CRUSTACEAN ZOOPLANKTON COMMUNITIES IN CHILOÉ ISLAND COASTAL LAKES (42°S, CHILE)

BY

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ABSTRACT

The lakes of Chiloé Island have a high dissolved organic carbon concentration (known as "humic") and show a connection with brackish water. They also display a high species richness of crustacean zooplankton. The aim of the present study is to characterize the potential factors that explain crustacean species richness in Chiloé Island lakes. To that purpose parameters of the abiotic environment were determined. The results of PCA performed on those data revealed the existence of three lakes with high crustacean species richness that are relatively deep, show high nitrogen concentrations, and are located at relatively high altitude. In contrast, there are two lakes with low species richness, high mineral concentration, and situated at low altitude. One of these lowland lakes gives rise to a river effluent to the sea, and it is connected to the other lake; these observations agree with the results of a performed cluster analysis. Nevertheless, the co-occurrence null model analysis revealed the absence of regulator patterns in species associations, which could be explained to the fact that many of the species occur in most of the lakes. These results are markedly different in comparison to Patagonian lakes of Argentina and Chile that have a low crustacean species number.

RÉSUMÉ

Les lacs de l'île de Chiloé ont une teneur élevée en carbone organique dissous et présentent une connexion avec l'eau saumâtre. Ils présentent également une grande richesse en espèces de crustacés zooplanctoniques. Le but de la présente étude est de caractériser les facteurs potentiels qui expliquent la richesse des espèces de crustacés dans les lacs de l'île de Chiloé. À cette fin, les paramètres de l'environnement abiotique ont été déterminés. Les résultats de l'ACP réalisée à partir de ces données ont révélé l'existence de trois lacs riches en espèces de crustacés, relativement profonds, riches en azote et situés à une altitude relativement élevée. En revanche, il y a deux lacs avec une faible richesse en espèces, une concentration élevée en minéraux et situés à basse altitude. L'un de ces lacs de basse altitude donne naissance à un effluent de rivière vers la mer et est relié à l'autre lac; ces observations

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sont en accord avec les résultats d'une analyse de cluster. Néanmoins, l'analyse du modèle nul de co-occurrence a révélé l'absence de modèles de régulation dans les associations d'espèces, ce qui pourrait s'expliquer par le fait que de nombreuses espèces sont présentes dans la plupart des lacs. Ces résultats sont nettement différents par rapport aux lacs de Patagonie d'Argentine et du Chili qui ont un faible nombre d'espèces de crustacés.

INTRODUCTION

The crustacean communities occurring in Chilean lakes have been studied mainly for Patagonian mountain lakes, and these communities are characterized by their low species richness due to the marked oligotrophy of these sites (De los Ríos-Escalante, 2016). Nevertheless, there are many coastal lagoons between 39° and 42°S (Hauenstein et al., 2002; Villalobos et al., 2003), and of these water bodies, only the lakes on Chiloé Island have been studied from a limnological point of view (Campos, 1997; Villalobos et al., 2003).

The Chiloé Island lakes now have a high dissolved organic carbon concentration [known as "humic"] and show a connection with brackish water. These lakes have undergone marked human intervention, due to alterations in their surrounding basins, due to the establishment of agricultural zones, the settling and development of rural human populations, and through salmon farming activities (Villalobos et al., 2003). Similar results have been reported earlier for northern Patagonian lakes at latitudes between 38° and 41°S (De los Ríos-Escalante, 2016). In this context, under human intervention in the surrounding basins, a transition from oligotrophy to mesotrophy has taken place, with consequent changes that resulted in an increase of the locally present numbers of species in the crustacean zooplankton (Soto & Zúñiga, 1991; Woelfl, 2007; De los Ríos-Escalante, 2016). Comparable results have been reported for New Zealand, for other Patagonian lakes (Jeppensen et al., 1997), and for central Chilean lagoons located at coastal zones (De los Ríos-Escalante, 2016).

From another point of view, the lakes on Chiloé Island experience a marked coastal influence due to the presence of river effluents that are directed towards the Pacific Ocean: that is where the rivers of the island discharge their fresh water (and its contents). In this scenario, if a lake is close to the Pacific coast, this lake is under marked marine influence (Villalobos et al., 2003), i.e., stronger winds and brackish water influences. It is probable that such conditions will have, in their turn, an influence on zooplankton community structure. The aim of the present study is to analyse the factors that would affect the numbers of crustacean species in the zooplankton in the lakes of Chiloé Island, based on a re-analysis of data published by Campos (1997) and Villalobos et al. (2003).

