species occurring at a site (column) is proportional to the column total for that sample. These null model analyses were performed using the Ecosim version 7.0 software (Gotelli & Etsminger, 2007). Finally a niche sharing null model was applied using Pianka's and Czekanowski's overlap indices with retained niche breadth and reshuffled zero states using the Ecosim version 7.0 software (Gotelli & Etsminger, 2007). The Ecosim program also determines whether measured overlap values differed from what would be expected in random sampling of the species data. Ecosim performs Monte Carlo randomisations to create pseudo-communities and then statistically compares the patterns of these randomised communities with those in the real data matrix (Gotelli & Etsminger, 2007). In this analysis all values of the general matrix were randomised 1000 times and the niche breadth was retained for each species. In other words, the algorithm retained the amount of specialisation for each species (Gotelli & Etsminger, 2007).

RESULTS AND DISCUSSION

High variability is found in almost all the parameters measured at the different sampling stations in the lake Laguna Lejía and the small pools to the east (table I; fig. 1). The oxygen concentrations are lower in the small pools than in the lake. The highest concentrations of dissolved oxygen are associated with the stations where the water temperature is highest (table I).

The results of the correlation analyses (table I) indicate that the abundance of *Macrothrix palearis* Harding, 1955 is directly related to the pH, conductivity and the abundances of *Alona* sp., *Diacyclops andinus* Locascio de Mitrovich & Menu-Marque, 2001 and Ostracoda; while the abundance of *Alona* sp. has a significant, directly proportional relation to the conductivity and the abundance of *D. andinus* and Ostracoda (table II). At the same time the abundance of harpacticoids has a significant, directly proportional relation to the temperature; and finally, the abundance of ostracodes has a significant, directly proportional relation to the pH, the conductivity and the abundance of *M. palearis* (table II).

The results of all simulations in null model species associations showed that the species associations were random (table III), while the results of the niche sharing model indicate that there are differences in the niche structure (table III). The results of the cluster analysis show that the eastern and southern sites are the most similar, followed by the lake East-1, lake East-2 and North sites, respectively (fig. 2).

The pH values recorded are higher than those recorded by Grosjean et al. (1995) in the same lake, and in the adjacent pools. The great variability in the conductivity

TABLE I
Physical and chemical parameters of the water, and taxa recorded in Laguna Lejía, northern Chile

	Sampling station					
	South	West	North	East	Eastern pool 1	Eastern pool 2
Physical and chemical water parameters						
pH	9.14	9.35	8.78	8.65	9.15	9.69
Temperature (°C)	9.80	11.17	21.60	18.63	11.47	13.17
Conductivity dil (5 : 50) (mS cm^{-1})	119.47	8.76	7.25	13.47	12.70	451.33
Dissolved oxygen (mg l^{-1})	5.00	5.66	6.25	6.54	2.89	3.74
Crustacean zooplankton (ind. l^{-1})						
Macrothrix palearis Harding, 1955	0.03	0.00	0.00	0.03	0.13	1.60
Alona sp.	0.00	0.00	0.00	0.01	0.00	0.02
Diacyclops andinus Locascio de Mitrovich & Menu-Marque, 2001	0.00	0.00	0.00	0.00	0.00	0.32
Harpacticoida indet.	0.00	0.00	0.03	0.00	0.00	0.00
Ostracoda indet.	0.00	0.00	0.00	0.00	0.00	0.03

TABLE II

Results of the correlation analyses for species associations and niche sharing

	Macrothrix palearis Harding, 1955	*Alona* sp.	*Diacyclops andinus* Locascio de Mitrovich & Menu-Marque, 2001	Harpacticoida	Ostracoda
pH	0.736*	0.410	0.729*	−0.449	0.729*
Temperature	−0.145	0.103	−0.118	0.757*	−0.118
Dissolved oxygen	0.965*	0.825*	0.969*	−0.263	0.969*
Conductivity	−0.491	−0.169	−0.432	0.419	−0.432
M. palearis		0.872*	0.997*	−0.228	0.997*
Alona sp.			0.878*	−0.292*	0.878*
Diacyclops andinus Locascio de Mitrovich & Menu-Marque, 2001				0.419	−0.432
Ostracoda					0.2000

* Significant associations and absence of randomisation ($P<0.05$).

both within the lake and between it and the pools to the east was also recorded by Grosjean et al. (1995) in Laguna Lejía and the neighbouring pools. As Risacher et al. (1998) suggest, marked salinity gradients in the direction of water run-off occur in the shallow lakes in the basins of Northern Chile due to intense evaporation. These authors measured a potential evaporation of 1500 mm year^{-1} in Laguna Lejía. The conductivity did not exceed the value of 6.4 mS cm^{-1} indicated by Grosjean et al. (1995) for Laguna Miscanti, which has the least saline waters in the Andean plateau, in any of the sampling stations.

