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Aquatic Crustaceans in the Driest Desert on Earth: Reports from the Loa River, Atacama Desert, Antofagasta Region, Chile

Patricio De los Ríos-Escalante¹ and Alfonso Mardones Lazcano²

¹Universidad Católica de Temuco, Facultad de Recursos Naturales,
Escuela de Ciencias Ambientales,

²Universidad Católica de Temuco, Facultad de Recursos Naturales,
Escuela de Acuicultura,
Chile

1. Introduction

Northern Chile includes the Atacama Desert, which is characterized by scarce, shallow, saline shallow endorheic lakes, small intermittent streams, and a few rivers (Niemeyer & Cereceda, 1984). One of the main rivers of this zone is the Loa River which is 440 km long and is the longest river in Chile. The river basin occupies 33,570 km². Situated in the Antofagasta region of Chile, it originates in the Andes Mountains, close to Bolivia, and receives flow from four tributaries rivers: the Salado, San Pedro, Toconce, and San Salvador Rivers. The Loa basin contains two reservoirs, the Conchi and Sloman (Pumarino, 1978; Niemeyer & Cereceda, 1984; Gutierrez et al., 1998). Studies of the native Loa aquatic fauna to date have only described the presence of the freshwater shrimp, *Cryphiops caementarius* (Molina, 1782) (Jara et al., 2006), amphipods such as *Hyalella fossamanchini* and *H. kochi* (González, 2003), and the native silverside *Basilichthys near semotilus*; Dyer 2000a,b; Ruiz & Marchant 2004; Vila et al., 2006). Introduced fish taxa in the Loa River and its tributaries include *Oncorhynchus mykiss* and *Salmo trutta* (Pumarino, 1978; Wetzlar, 1979; Iriarte et al., 2005). Overall, there is little detailed information about aquatic species, their distribution, population status, and associations in the Loa River.

The Loa River and its basin are subjected to strong human influences due to water use for mining, domestic needs, and agriculture (Niemeyer & Cereceda, 1984; Gutiérrez et al., 1998). The biological resources of the basin also are known to be under pressure from fishing, particularly in the case of the shrimp, *C. caementarius* (Meruane et al., 2006a,b), and rainbow and brown trout populations (Pumarino, 1978; personal observations). Nevertheless, it is difficult to determine the status of the aquatic fauna in the Loa basin due to a lack of study stemming largely from the inaccessibility of water bodies in northern Chile (Chong, 1988). Our study aims to rectify this lack of knowledge by determining the faunal species inhabiting the Loa River, characterizing species associations along altitudinal and spatial gradients within the river, and testing for regulating factors potentially influencing aquatic community composition.

2. Material and methods

The Loa River originates in the Andes Mountains close to the boundary with Bolivia, and flows first from north to south, proceeds in a westerly direction, changes back to a northerly direction, and finally flows west to its confluence with the Pacific Ocean (Fig. 1). We compiled information from two data sets, one collected during field studies in January 2008 that included nine sites along the Loa River (De los Ríos et al., 2010; Table I), and the other from field studies in 1980 from lower reaches of the Loa River between the outlet to the middle zone. The latter dataset included *C. caementarius* habitat (Alfaro et al., 1980; Table II). Altitude, in meters above sea level, was recorded for all sites. We tested for relationships between species richness and two physical variables, salinity (using a YSI-30 sensor) and altitude, using correlation coefficients (Rho-Spearman), calculated in the software SPSS v.12.

Crustacean community structure was explored using a co-occurrence null model analysis, which tests whether species co-occur less frequently than expected by chance (Gotelli, 2000). A checkerboard score ("C-score") was calculated based upon an absence/ presence matrix, representing a quantitative index of co-occurrence. We used this method for analysis and evaluated results in relation to those of other studies (Tondoh, 2007; De los Ríos et al., 2008; De los Ríos-Escalante, 2011). A community may be structured by competition when the C-score is significantly larger than that expected by chance (Gotelli, 2000, 2001). In order to determine whether a particular score is statistically significant, a set of randomizations of the species occurrence data are performed and a null distribution for the coexistence index is created. Gotelli & Entsminger (1997) Tiho & Johens (2006), and Tondoh (2007), suggested the following three statistical models for creating randomized communities, with the species placed in rows and the sites in columns:

1. Fixed-Fixed Model. 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 Model. 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-Proportion Model. In this algorithm species occurrence totals are maintained as in the original community, and the probability that a species occurs at a site (column) is proportional to the column total for that sample.