MATERIAL AND METHODS

Data on the numbers of species in the zooplankton and their morphometrics, as well as chemical data, were obtained from Campos (1997) and Villalobos et al. (2003) for five Chiloé Island lakes: Natri, Cucao, Huillinco, Tepuhueico, and Tarahuín (fig. 1, table I). These data were analysed by us in three steps: first, to determine the main factors explaining the differences between the studied sites, a principal component analysis (PCA) was applied using the software R (R Core Team, 2009), and the HSAUR R-package (Everitt & Hothorn, 2016).

In the following steps, a species absence / presence matrix was constructed, with the species in rows and the sites in columns (table I, bottom part). The second step consisted of performing a UPGMA cluster analysis, using the Neighbour-joining method for determining potential similarities between sites on the basis of species associations, using the R package Phangorn (Schliep, 2011). Thirdly, we calculated 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). A community is structured by competition when the C-score is significantly larger than expected by chance (Gotelli, 2000; Tondoh, 2006; Gotelli & Entsminger, 2007; Tiho & Johens, 2007). From that C-score, we compared co-occurrence patterns with null expectations via simulation. Gotelli & Ellison (2013) suggested the use of only the statistical null model "Fixed-Fixed", as this is the most robust. In this model, the row and column sums of the original 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). The null model analyses were performed using the package EcosimR version 7.0 (Gotelli & Ellison, 2013).

RESULTS

The results revealed a relatively mesotrophic status for three of the five lakes studied on Chiloé Island, i.e., with low mineral concentrations in the lakes Natri, Tarahuín and Tepuhueico; in contrast, there were high mineral concentrations in the lakes Cucao and Huillinco (table I). The results of the PCA showed that the main contributing variables for axis 1 were total dissolved solids, salinity, nitrate, ammonium, organic nitrogen, total nitrogen, orthophosphate, total phosphorus, organic seston, inorganic seston, calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate, and alkalinity (table II, fig. 2). Whereas for the second axis, the main contributor variables were maximum depth (Z_{max}), mean depth (Z_{mean}), relative depth (Z_{rel}), conductivity, nitrite, colour and turbidity (table II, fig. 2).

Fig. 1. Map of the studied sites on Chiloé Island, Chile (1: Cucao; 2: Huillinco; 3: Tarahuin; 4: Tepuhueico; 5: Natri). Source: Google Earth: https://www.google.cl/maps/@-42.8693554,-73.4747229,355972m/data=!3m1!1e3.

TABLE I

Geomorphometrics, chemical parameters, and zooplankton species reported for Chiloé Island lakes (cf., Campos, 1997; Villalobos et al., 2003)