Hann (1986), in his review of the genus *Daphniopsis* Sars, 1903 (Cladocera, Daphniidae), described *Daphniopsis chilensis* Hann, 1986 from the crater lake of

TABLE III

Results of the null model analyses for species associations and niche sharing

Model	Observed index	Average index	Standard effect of size	Variance	*P*
Species association					
Fixed-Fixed	0.800	0.846	−0.230	−0.040	0.683
Fixed-Proportional	0.800	0.738	0.154	0.160	0.476
Fixed-Equiprobable	0.800	1.267	−1.125	0.172	0.875
Niche sharing					
Pianka's index	0.100*	<0.001	<0.001	<0.001	<0.001
Czekanowski's index	0.100*	<0.001	<0.001	<0.001	<0.001

* Significant associations and absence of randomisation ($P<0.05$).

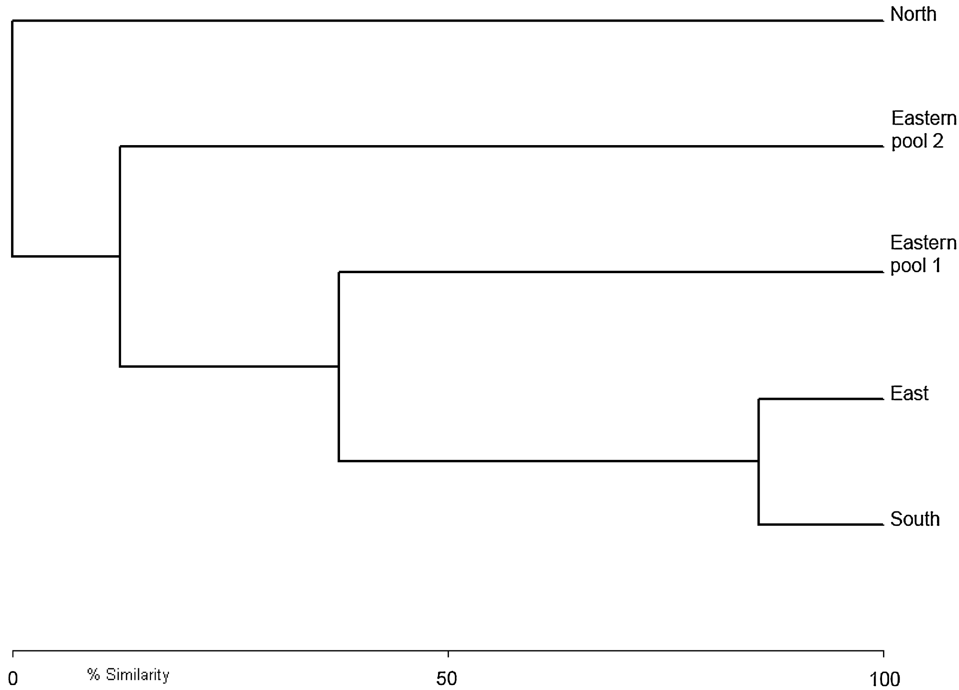

Fig. 2. Similarity dendrogram of the sites considered in the present work.

the Licancabur volcano (22°50′S 67°50′W), but this species was not recorded in Lejía, despite the relative proximity of the two wetlands.

Information on limnic zooplankton in high Andean wetlands indicates that there is a significant inverse relation between the number of species and the salinity (De los Ríos-Escalante, 2010). In general it is observed that at salinities between 5 and 90 g l^{-1}, the halophilic copepod *Boeckella poopoensis* Marsh, 1906, predominates and may even be the exclusive zooplankton species; while at salinities greater than 90 g l^{-1}, *Artemia franciscana* Kellogg, 1906, predominates, and may also be the exclusive component of the zooplankton (De los Ríos-Escalante, 2010; De los Ríos & Gajardo, 2010). At salinities below 5 g l^{-1} there is a relatively high richness of species, in which calanoid copepods proper to low salinities, such as *Boeckella gracilipes* Daday, 1902, or *Boeckella occidentalis* Marsh, 1906, can coexist with cladocerans principally of the Daphnidae and Chydoridae families (De los Ríos-Escalante & Gajardo, 2010). Thus the type of zooplankton community observed in the present study fits relatively well with that observed in other low salinity, high Andean wetlands, even if no calanoid copepods were found.

The species recorded in Laguna Lejía were observed in high Andean zones. *M. palearis* and *D. andinus* have been described for Chungará Lake (Araya & Zúñiga, 1985; De los Ríos-Escalante, 2010) and high Andean shallow lakes in countries bordering Chile (Locascio de Mitrovich et al., 2005; De los Ríos & Gajardo, 2010). The absence of species with wide geographical distribution which are proper to low salinity, high Andean environments, such as *Daphnia pulex* Leydig, 1860 and *B. gracilipes* Daday, 1901, is presumably due to the presence of many geographical and environmental barriers.

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