All three of these models exhibit fairly reasonable combinations of Type I and Type II error rates, although model 3 has a high Type I error rate (false positives) using the C-score index, with differences in underlying assumptions and behaviour (Gotelli, 2000). The fixed-fixed model is suggested to be most appropriate for island species lists, in which species-area effects are expected, while the fixed-equiprobable model would be most appropriate for standardized samples in a homogeneous environment (Gotelli, 2000). The fixed-proportional algorithm represents an intermediate model, which might be most appropriate in our system due to habitat connectivity and heterogeneity, as well as differences in depth and width along the river. Differing results among models can provide insights into community structure. The null model analysis was using the software ECOSIM, version 7.0 (Gotelli & Entsminger, 1997).

	Santa Bárbara	Conchi	Salado	Chiuchiu	Chacance	Salvador
Geographical location	21° 58.7'	22° 00.5'	20° 20.4'	20° 20.4'	22° 23.8'	22° 23.8'
(South latitude / West longitude)	68° 36.7'	68°36.7'	68° 39.2'	68° 39.2'	69° 31.6'	69° 31.6'
Altitude (m a.s.l)	3304	3272	2784	2768	1328	1328
Salinity (g/l)	1.8	1.5	4.2	1.5	8.3	4.8
Cladocera						
<i>Ceriodaphnia dubia</i> (Richard, 1894)		x				
<i>Daphnia pulex</i> (De Geer, 1877)		x				
<i>Chydorus sphaericus</i> (O.F. Müller, 1785)			x			
Copepoda						
<i>Eucyclops serrulatus</i> (Fisher, 1851)		x				
Unidentified cyclopoida			x			
<i>Tigriopus</i> sp.						
Ostracoda						
<i>Heterocypris panningi</i> (Brehm, 1934)			x		x	
<i>Cubacandona</i> spp. (Broodbakker, 1983)						
Amphipoda						
<i>Hyalella fossamanchini</i> (Cavalieri, 1959)	x	x	x			x
<i>H. kochi</i> (González & Watling, 2001)	x	x	x			

Table 1. Geographical location, altitude, conductivity, salinity, and species reported for the studied sites during the 2008 sampling period.

3. Results and discussion

Our results revealed the presence of a small number of crustacean species in the Loa River (Table 1). . In the Quillagua River, no crustacean species were found, but the introduced fish species *Gambussia affinis* was abundant, whereas in Sloman and Chacance River, only the ostracod *Heterocypris panningi* was detected. By contrast, the Salado River harbored unidentified cyclopoid copepods, the cladoceran *Chydorus sphaericus*, *H. panningi*, and the amphipods *H. fossamanchini* and *H. kochi*. The Conchi Reservoir supported similarly high species richness, with *H. fossamanchini*, *H. kochi*, *Eucyclops serrulatus*, *Ceriodaphnia dubia*, and *Daphnia pulex* (Table I). Among data collected in 1980 in the lower Loa River basin, *H. panningi* was reported at all sites, and unidentified Harpacticoida were reported at all sites except in the Sloman reservoir, and *E. serrulatus* was found in El Borax, La Poroma and Angostura (Table 2).