	Lake Natri	Lake Tepuhueico	Lake Taarahuin	Lake Huillinco	Lake Cucao
Latitude/longitude	42°47′S 73°50′W	42°47′S 73°58′W	42°43′S 73°45′W	42°40′S 73°57′W	42°38′S 73°40′W
Altitude (m a.s.l.)	39.0	25.0	66.0	13.0	10.0
Volume (km^3)	0.273	0.128	0.170	0.395	0.127
Surface (km^2)	7.8	14.3	7.7	19.1	10.6
Maximum depth (Z_{max}) (m)	58.0	25.0	33.0	47.0	25.0
Mean depth (Z_{mean}) (m)	35.0	9.0	22.2	20.7	12.0
Relative depth (Z_{rel}) (m)	1.8	0.6	1.1	1.0	0.7
Colour (Platinum-Cobalt units)	41.4	131.4	40.0	92.8	81.6
Turbidity (mg/l)	2.8	5.3	2.8	4.3	3.9
pH	6.4	5.8	6.7	6.9	6.8
Conductivity (mS/cm)	41.4	30.2	50.9	27 326.00	156 858.00
Salinity (g/l)	0.10	0.1	0.10	18.9	10.4
Total dissolved solids (mg/l)	43.4	31.6	52.9	942.9	732.8
Oxygen (mg/l)	8.5	9.5	8.4	3.5	6.0
N-NO_3^- (μg/l)	565.9	445.0	154.4	3527.5	2154.2
N-NO_2^- (μg/l)	2.1	6.3	1.9	8.0	24.8
N-NH_4^+ (μg/l)	9.3	13.9	9.3	1470.0	123.5
Organic nitrogen (μg/l)	165.0	144.0	150.7	5138.5	2448.9
P-PO_4^{3-} (μg/l)	5.7	2.8	3.4	88.3	16.9
Total phosphorus (μg/l)	23.6	15.9	23.5	496.9	223.0
Organic seston (mg/l)	1.1	1.5	1.7	2.2	1.8
Inorganic seston (mg/l)	0.5	0.4	1.0	5.6	3.8
Calcium (Ca, mg/l)	1.7	1.4	3.3	181.5	111.9
Magnesium (Mg, mg/l)	1.2	0.9	1.6	562.2	301.5
Sodium (Na, mg/l)	4.7	4.4	4.8	1386.6	1300.0
Potassium (K, mg/l)	0.7	0.6	0.9	211.0	115.7
Chloride (Cl, mg/l)	8.8	8.0	8.4	11 473.0	7055.0
Sulfate (SO_4^{2-}, mg/l)	28.0	62.2	23.7	19 241.1	12 839.0
Bicarbonate (HCO_3^-, mg/l)	12.9	9.8	22.5	183.0	72.1
Alkalinity	0.2	0.2	0.4	3.0	1.2
Presence					
Cladocera					
Ceriodaphnia dubia Richard, 1894	X	X		X	
Daphnia pulex Leydig, 1860			X		
Diaphanosoma chilense Daday, 1902		X	X	X	
Chydorus sphaericus (O.F. Müller, 1785)	X		X		
Alona sp.				X	X
Neobosmina chilensis (Daday, 1902)	X	X	X		X

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TABLE I

(Continued)

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	Lake Natri	Lake Tepuhueico	Lake Taarahuin	Lake Huillinco	Lake Cucao
Ilyocryptus sp.			X		
Copepoda					
Boeckella gracilipes Daday, 1901	X	X	X		
Tumeodiaptomus diabolicus (Brehm, 1935)		X		X	X
Mesocyclops longisetus (Thiébaud, 1912)	X	X	X	X	
Tropocyclops prasinus (Fischer, 1860)	X	X	X	X	X
Cyclops sp.			X		
Harpacticoida indet.	X		X	X	X
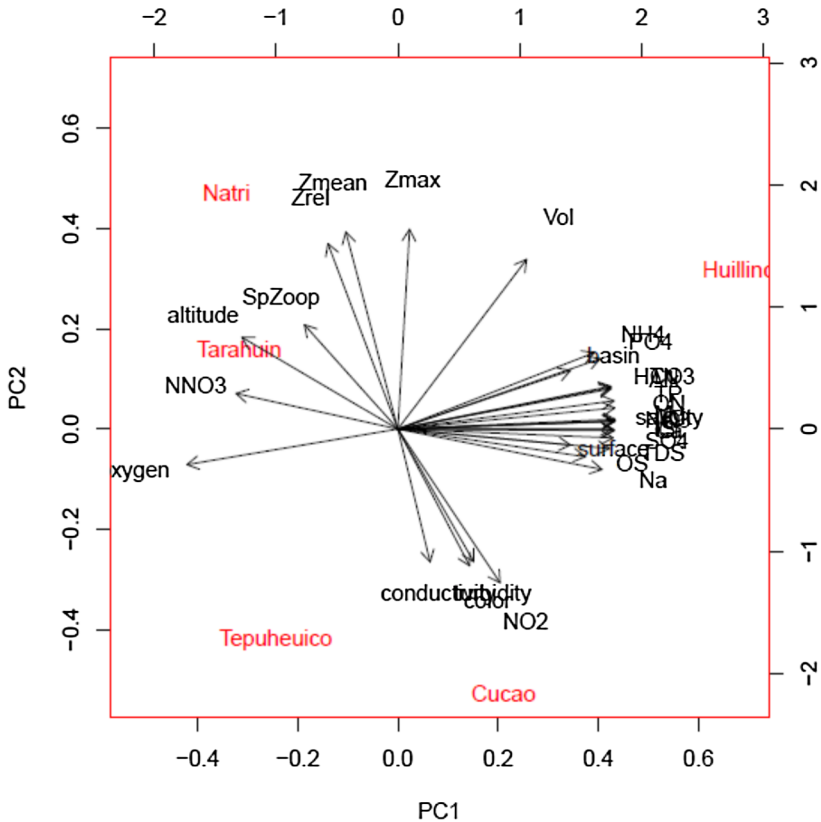
Fig. 2. Results of the PCA performed for the physico-chemical parameters of the studied sites.

	Axis 1	Axis 2
Altitude (m a.s.l.)	−0.15	0.18
Surface (km^2)	0.16	−0.06
Basin (km^2)	0.16	0.08
Maximum depth (Z_{max}) (m)	0.01	0.37
Mean depth (Z_{mean}) (m)	−0.04	0.38
Relative depth (Z_{rel}) (m)	−0.06	0.36
Volume (km^3)	0.12	0.31
Colour (Platinum-Cobalt units)	0.06	−0.29
Turbidity (mg/l)	0.06	−0.28
pH	0.13	0.15
Conductivity (mS/cm)	0.03	−0.22
Salinity (g/l)	0.21	−0.01
Total dissolved solids (mg/l)	0.20	−0.03
Oxygen (mg/l)	−0.21	−0.07
$N-NO_3^-$ (μg/l)	−0.16	0.13
NO_3^- (μg/l)	0.21	0.03
$N-NO_2^-$ (μg/l)	0.10	−0.27
$N-NH_4^+$ (μg/l)	0.19	0.13
Organic nitrogen (μg/l)	0.21	0.03
Total nitrogen (μg/l)	0.20	0.07
$P-PO_4^{3-}$ (μg/l)	0.19	0.12
Total phosphorus (μg/l)	0.21	0.04
Organic seston (mg/l)	0.18	−0.05
Inorganic seston (mg/l)	0.21	0.01
Calcium (Ca, mg/l)	0.21	−0.01
Magnesium (Mg, mg/l)	0.21	0.01
Sodium (Na, mg/l)	0.20	−0.07
Potassium (K, mg/l)	0.21	0.01
Chloride (Cl, mg/l)	0.21	−0.01
Sulfate (SO_4^{2-}, mg/l)	0.21	−0.01
Bicarbonate (HCO_3^-, mg/l)	0.20	0.07
Alkalinity	0.21	0.07
Number of species	−0.09	0.20

The results of the PCA also revealed that lakes Huillinco and Cucao are markedly different from the other three lakes, because both lakes have high mineral contents, a shallow depth, a low oxygen concentration, are situated at low altitude, and harbour a low number of crustacean zooplankton species (table I, fig. 2). A different situation occurs in the other three lakes, first for lakes Natri and Tarahuin, which are both relatively deep, are situated at high altitude, and show high concentrations of oxygen and nitrate; they have high numbers of crustacean
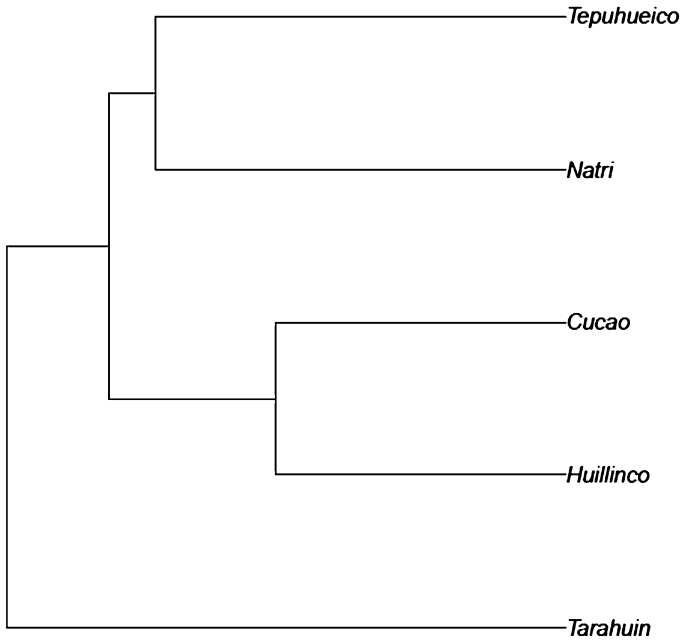
Fig. 3. Results of the UPGMA cluster analysis for the sites and crustacean species studied.

species (table I, fig. 2). Finally, for Tepuhueico lake, this has a low number of crustacean species, a high conductivity and a relatively shallow depth, as well as a low concentration of nutrients (table I, fig. 2).