	Chacance	San Lorenzo	El Borax	Sloman	La Poroma	Angostura	Desembocadura
Geographical location	22° 23.8'	22° 12.0'	21° 06.0'	21° 51.2'	21° 39.0'	21° 36.0'	21° 27.0'
(South latitude / West longitude)	69° 31.6'	69° 24.0'	69° 30.0'	69° 30.9'	69° 30.0'	69° 36.0'	71° 00.0'
Altitude (m a.s.l)	1328	1180	1100	1085	800	700	1.5
Salinity (g/l)	4.99	5.64	6.33	6.33	7.46	7.61	8.72
Cladocera							
Cladocera							
<i>Ceriodaphnia dubia</i> (Richard, 1894)							
<i>Daphnia pulex</i> (De Geer, 1877)							
<i>Chydorus sphaericus</i> (O.F. Müller, 1785)							
Copepoda							
<i>Eucyclops serrulatus</i> (Fisher, 1851)			x		x	x	
Unidentified cyclopoida							
Unidentified harpacticoida sp.	x	x	x	x	x	x	x
Ostracoda							
<i>Heterocypris panningi</i> (Brehm, 1934)	x	x	x		x	x	x
<i>Cubacandona</i> spp. (Broodbakker, 1983)							
Amphipoda							
<i>H. fossamanchini</i> (Cavalieri, 1959)							
<i>H. kochi</i> (González & Watling, 2001)							

Table 2. Geographical location, altitude, conductivity, salinity, and species reported for the studied sites in the Loa River during the 1980 sampling period.

Among data collected in 2008, Spearman rho correlation values indicated no relation between species number and salinity ($r = -0.39$; $P = 0.149$) however, a significant and positive relationship was detected between species richness and altitude ($r = 0.61$; $P = 0.041$) (Table 2). In contrast, among data collected in 1980, the Spearman rho correlation values indicated no relation between species number and salinity ($r = -0.391$; $P = 0.149$) or between diversity and altitude ($r = 0.189$; $P > 0.05$) (Table 3)).

	Salinity	Altitude		
Number of species	R = -0.391; P = 0.149	R = 0.610; P = 0.041		
Results of null model analysis				
Simulation	Observed index	Mean	Standard effect size	P
Fixed-Fixed	1.250	1.132	1.066	0.155
Fixed- Proportional	1.250	1.105	0.443	0.372
Fixed- Equiprobable	1.250	1.873	-2.301	0.982

Table 3. Results of correlation and null-model analyses. Correlation coefficients are provided between species richness and conductivity, salinity, and altitude, respectively, along the Loa River (sampling period 2008). The null-model analysis (see text) suggests that crustacean community structure is random.

The results of the null model analysis among all simulations within 2008 data revealed that crustacean community composition appears to be random (Table 4). However, small sample size can mask other underlying patterns (De los Ríos-Escalante, 2011). A different situation was observed within the 1980 data, where the fixed-proportional denoted the presence of regulatory factors, and the fixed-equiprobable analysis indicated a weak presence of regulator factor presence (Table 4).

Unfortunately chemical and other physical parameters were not measured in situ; however, human influences on the river may be potentially regulatory factors. Such influences have been documented on central Chilean rivers (Figueroa et al., 2003). The upper reaches of the Loa River are subject to lower levels of anthropogenic impact, given that human population size is small in relation to that in the lower reaches, which are subject to urbanization and and mining activities (Alvarez, 1999; Melcher, 2004).

The present literature on Chilean rivers only contains descriptions of invertebrate species associations in south-central rivers, and most studies attempt to use such information for bio-indication of water quality (Figueroa et al., 2003, 2007). These studies generally report differences in macroinvertebrate assemblages (mainly insects and crustaceans) in relation to water pollution along the river courses (Figueroa et al., 2003, 2006). These studies indicate that the fluvial aquatic fauna of Chilean is regulated by deterministic factors, namely water quality as influenced by the level of human alteration (Figueroa et al., 2003, 2006). However, Figueroa et al., (2003, 2006) only described the riverine biota to the family level, and this lack of species-level data precludes more precise statistical treatments of community structure (Gotelli & Graves, 1996; Gotelli & Ellison, 2000; Jaksic, 2001). Our study included only

crustaceans, but emphasized species-level taxonomy, whereas Figueroa et al., (2003, 2006) studied all benthic invertebrates including aquatic insects, which are diverse compared to crustaceans. Future studies of riverine community structure should expand upon our studies in order to include aquatic insects at the species level. Aquatic insects are likely to ecologically interact with crustaceans in fluvial benthic communities, in turn affecting abundances and patterns of co-occurrence among both taxonomic groups (Parra et al., 2001).

Biogeographically, the presence of the amphipods *H. fossamanchini* and *H. kochi* in the Loa River has been previously described by Gonzalez (2003) and Jara et al. (2006). However, those descriptions did not specify details about the localities at which the species were found. Thus, our study presents new information to the knowledge of crustacean distribution. The absence of specimens of the northern river shrimp, *C. caementarius*, indicates that this species is threatened by excessive fishing as human food (Jara et al., 2006), and probably also by the presence of exotic fishes, such as *Gambusia affinis*, *Oncorhynchus mykiss* and *Salmo trutta*. All of those fish species are active predators on native aquatic invertebrates (Leyse et al., 2005).

Regarding the presence of ostracods in Chile, there are currently only records of *H. panningi* and *Cucacandona* spp., which also have been reported for other South American inland waters (Martens & Behen, 1994). Spatial differences in community composition were detected, with the presence of ostracods related to the absence of amphipods in the lower reaches of the Loa River, reaches that exhibit relatively high salinity and conductivity (Table 3). In contrast, the high-altitude zones of the Loa, as well as the Salvador River, have relatively lower salinity, with species associations between the amphipods *H. fossamanchini* and *H. kochi* (Table 1). The presence of microcrustaceans, specifically copepods and cladocerans in Conchi Reservoir, corroborates their distribution as reported in the literature (Araya & Zúñiga, 1985; Reid, 1985, Ruiz & Bahamonde, 1989). Although distributional data denote a segregation of species into low and high altitude reaches (Table 1), with significantly higher species richness at higher altitudes, the null model results suggest that crustacean species associations are random (Table 3). These results are seemingly in disagreement; however, the low total species richness and small number of study sites may preclude the detection of a true underlying pattern (De los Ríos-Escalante, 2011).

Nevertheless, the negative relationship between species richness with salinity and altitude (Table 4), is explained by predation by *C. caementarius* on microcrustaceans (Alfaro et al., 1980; López et al., 1986). This may represent a top-down trophic cascade that affects community structure. This scenario would be similar to descriptions of Chilean (Soto et al., 1994; De los Ríos, 2003) and Argentinean (Reissig et al., 2004) Patagonian lakes. Considering the present results, two main forces likely regulate aquatic community structure: salinity variation and predator presence. Such a combination of factors have been reported in shallow Andean mountain saline and sub-saline lakes (Hurlbert et al., 1986; De los Ríos-Escalante, 2011).

Our results contribute to understanding of the community ecology of inland water invertebrates in northern Chilean streams. Unfortunately, these ecosystems have been understudied to date due primarily to problems of accessibility. Further work on the crustacean and other aquatic faunae of northern Chilean rivers is clearly needed.

	Salinity	Altitude		
Number of species	R = -0.031; P > 0,05	R = 0,189; P > 0,05		
Results of null model analysis				
Simulation	Observed index	Mean	Standard effect size	P
Fixed-Fixed	2.833	2.764	0.272	0.346
Fixed- Proportional	2.833	1.506	1.715	0.039
Fixed- Equiprobable	2.833	1.665	1.523	0.057

Table 4. Results of correlation and null-model analyses. Correlation coefficients are provided between species richness and conductivity, salinity, and altitude, respectively, along the Loa River (sampling period 1980). The null-model analysis (see text) suggests that crustacean community structure is random.

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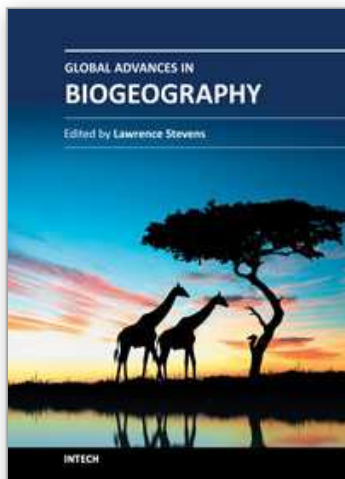
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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