These results would partially agree with the UPGMA, which revealed that the most similar lakes are Cucao and Huillinco, that are joined by a second group consisting of lakes Natri and Tepuhueico, and to conclude the most different appeared to be Tarahuin lake (fig. 3). Finally, the results of the co-occurrence species null model revealed the absence of any regulatory patterns (Mean index = 0.883; Observed index = 0.923; $P = 0.15$), which would not agree with the cluster analysis.

DISCUSSION

As exposed by the above results, a different pattern in zooplankton species composition and their respective regulator factors would apply to these Chiloé Island lakes in comparison to the earlier observations on Argentinean and Chilean Patagonian, as well as New Zealand lakes, where only oligotrophy would be the main regulator factor of crustacean species numbers (Soto & Zúñiga, 1991; Jeppensen et al., 1997; Modenutti et al., 1998; Woelfl, 2007; De los Ríos-Escalante, 2016).

The results obtained in the present study revealed the probable role of marine influence, as indicated by the high mineral contents of lakes Cucao and Huillinco, which are close to, and even connected to, the Pacific coast. These two lakes have a low number of crustacean species, in comparison with the other lakes that are connected indirectly to the Pacific Ocean by effluent rivers (Campos, 1997; Villalobos et al., 2003). Although the literature revealed the role of a combined effect between chlorophyll *a* concentration and salinity as a regulator of crustacean zooplankton assemblages in southern Patagonian lakes that show marked marine influence due to strong winds (Soto & De los Ríos, 2006), the results obtained in the present study would be different, because the lakes Cucao and Huillinco are interconnected, and Lake Cucao has an effluent river to the Pacific Ocean (Campos, 1997; Villalobos et al., 2003).

As regards species composition, the species found (table I) are similar to those reported for Chilean northern Patagonian lakes, and these species are widespread among many lakes (Soto & Zúñiga, 1991; De los Ríos-Escalante, 2016). In this scenario, under a mesotrophic status, this system of two lakes and a river discharging into the Pacific, would exhibit a marked increase in species number, in the same sense as has been reported for northern Patagonian lakes (Woelfl, 2007), with the same species occurring in many of the water bodies under study (De los Ríos-Escalante, 2016). This condition would agree with the results of the null model analysis. In this case, a similar situation would probably be enhanced by additional river connections of some lakes and lagoons on Chiloé Island, such as lakes Cucao and Huillinco (fig. 1; Campos,1997; Villalobos et al., 2003).

An inverse relationship between number of crustacean species and salinity has been reported for saline lakes (Anton-Pardo & Armengol, 2012; Gutkowska et al., 2012; Ginatullina et al., 2017; Hemraj et al., 2017), and salinity can have a combined effect with the lake's trophic status in terms of nutrients increasing in coastal lakes (Whitman et al., 2004), which would agree with the results obtained in the present study. Also, a similar result has been reported for data from connected coastal lagoons in Indonesia (Pratiwi et al., 2016). In this scenario, the results obtained for the lakes on Chiloé Island would agree with similar results reported in the literature, and it would be necessary to do more studies, i.e., also for other Chilean coastal lakes that have a coastal and estuarine connection by effluent rivers.

The assessment and monitoring of the ecosystem components changes both in the inland and in the coastal waters of Chile, under a combination of stressor scenarios. In the case of the spatial distribution of zooplankton, no study has yet been conducted on the use of these organisms as trophic indicators. Nonetheless, linking the pelagic ecosystems of the catchment basins and the lakes on Chiloé more broadly with other water bodies in Chile is a necessary tool for sustainable

management. Obviously, viz., linking the Integrated Environmental Management to the Integrated Coastal Zone Management (IEM-ICZM), to achieve a Good Environmental Status (GEnS), which is the main objective of the Water Framework Directive (WFD), requires reliable data on the physico-chemical as well as the biological characteristics of the components, i.e., rivers, lakes, and lagoons in the entire area.

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